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ALGAE USE EVALUATION FOR BIOGAS PRODUCTION IN LATVIA

Doctoral Thesis

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ANOTĀCIJA

Lai nodrošinātu pieaugošo energoresursu pieprasījumu, nepieciešams meklēt alternatīvas līdz šim plaši izmantotajiem neatjaunojamiem energoresursiem. Ierobežotais fosilo resursu daudzums un to ietekme uz vidi, ir pamats diskusijām par atjaunojamajiem energoresursiem ne tikai zinātnieku, bet arī pasaules līderu vidū. Kamēr tiek diskutēts par piemērotākajiem variantiem un to ieviešanu, Eiropas Savienība rīkojas. Eiropas Savienība 2020. un 2030. gadam ir uzstādījusi mērķi palielināt atjaunojamo energoresursu īpatsvaru gala patēriņā par 20 % un 40 % attiecīgi. Lai sasniegtu šos mērķus, nepieciešams atbalstīt un attīstīt gan jau esošo atjaunojamo energoresursu pielietojumu, gan arī meklēt jaunus resursus vai jaunus veidus to pielietojumam.

Latvijas bioekonomikas stratēģija 2030. gadam un Latvijas ilgtspējības stratēģija 2030. gadam nosaka nepieciešamību pilnvērtīgāk izmantot vietējos energoresursus, pieminot no jūras izskalotās aļģes, kā vienu no visnepilnīgāk izmantotajiem vietējiem resursiem. Lai gan aļģu izmantošanas pētniecība ir aktuāla nozare, neeksistē novērtējuma metodika, kas novērtētu aļģu izmantošanas potenciālu biogāzes ražošanai no enerģētikas, vides un ekonomiskajiem aspektiem vienkopus.

Pamatojoties uz ES izvirzītajiem mērķiem klimata un enerģētikas jomā un Latvijas izvirzītajiem rīcības plāniem šo mērķu sasniegšanai, autore promocijas darbā izvirza mērķi izstrādāt no aļģēm ražotas biogāzes novērtējuma metodiku. Novērtējuma metodikā iekļaujot enerģētiskos aspektus (enerģijas potenciāla novērtēšana), vides aspektus (ietekmes uz vidi novērtējums) un ekonomiskos aspektus (pilna dzīves cikla izmaksu novērtējums).

Promocijas darba pamatā ir 7 tematiskie vienotas zinātniskas publikācijas, kas publicētas dažādos zinātniskos žurnālos, un pieejamas zinātniskajās informācijas datu krātuvēs un starptautiskajās datubāzēs. Šo publikāciju mērķis ir pārnest un aprobēt aļģu izmantošanas biogāzes ražošanai novērtējuma metodikas ietvaru. Darbs sastāv no ievada un 4 daļām.

Darba ievads definē tā mērķi un uzdevums, apraksta darbā pielietoto metodoloģiju un sniedz īsu pārskatu par promocijas darba aprobāciju. Pirmā nodaļa satur literatūras apskatu. Otrā nodaļa satur izstrādātās metodikas izveides pamatu un detalizēti apraksta pielietoto metodoloģiju. Trešā nodala satur gadījuma analīzes scenāriju aprakstu. Ceturtajā nodaļā aprakstīti scenāriju analīzes rezultāti, kā arī veikta modeļa testēšana un novērtēšana. Iegūtie secinājumi ir apkopoti darba noslēgumā.

ANNOTATION

In order to meet the growing demand of energy resources, alternative resources are needed to replace and supplement the use of fossil fuels. The limited fossil resources and their impact on climate change are a topic of discussion not only among scientists, but world leaders as well. While the discussions are still on-going European Union is taking action by setting targets for year 2020 and year 2030 for climate and energy sectors. The aim is to increase the share of renewable resources up to 20 % and 40 % respectively. In order to meet these targets, the existing renewable energy resources need to be supported and their use expanded as well as new resources need to be researched and supported.

The Sustainable Development Strategy of Latvia 2030 and Latvian Bioeconomy Strategy 2030 highlights the need for a more sustainable use of local, available nature resources, also mentioning that washed-out marine algae are one of the least used local resources. Even though the algae research is a topical field, there is no evaluation methodology for determining the algae use potential for biogas production that would take into account energetic, environmental and economic aspects together.

Based on the EU targets for climate and energy sectors and Latvian strategies on how to reach those targets, the author of this thesis sets an aim to develop and test a methodology for evaluating algae use for biogas production taking into account three main aspects – energetic (experimental determination of energetic values), environmental (Life Cycle Assessment) and economic (Life Cycle Cost Analysis). The methodology development is based on a case study of locally available algae species in Latvia.

The basis of thesis is 7 thematically unified peer-reviewed scientific publications that are published in different scientific journals, available at different scientific information storages and international databases. The aim of these publications is to transfer and approbate the evaluation methodology. The thesis consists of introduction and four chapters.

Introduction defines the aim and tasks of the study, describes the structure of study and the methods used as well gives information about the approbation of the study. The first chapter contains the literature review. The second chapter contains the methodology development description as well as methods used within descriptions. The third chapter contains case study description. The fourth chapter describes the results of the case study, as well as contains the testing and evaluation of the methodology itself. The conclusions are summarized at the end of the thesis.

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TABLE OF CONTENTS

NOMENCLATURE

$\Delta I0$	Initial investment costs associated with the project alternative, EUR
ΔIt	Additional investment costs associated with the project alternative, EUR
α	significance level
a	Subscript of carbon
A^+	The ideal action of criteria i
AD	Anaerobic digestion
AHP	Analytic hierarchy process
ANOVA	Analysis of variance
b	Subscript of Hydrogen
B_0	Specific methane yield, L CH_4 / g_{VS}
$B_{INOCULUM}$	Measured inoculum methane amount of blank batch, mL CH_4
BMP	Biochemical methane potential, L CH_4 / kg_{VS}
BP	Biogas price, EUR / t.m^3 biogas
$BP_{NPV=0}$	Biogas price, where NPV of the project is 0, EUR / t. m^3 biogas
B_{SAMPLE}	Biochemical methane potential of sample, L CH_4 / kg_{VS}
B_{TOTAL}	Measured total methane amount of batch, ml CH_4
c	Subscript of oxygen
C_a	Relative closeness of alternative a to the ideal solution coefficient
CC	Climate change, kg CO_2 equivalents
CD	*Cerathophyllum demersum*
C_{DEBT}	Debt payments for biogas production, EUR
CF	Cash flow, EUR
CHP	Combined heat and power
C_i	Criteria i
C_{INS}	Insurance costs for biogas production, EUR
C_{LAB}	Labor costs for biogas production, EUR
$C_{O\&M}$	Operation and maintenance costs for biogas production, EUR
d	Subscript of nitrogen
dr	Discount rate, %
DALY	Disability adjusted life years
d_a^-	Performance value distance from negative-ideal action
d_a^+	Performance value distance from positive-ideal action
DPB	Discounted payback period, years
E_{CHP}	Total electrical and heat energy used for operating CHP unit, MWh / year
$E_{CLEANING}$	Total electrical and heat energy used for biogas cleaning, MWh / year
$E_{DIGESTION}$	Total electrical and heat energy used for digestion, MWh / year
$E_{PRE\text{-}TREATMENT}$	Total electrical and heat energy used for pre-treatment, MWh / year
$E_{PRODUCED}$	Total electrical and heat energy produced, MWh / year
EQ	Ecosystem quality, PDF per m^2 per year
ER	Energy input / output ratio

E_{STORAGE}	Total electrical and heat energy used for storage, MWh / year
EU	European Union
FS	Fixed solids
FS %	Fixed solid content, % or mg / kg
FV	*Fucus vesiculosus*
GDP	Gross domestic product
$GDP\ Def_{\mathrm{In\ a\ base\ year}}$	GDP deflator index in a past year
$GDP\ Def_{\mathrm{In\ a\ specific\ year}}$	Gross domestic product deflator index in a specific year
GHG	Greenhouse gases
HH	Human health, DALY
K	Initial investment at the base year, EUR
LCA	Life cycle analysis
LCCA	Life cycle cost analysis
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
MCA	Multi-criteria analysis
n	Number of parameters
NPV	Net present value, EUR
O&M	Operation and maintenance
p	probability value
PDF	Potentially Disappeared Fractions of species
$Price_{\mathrm{In\ a\ base\ year}}$	A price level in a past year, EUR
$Price_{\mathrm{In\ a\ specific\ year}}$	A price level in a specific year, EUR
Pt.	Points
r	Discount rate, %
R_{BG}	Revenues from selling biogas from biogas production, EUR
RD	Resource depletion, MJ
R_{DIG}	Revenues from selling digestate as fertilizer, EUR
RES	Renewable energy (re)sources
r_{ai}	Normalized performance of alternative a with respect to criteria i
SD	Standard deviation
S_t	Savings in operation costs in year t associated with a given alternative, EUR
TOPSIS	Technique for order preference by similarity to ideal solution
TS	Total solids
TS %	Total solids content, % or mg / kg
UI	*Ulva intestinalis*
US EPA	United States Environmental protection agency
v_{ai}	Weighted normalized performance of alternative a with respect to criteria i
V_{BG}	Amount of biogas sold, thousand m^3 biogas
v_I^-	Minimum performance value if the criterion i is to be minimized
v_I^+	Maximum performance value if the criterion i is to be maximized
V_m	Normal molar volume of methane, m^3

VS	Volatile solids
VS_{SAMPLE}	Volatile Solid content of measured sample in batch, kg
VS %	Volatile solids content, % or mg / kg
W_{dish}	Weight of the dish after igniting, g
w_i	Weights of criteria i
W_N	Weight of criteria n
W_{sample}	Weight of the dish with wet sample, g
W_{total}	Weight of the dish with dry sample, g
$W_{volatile}$	Weight of the residues and dish after igniting, g
x_{ia}	Performance of alternative a with respect to criteria i
y	Minimum length of time over which future net cash flows have to be accumulated in order to offset initial investment costs, years
Π	Multiplication of all elements in a row

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. RES could meet the long-term demand and they are also carbon neutral. Carbon dioxide and other greenhouse gases (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 GHG, 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 year 2021 until year 2030 EU 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 members also have the option to set their targets 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 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 Latvian National Energy and Climate Plan 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 identifies the need for a more sustainable use of locally, available nature resources. It includes several RES that are already used as well as support for research. These documents also mention the use and the 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). The yearly available biomass quantifiable in thousand tons of algae could be potentially used as renewable resources. European Union 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 the 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.

   a. Develop the design of experiment for methane potential determination in a laboratory setting and perform the experiments with locally available algae species.
   b. Perform life cycle assessment and evaluate the environmental impact of developed scenarios.
   c. Perform life cycle cost analysis and evaluate the total costs of the developed scenarios.
   d. 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).

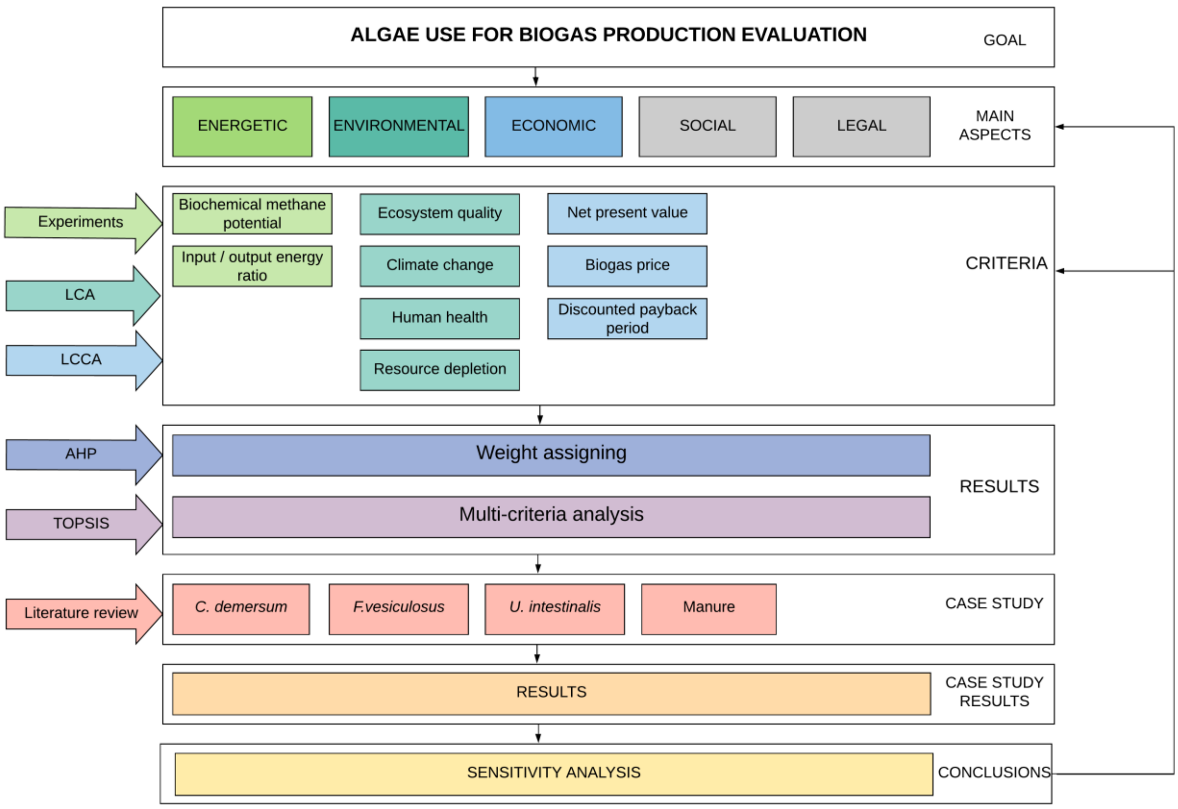

Fig. 1. Main methods used within the developed methodology.

Design of experiment is used to set-up experimental plan and statistical methods like analysis of variance (ANOVA) is used to analyze input factor influence on 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 EU 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 the 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 insights into the projects, allowing to determine the weak spots or areas that need improvement at the municipal or governmental level.

The outcomes from carried out evaluations gives 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 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.
2. Pastare, L., Romagnoli, F., Blumberga, D. Comparison of biomethane potential lab tests for Latvian locally available algae. "Energy Procedia", 2018, Vol 147, pp.277.–281. Available: doi: 10.1016/j.egypro.2018.07.092.
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 Prelimenary 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, Nr.5, pp. 1-8. eISBN: 978-609-457-538-9

Other Publications

8. 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.
9. 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.
10. Lauka, D., Pastare, L., Blumberga, D., Romagnoli, F. Preliminary analysis of anaerbic digestion process using *Cerathophyllum demersum* and low carbon content additives: a batch test study. “Energy Procedia”, 2015, Vol 72, pp. 142.–147. Available: doi: 10.1016/j.egypro.2015.06.020.
11. Pastare, L., Ozoliņa, L., Blumberga, D. Production of Foliage Extracts. In: International Scientific Conference "Environmental and Climate Technologies": Abstract Book, Latvia, Rīga, 14-16 October, 2013. Riga: RTU Press, 2013, pp. 30-31. ISBN 978-9934-8302-9-7
12. 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 Prelimenary 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 anaerbic 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. Rīga: RTU Izdevniecība, 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 methodology includes following aspects: Energetic, Environmental and Economic.

The Doctoral Thesis contains Introduction and 4 chapters:

- Literature analysis;
- Methodology development;
- Case study;

- Case study results and analysis of methodology.

The introduction defines the aim and tasks of the study, describes the structure of study and the methods used within, as well as gives information about the approbation of the study.

The first chapter is literature analysis that gives an insight into the topic. The second chapter describes the development of the methodology and methods used within to calculate the selected criteria. The third chapter describes the case study and the scenarios used for methodology approbation. The case study results of each criterion for scenarios are described in fourth chapter. The methodology testing, evaluation and approbation are also described within the fourth chapter. Conclusions and discussion are summarized at the end of study.

The Bibliography contains 65 titles but taking into account the fact that the Thesis is a thematically unified 7 publications, the total number of used references is 191.

1. LITERATURE ANALYSIS

1.1. Algae

Algae are simple aquatic organisms without differentiation into leaves, stems and roots. They are chlorophyll-containing organisms composed of one cell or grouped together in colonies or as organisms with many cells, sometimes collaborating together as simple tissues. Algae are fundamentally autotrophic and photosynthetic. (Bruton, Lyons, Lerat, Stanley, & Rasmussen, 2009)

Algae are heterogeneous group of organisms with two distinct types of algae – macro algae (i.e. seaweeds in case of marine macro algae) and microalgae. The macroalgae include sub-groups of green, red and brown algae that occupy the littoral zone while microalgae are found in benthic and littoral habitats, also as phytoplankton. For the purpose of this work, the term algae will refer to macroalgae only. (Hagen, 2009)

The gross chemical composition of micro- and macro-algae is highly dependent on different factors such as light intensity, temperature, nutrients available, location, season, salinity and species. Generally algae contain different properties of proteins, lipids, carbohydrates, pigments, vitamins, fats and others. (Bruton et al., 2009)

Generally, algae can be divided into marine and freshwater species. But as there also are brackish water environments and places with changing salinity level (river estuary into sea or ocean), there are both freshwater and marine species that have adapted to the environment. The main differences between marine and freshwater species are within the cell walls of algae. Due to the salinity in water algae cells must equalize the osmotic pressure, meaning that marine species (or freshwater species grown in brackish waters) have harder to break down cell walls. This should be taken into account when several species are evaluated for processing them with fermentation or other conversion methods. (Wellinger, 2009)

The high growing rates and availability of algae worldwide means that, it is a potentially high-valued resource, but correct application methods should be found. As water pollution is also a globally recognized issue, the use of washed out or overcrowded algae or the introduction of algae in some cases might became a vital point for viability and sustainability. In general algae group includes a wide range of organisms with different cell structure, different sizes, colors and characteristics. Each of the groups has a different potential for being used either for extracting compounds or producing energy

Different aspects like salinity, available nutrients, temperature and lighting impact the type of algae growing in specific region. In order to diminish the impact and costs of transportation of resources, locally available species should be evaluated first. The commonly available species as well as potentially farmable species should be evaluated as a useful resource. The most common use of leafy plants and alike is biogas production.

1.2. Biogas production

Anaerobic digestion (AD) is a biological process, which occurs naturally in environments with little or no oxygen. Microorganisms that prefer such environment depredate organic matter and produce biogas, primary methane and carbon dioxide. The unique ability to provide both treatment for organic wastes and source of renewable energy is the reason for its success worldwide. If digestate is not classified as waste, it removes a barrier to implement such productions. Though most commonly sewage treatment leftovers or animal wastes are chosen as feedstock, other organic matter as wastepaper, food waste, algae and more can be successfully used. To boost the productivity of such plants, energy crops can be used. As AD process is appropriate for high moisture content substrates (up to 80 % – 90 % moisture) algae can easily be used and a pre-treatment phase of dewatering can be skipped. To increase the digestion process and methane production, feed is usually shredded, minced or hydro-crushed to increase surface area available for digestion. Different feedstock will produce different quality residues; its characteristics should be examined to find most useful usage of it. (Kelly & Dworjanyn, 2008; Lewis, Salam, Slcak, Winton, & Honson, 2011; Singh & Olsen, 2011)

The product of anaerobic digestion is biogas that consists of:

- Methane (CH_4) 50 % – 75 %;
- Carbon dioxide (CO_2) 25 % – 50 %;
- Nitrogen (N_2) 0 % – 10 %;
- Hydrogen (H_2) 0 % – 1 %;
- Hydrogen sulphide (H_2S) 0 % – 3 %;
- Oxygen (O_2) 0 % – 1 %.

Majority of studies shows proportion of methane in biogas produced in range of 59 % – 75 % regardless of species, pre-treatments used and other operation conditions. This reveals that alga has a great potential of feasible conversion of algae. Since the produced gas is not directly released into the atmosphere and carbon dioxide comes from an organic source, biogas does not contribute to increasing atmospheric carbon dioxide concentrations. (Kelly & Dworjanyn, 2008; Lewis et al., 2011; Sialve, Bernet, & Bernard, 2009)

Anaerobic biodegradation is carried out by 3 groups of bacteria:

- Hydrolytic and fermentative bacteria, which hydrolyse polymers, and ferment their resulting monosaccharide to carboxylic acids and alcohols;
- Acetogenic bacteria which convert these acids and alcohols to acetate, hydrogen and carbon dioxide;
- Methanogenic bacteria, which converts the end products of acetogenic reactions to methane and carbon dioxide. (Vergara-Fernández, Vargas, Alarcón, & Velasco, 2008)

Anaerobic digestion can be carried out in different types of reactors – continuous stirred tank reactors, batch reactors and semi-continuous reactors. As algae needs longer time for breaking down the cell walls, a reactor with longer retention time should be used. Digester

tank size range is from around 1 m^3 for small households up to 2 000 m^3 for large commercial installations. (Demirbaş, 2001; Zamalloa, Vulsteke, Albrecht, & Verstraete, 2011)
The theoretical methane yield can be evaluated if organic matter composition is known. The methane yield of anaerobic digestion process is adapted from stoichiometry reaction of organic matter converted into methane, carbon dioxide and ammonia (see Eq. 1.1 and Eq. 1.2). (Raposo, De La Rubia, Fernández-Cegrí, & Borja, 2012)

$$C_aH_bO_cN_d + \left(\frac{4a - b - 2c + 3d}{4}\right) \cdot H_2O \rightarrow$$
$$\rightarrow \left(\frac{4a + b - 2c - 3d}{8}\right) \cdot CH_4 + \left(\frac{4a - b + 2c + 3d}{8}\right) \cdot CO_2 + d \cdot NH_3 , \qquad (1.1)$$

where
a – subscript of carbon;
b – subscript of hydrogen;
c – subscript of oxygen;
d – subscript of nitrogen.

The specific methane yield is expressed in liters of methane per gram of volatile solids (VS) and is calculated as (Raposo et al., 2012):

$$B_0 = \left(\frac{4a - b - 2c - 3d}{12a + b + 16c + 14d}\right) \cdot V_m , \qquad (1.2)$$

where
B_0 – specific methane yield, L CH_4/ g_{VS};
V_m – normal molar volume of methane, L.

The theoretical approach allows estimating the maximum potential yields which in reality is different and lower. (Raposo et al., 2012)

Marine and freshwater biomass (macro-algae, macrophytes) has been shown to be a good substrate for fermentation and could be a good alternative for natural gas. Research in this field began in the eighties and focused on different species. Compared to traditional terrestrial biomasses, such as wood and straw, information about aquatic biomass as a feedstock for thermochemical conversion is scarce. The main problems with algae digestion are the biochemical composition and the nature of cell walls in algae, possibility of forming toxic ammonia due to high nitrogen content (mostly because of low C/N ratio) and the presence of sodium in the marine species. These problems can be subverted with pre-treatment methods in most of the cases. Generally, two pre-treatment processes can be distinguished – chemical and physical. Chemical, thermal and ultrasonic treatments improve the disintegration of the most refractory organic fractions (increase of production kinetics and/or methane yield). Separation techniques, concentration or dehydration mobile and maximize the proportion of digestible organic matter. Even though some of the studies indicate that pre-treatment methods don't increase the overall energy gain of CH_4 production (as most of them uses more energy than what is gained afterwards) positive examples demonstrating improvement on methane yield exist. An evaluation of pre-treatment method efficiency should be carried out for each case individually to validate its need. (Kepp, Machenbach, Weisz, & Solheim, 2000; Lakaniemi, Tuovinen, & Puhakka, 2013; Pragya, Pandey, & Sahoo, 2013)

Some of the problems arising from algae characteristics (like poor C/N ratio that contributes to lowering the methane yield) can be easily overcome with using algae in co-digestion with a low nitrogen level substrate. In such way the optimal influent composition can be achieved together with higher methane yield. The optimal proportion of carbon and nitrogen is between 20 and 35. (Sialve et al., 2009)

2. DEVELOPMENT 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 opportunities 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 2.1 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 2.1 for more details.

New renewable energy opportunity developments 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 (or damage) categories – ecosystem quality, climate change, human health and resource depletion. See Chapter 2.2 for more details.

There are several methods how to evaluate the cost-effectiveness of a project, but life cycle costs 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 2.3 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 2.4. 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 maker 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 2.5. 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. 2.1 for the full developed methodology scheme.

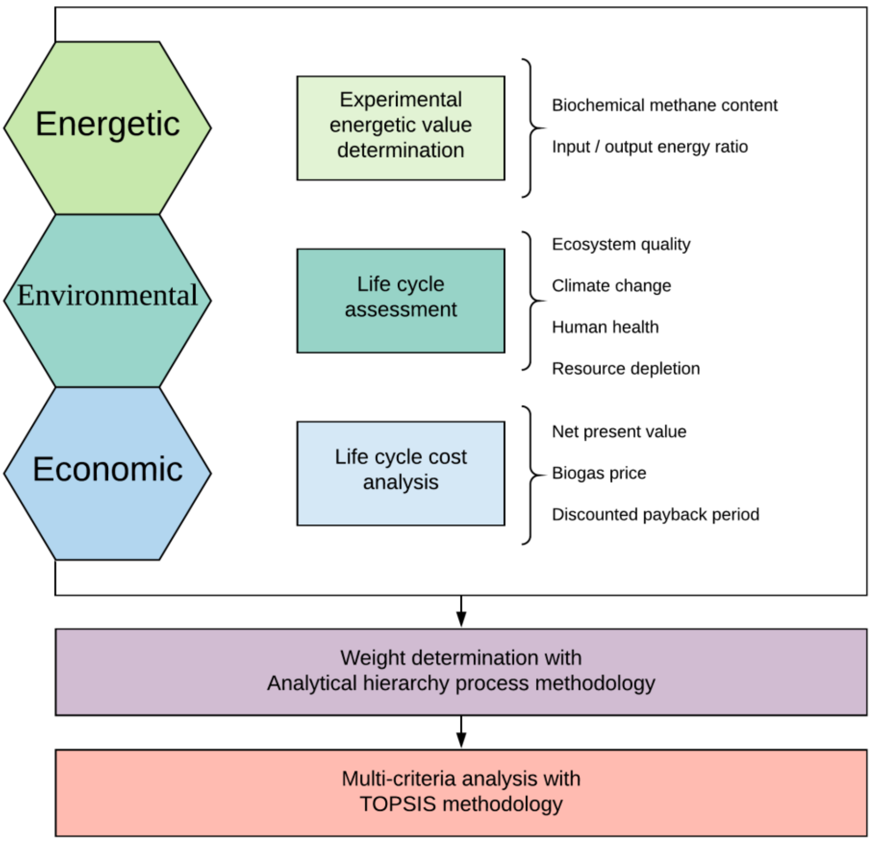

Fig. 2.1. Overall methodology development scheme.

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

2.1. 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 ratios 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 and total solids are determined prior 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)

The experiment plan can be described in steps to be followed and type of methods used for result gain. In order to achieve the aim the main phases in experiment conduction are as follows:

1. Sampling.
2. Characteristics determination:
    a. total solids (TS);
    b. volatile solids (VS);
    c. fixed solids (FS).
3. BMP determination.
4. Data analysis.

Total solid, volatile solid and fixed solid content for samples was determined by method 1684 developed by the United States Environmental Protection Agency "Total, Fixed and Volatile Solids in Water, Solids, and Biosolids". The procedure for total solids determination is carried out in 5 steps. Step one - preparation of the evaporating dishes and watch glasses by igniting them for 1 hour in 550 °C (1022 °F) or 105 °C (221 °F) (depending whether also fixed and volatile solids will be determined). After that dishes are cooled in desiccator and weighed. Next step is preparation of samples by adding them to cooled dishes. For the first step heating an *Ecocell BMT standart 55* dryer oven was used, but for the next step heating of 550 °C (122 °F) a muffle furnace *Nabertherm L5/11* was used. (US Environmental Protection Agency, 2001) The next step is the drying of the samples at temperatures in range from 103 °C to 105 °C for 12 hours. Then cooling of the samples in desiccators, weighing of the dishes with dried samples. Repeated drying of the dishes in 103 °C to 105 °C (217 °F to 220 °F) for 1 hour, cooling in desiccator and weighing of the dishes. Repetition must be done till the weight change is less than 4 % or 50 mg (whichever is less). Calculations of the total solids content of the samples according to US EPA are described in Eq. 2.1 – 2.3. (US Environmental Protection Agency, 2001)

$$\mathrm{TS}\ \% = \frac{\mathrm{W_{total}} - \mathrm{W_{dish}}}{\mathrm{W_{samples}} - \mathrm{W_{dish}}} * 100\ \%, \tag{2.1}$$

where
W_{dish} – weight of the dish after igniting, g;
W_{sample} – weight of the dish with wet sample, g;
W_{total} – weight of the dish with dry sample, g.

The determination of fixed solids (FS) and volatile solids (VS) is similar to TS determination procedure and is carried out in following steps:

- to heat the dish with dried residues in muffle furnace in 550 °C (1022 °F) for 2 hours. Cooling in desiccator and weighing of the dishes;
- repeated igniting of the dishes ($W_{volatile}$) in 550 °C (1022 °F) for 30 min till the weight change is less than 4 % or 50 mg (whichever is less);
- calculations of the FS and VS content of the samples. (US Environmental Protection Agency, 2001)

Fixed solids content calculation according to EPA Method 1684:

$$\mathrm{FS}\ \% = \frac{\mathrm{W_{volatile}} - \mathrm{W_{dish}}}{\mathrm{W_{total}} - \mathrm{W_{dish}}} * 100\ \%, \tag{2.2}$$

where
FS % – Fixed solid content, % or mg / kg;
$W_{volatile}$ – weight of the residues and dish after igniting, g. (US Environmental Protection Agency, 2001)

The calculation of volatile solids content: (US Environmental Protection Agency, 2001)

$$\mathrm{VS}\ \% = \frac{\mathrm{W_{total}} - \mathrm{W_{volatile}}}{\mathrm{W_{total}} - \mathrm{W_{dish}}} * 100\ \%, \tag{2.3}$$

where
VS % - Volatile Solids content, % or mg / kg.

This method is used for both determining the TS and VS content of used biomass and inoculum, as well as for determining the total solid contents after samples have stopped producing biogas. Chemical composition analysis of algae is carried out with dry mass of algae.

When the chemical composition and TS/VS content of chosen algae species and inoculum are known, biogas yield tests can be conducted. In order to produce biogas certain conditions must be maintained during the whole experiment time. The BMP determination was carried out with batch tests. There are several known methods how to perform BMP tests (German Standard Procedure VDI 4630, Moller method and Hansen method), how to measure the produced biogas volume (liquid replacement at intervals, liquid replacement continuously or syringe at intervals) and how to determine the methane content in biogas (gas chromatograph or absorption of CO_2 in alkaline liquid). (Hansen et al., 2004; Møller, Sommer, & Ahring, 2004; Pham, Triolo, Cu, Pedersen, & Sommer, 2013; VDI, 2006) Based on Pham et. al. the differences in results between methods are not statistically significant and the simpler methods can be used when access to gas chromatography and other equipment are not available. The Moller method, measurements with syringe and adsorption of CO_2 are chosen based on available equipment and substrates.

The basic principle of these tests is to create an anaerobic environment with a specific temperature (37 °C or 98.6 °F) where methanogenic bacteria could digest the input biomass to digestate and biogas. As the aim of the experiment is to determine the biogas yield, but the yield is dependent on several parameters – biomass type, size, pre-treatment methods, used additives, temperature regime, inoculum-biomass ratio and more. The chosen parameters to change and determine their impact on biogas yield are input biomass particle size and biomass-inoculum ratio. Literature review suggests that smaller particle size leads to faster fermentation thus a higher biogas yield. The biomass-inoculum ratio however is dependent on biomass and inoculum used. The logic would suggest the more inoculum, the more bacteria, the faster the fermentation can happen, but that directly impacts total produced biogas yield, not necessarily the specific biogas yield of input biomass itself.

The experimental plan is based on the aim of the experiment – to determine the biogas yield and find the optimal parameters for higher yield. Based on the literature review, the following parameters have been selected:

- size of the feedstock particles;
- the ratio of input biomass versus inoculum;
- the additives such as buffers and water.

Benchmarking or blank sample is also used to determine the biogas yield of algae alone (by subtracting the benchmarking sample yield from all the other samples). In order for the benchmarking scenario data to be usable it should be prepared in the same manner as others. The buffer for pH normalization is also added to blank samples.

When the alga is prepared, all the components can be added into the bottles. All samples are prepared in triples. The batch tests were carried out in 100 mL serum type bottles with a working volume of around 50 mL. The alga biomass and water are added to the bottles. Buffer $NaHCO_3$ is added to the samples (3 g per liter of working volume). The buffer stabilizes the pH level of samples so that the methanogen bacteria can survive. The last added element is the inoculum. The inoculum used is a digestate of wastewater sludge digestion process. Before using the inoculum for biogas tests, it was degassed for a week. The degassing step lowers the yield of inoculum thus expanding the time between two measurements. After inoculum is added to bottles, they are sealed with CO_2 or N_2 to ensure that there is no oxygen within the bottles (as the process is anaerobic). The flushing is carried out for 30 seconds, and then the bottles are closed with rubber stoppers with crimped aluminum bottle caps. When the samples are prepared, they are shaken and put in the incubator at a temperature of 37 °C (98.6 °F).

The measurements of produced gas yields are carried out using a syringe at intervals method. As the bottle cap is sealed the produced biogas stay inside the batch bottle. Measurements are carried out twice a week at the beginning and the time between measurements can be lengthened in necessary. In order to measure the yield of samples a needle attached to a syringe must be stuck through the rubber bottle cap. The determination of methane content of biogas is carried out in the same step using adsorption of CO_2 in alkaline liquid. In order to measure the yield of methane rather than the overall biogas yield (as methane is the part of biogas with the highest energetic value) the 20 ml plastic syringe is filled with 5 ml of a 3 M NaOH solution. As carbon dioxide dissolves in this solution and other biogas impurities comprise small amounts, for this reason the measurements can be directly associate to the total amount of biochemical methane yield with a negligible error. (Pham et al., 2013) As the pressure in the bottle increases due to the produced gas amount, the moment when a needle is stuck into the cap, gas starts to bubble through the solution (dissolving the CO_2) and moving the plunger top. See Fig. 2.2 for the schematic representation of the BMP measurements. The amount of gas inflowing in the syringe equals the amount of produced gas in a certain time period as the pressure equalizes. The measurements are carried out for 30 days or when most of the samples have stopped producing biogas for at least 4 days. For those samples that are still producing biogas the amount not produced can be omitted, as when using a continuous type of digestion reactors, the amount of time spent in it is limited.

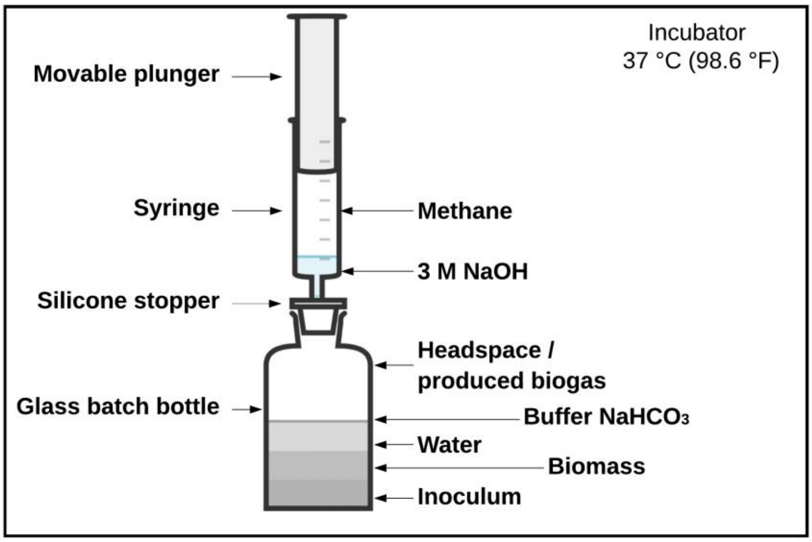

Fig. 2.2. Scheme of biogas batch test and measurement of BMP.

The BMP value calculations after the measurements are shown in Eq. 2.4.

$$B_{SAMPLE} = \frac{B_{TOAL} - B_{INOCULUM}}{VS_{SAMPLE} * 1000}, \quad (2.4)$$

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 are afterwards analyzed using ANOVA statistical testing. (Smalheiser, 2017) More details about experiments can be found in publications Pastare, Aleksandrovs, Lauka, & Romagnoli, 2016; Pastare, Romagnoli, Rugele, Dzene, &

Blumberga, 2015; Pastare & Romagnoli, 2019; Romagnoli, Pastare, Sabūnas, Bāliņa, & Blumberga, 2017.

The second energetic criterion is Energy input/output ratio, which describes the amount of energy needed to produce one unit of energy. It takes into account the electricity and heat need for the production process (but excludes the transportation needs) per year and the amount of heat and electricity produced in the CHP unit per year. The criterion ER calculation is shown in Eq. 2.5.

$$ER = \frac{E_{STORAGE} + E_{PRE-TREATMENT} + E_{DIGESTION} + E_{CLEANING} + E_{CHP}}{E_{PRODUCED}}, \quad (2.5)$$

where

$E_{STORAGE}$ – total electrical and heat energy used for storage, MWh per year;
$E_{PRE\text{-}TREATMENT}$ – total electrical and heat energy used for pre-treatment, MWh per year;
$E_{DIGESTION}$ – 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 higher the ratio, the less favorable the scenario is. For the selected scenarios and production scheme, the electrical energy needs for storage, pre-treatment, digestion, biogas cleaning and operating the CHP and biogas unit is considered as well as the heat needs for digestion. The fuel needs for transportation are not included in the ER.

2.2. 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. There are several definitions of LCA that include several methods, but what they all have in common is a holistic view of the life cycle and dealing with the environmental aspects, emissions, materials and waste. Even though there is no internationally accepted methodology for LCA, ISO standard 14040 outlines the procedure. (Guinée & Heijungs, 2017; ISO, 2006)

The main phases of conducting a life cycle assessment study are:

- defining the goal and scope of the study;
- life cycle inventory (LCI) – collection of input and output data;
- life cycle impact assessment (LCIA) – environmental relevance of inputs and outputs;
- interpretation of the study.

It is possible to perform life cycle assessment in several ways, as long as documentation is kept of everything.

In order to quantify the environmental impacts of the study the program *SimaPro* has been used. Within the program the chosen calculation method is *IMPACT 2002+*. It gives the overall impact in 4 damage categories each expressed with a different unit. The 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). Score of 0.2 PDF / m^2 per year implies the loss of 20 % of species of 1 m^2 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)

This method combines 14 mid-points (human toxicity, respiratory effects, ionizing radiation, ozone layer depletion, photochemical oxidation, aquatic eco-toxicity, terrestrial eco-toxicity, terrestrial acidification/nutrification, aquatic acidification, aquatic eutrophication, land occupation, global warming, non-renewable energy, mineral extraction) and 4 previously mentioned damage categories (see Fig. 2.3). (Goedkoop et al., 2008; Goedkoop, Oele, Leijting, Ponsioen, & Meijer, 2013)

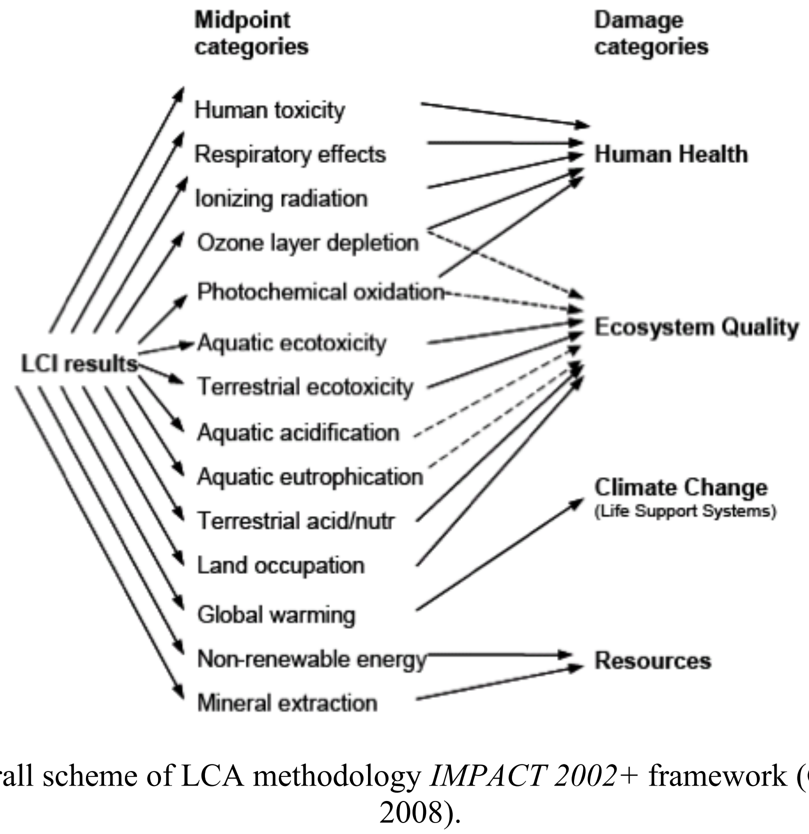

Fig. 2.3. Overall scheme of LCA methodology *IMPACT 2002+* framework (Goedkoop et al., 2008).

An arrow symbolizes that a relevant impact pathway is known or assumed to exist. Dotted arrows represent uncertain impact pathways between midpoint and damage levels that are not modeled quantitatively. Midpoint characterization factors are based on equivalency principles, i.e. midpoint characterization scores are expressed in kg-equivalents of a substance compared to a reference substance. The principal scope is common to all impact categories: overall long-term effects are being considered through the use of infinite time horizons. (Althaus et al., 2007; Goedkoop et al., 2008; Humbert, Schryver, Bengoa, Margni, & Jolliet, 2014; Jolliet et al., 2003)

The normalization of damage categories expresses the final value as the equivalent persons affected during 1-year period per unit of emissions. The normalization factors used in *IMPACT 2002+* are listed in Table 2.1.

Table 2.1.

Normalization Factors for Damage Categories in Europe within LCA Methodology IMPACT 2002+ (Goedkoop et al., 2008)

Damage categories	Normalization factors	Unit
Ecosystem quality	13 700	Potentially disappeared fraction per m^2 per person per year
Climate change	9950	Kg carbon dioxide equivalent per person per year
Human health	0.0071	Disability adjusted life years per person per year
Resource depletion	152 000	MJ per person per year

The goal of this study is to compare the environmental impact of selected algae-based biogas production scenarios. The results of LCA will be used as part of larger MCA and provide the environmental impact data. As the goal is comparison of scenarios, all differences in processes should be reported with attention to detail. The main boundaries and assumptions for scenarios are set in Chapter 2.1. 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). Life cycle inventory can be seen in Table 2.2.

Table 2.2.

Life Cycle Inventory of Scenarios

Parameter	Value				Unit	Source
	F.vesiculosus	*U.intestinalis*	*C.demersum*	Manure		
Algae collection and transportation						
Transportation distance from algae collection site to biogas plant	100	100	100	-	km	Assumption
Algae input per year	6663	9055	6328	-	t	Calculated
Manure input per year	14 432	14 432	14 432	17 318	t	Calculated
Barge ship use (Diesel, max 350 t, 50 % empty return)	-	-	126 560	-	t*km	Calculated
Excavator truck use (Diesel, 100 kW capacity, 50 % empty return)	6663	9055	-	-	t	Calculated

Table 2.2 continued

Parameter	Value				Unit	Source
	F.vesiculosus	*U.intestinalis*	*C.demersum*	Manure		
Transportation truck use (Diesel, max 20 t, emission class EURO4, 50 % empty return)	666 300	905 500	632 800	-	t*km	Calculated
Storage						
Electricity need	17 280	17 280	17 280	-	kWh	Calculated
Pre-treatment						
Electricity need	54 750	82 125	54 750	-	kWh	Calculated
Transportation use (light truck, diesel)	666.3	905.5	632.8	-	t*km	Calculated
Groundwater	45 274	33 316	-	-	ton	Calculated
Wastewater	45 274	33 316	-	-	ton	Calculated
Digestion						
Transportation use (skid steer, diesel)	14 432	14 432	14 432	17 318	m^3	Calculated
Electricity need	153.3	153.3	153.3	153.3	MWh	Calculated
Heat need	1182.6	1182.6	1182.6	1182.6	MWh	Calculated
Methane emissions	2863	2863	2863	2863	kg	Assumption
Avoided phosphate fertilizer as P_2O_5 from digestate	188	169	166	139	t	Calculated
Avoided nitrogen fertilizer as N_2 from digestate	338	304	299	249	t	Calculated
Avoided potassium fertilizer as K_2O from digestate	169	152	149	125	t	Calculated
Biogas cleaning						
Groundwater	1231	1231	1231	1231	kg	Calculated
Activated carbon	123	123	123	123	kg	Calculated
Wastewater	1.354	1.354	1.354	1.354	m^3	Calculated
Use						
Carbon dioxide, biogenic	1226.4	1226.4	1226.4	1226.4	ton	Calculated

The construction phase and end-of life for the biogas plant is not taken into account. Produced digestate is seen as avoided product as it can be used as liquid fertilizer.

2.3. Economic Criteria

The proposed concept of a life cycle cost analysis is widely used to analyze and evaluate various kind of project alternatives on their profitability over the whole life span starting from acquiring and ending with disposing in order to support decision-making process. 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 main advantages of using LCCA are that projections of significant and relevant cash flows over the project life span are included; that economic analysis considering the time value of money are included; that comparison of various alternatives is included; that planning and budgeting long term is included; that it offers assistance in decision making; that it is basis of cost reduction at early stage; that analysis of the most critical cost positions is included. The constrains of using LCCA are that usually indirect costs are out of boundaries; that it is time consuming approach; that lack of reliable data may lead to unreliable results; that it is impossible to compare alternatives with different non-monetary benefits.

Overwhelmingly typical cost structure of any project consists of four main positions such as acquisition and design costs, while developing the project, construction costs, operating, maintenance and repair costs, and residual costs, namely, salvage value.

However, there exist considerable disadvantage, this conventional cost analysis approach can lead to incorrect investment decisions for environmental projects (Gluch & Baumann, 2004). For example, usually indirect costs such as environmental and social externalities are out of boundaries due to impossible or tough monetization process.

As it was mentioned before LCCA is based on economic analysis in order to evaluate the life cycle cost of a project proposed over its life cycle. The main advantage of this economic analysis is consideration of the time value of money. The approach requires using discounted cash flows or in other words present value of money (Fuller & Petersen, 1995). Consideration of the time value of money is essential, because generally present time money has a higher value than the same amount of money in future as it fluctuates with time. Additionally, consideration of the time value of money by using the discount rate in general case reflects the opportunity costs. (Crowe, 2005) Thereby, generally discounting takes into consideration the opportunity costs, i.e., the opportunity missed by investing money in a certain project.

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). In order to convert cash flows to present values different parameters are required.

Cash flows are discounted, or present values are obtained by multiplying discount factor and the value of money in a given year. All calculations obtained over the years are summed up which represent as discounted cash flow amount, or NPV, respectively. In practice, it is usually assumed that discount rate is constant over time (r1 = r2 = rn).

With a time-invariant discount rate NPV value of cash flows (including initial investment) can be obtained by using general Eq. 2.6.

$$\mathrm{NPV} = -\mathrm{K} + \frac{CF_1}{(1+r)^1} + \frac{CF_2}{(1+r)^2} + \frac{CF_3}{(1+r)^3} + \cdots + \frac{CF_n}{(1+r)^n}\,, \tag{2.6}$$

where

NPV – net present value, EUR;

K – initial investment at the base year, EUR;

r – discount rate, %;

CF – cash flow, EUR;

n – number of years ahead.

It is worth to outline, that cash flow discounting commonly is conducted in terms of constant value of money. (Fuller & Petersen, 1995) In other words, in valuations there is no specific provision for future inflation or deflation. Constant value of money has uniform purchasing power, which is linked to the base year. Thereby, it is implicitly assumed that costs and revenues are likely to escalate at the same rate.

Another metric used for comparing and evaluating the different biogas production scenarios is the produced biogas price (BP). The costs of biogas production are calculated considering the revenues from digestate and biogas itself, 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 considered. The BP is calculated using iteration, to find the price that corresponds with NPV value of 0 (Eq. 2.7). In this case there are no profits during the whole life cycle and the corresponding revenue just covers the costs of production. For the alternatives to be profitable, the biogas selling price should be higher as this criterion represents the 0 losses point.

$$BP_{NPV=0} = f\left(\frac{(C_{LAB} + C_{INS} + C_{O\&M} + C_{TAX} + C_{DEBT}) - (R_{DIG} + R_{BG})}{V_{BG}}\right), \tag{2.7}$$

where

$BP_{NPV=0}$ – biogas price, where NPV of the project is 0, EUR / t. m^3 biogas;

C_{LAB} – labor costs for biogas production, EUR;

C_{INS} – insurance costs for biogas production, EUR;

$C_{O\&M}$ – operation and maintenance costs for biogas production, EUR;

C_{DEBT} – debt payments for biogas production, EUR;

R_{DIG} – revenues from selling digestate as fertilizer from biogas production, EUR;

R_{BG} – revenues from selling biogas from biogas production, EUR;

V_{BG} – amount of biogas sold, thousand m^3.

An additional supplementary measure is Discounted Payback (DPB). Although either Simple Payback or Discounted Payback measures the time necessary to recover initial investment costs, Discounted Payback is more preferable because it uses discounted cash flows. It is worth to mention, the measure cannot be applied for selecting among mutually-exclusive project alternatives. Eq. 2.8 shows the calculation of discounted payback period for a project. (Gallagher & Andrew, 2003)

$$\sum_{t=1}^{y} \frac{S_t - \Delta l_t}{(1 + dr)^t} \geq \Delta l_0, \tag{2.8}$$

where

y – minimum length of time over which future net cash flows have to be accumulated in order to offset initial investment costs, years;

S_t – savings in operation costs in year t associated with a given alternative, EUR;

ΔI_0 – initial investment costs associated with the project alternative, EUR;

ΔI_t – additional investment costs associated with the project alternative, EUR;

dr – discount rate, %.

Discounted payback period measure presents how long recovery of initial investment will take place. The measure can be used to accept or reject a certain project.

As previously discussed, net present value (NPV) and supplementary measures such as biogas price and discounted payback period, assist decision-making process. If NPV value is larger than 0, project can be accepted. If NPV value is below 0, project should be rejected or the highest NPV value of all alternatives should be chosen. NPV indicates the amount of net benefit of a project, however, show nothing on returns per unit. Therefore, to obtain a complete picture on project cost-effectiveness it is necessary to compute supplementary measures indicated before. The alternative with the lowest production costs is more favorable. DPB should be shorter that study period when screening projects. (Gallagher & Andrew, 2003)

In addition, cost estimation is gathered from various sources such as books and manuals, pilot projects, publications, laboratory experiments, expert enquires, if necessary, internet sources with a certain extent on reliability, technology suppliers etc. All cost estimations are subject to reference. It is worth to outline, that cost estimation is made with a consideration of the time value of money and currency rates, namely, to convert that price into today's units, GDP deflator (Gross Domestic Product deflator) as price index and currency rates are used. GDP deflator is defined as „a measure of the price level calculated as the ratio of nominal GDP to real GDP times 100" (Mankiw, 2017). In other words, GDP deflator is a measure of the price level of domestically produced goods and services. It is broader measure of the price level and shows overall inflation rates than consumer price index.

Eq. 2.9 is used to convert past prices to price level in a specific year by using GDP deflator value for a specific year. (Mankiw, 2017)

$$\text{Price}_{\text{in a specific year}} = \frac{\text{GDP Deflator}_{\text{in a specific year}}}{\text{GDP Deflator}_{\text{in a base year}}} \text{ x Price}_{\text{In a base year}}, \tag{2.9}$$

where

$Price_{\text{In a specific year}}$ – a price level in a specific year, EUR;

$Price_{\text{In a base year}}$ – a price level in a past year, EUR;

$GDP\ Deflator_{\text{In a specific year}}$ – GDP deflator index in a specific year;

$GDP\ Deflator_{\text{In a base year}}$ – GDP deflator index in a past year.

The main scenario boundaries are set in the chapter 3. More details specific to LCCA are further mentioned in this section. The LCCA is based on LCA previously performed. The main relevant costs are design & licensing, capital investment, O&M. Design and licensing costs are estimated to be 3 % of total capital investments. Residual phase is not considered within this study. The capital investment costs are the sum of costs of equipment for algae collection, transportation, storage units, container units, pre-treatment equipment, biogas plant, biogas cleaning plant and CHP unit. Land acquisition costs are not included.

Insurance costs are assumed to be 0.05 % of capital investments. Loan is calculated as 70 % of total investments, inflation rate is 2 %, rate on loan is 3.5 %, income tax is 15 %. Study period is 20 years, discount rate is 5 %. Post financing is 70 % debt capital and 30% equity capital with loan period of 10 years.

O&M costs include labor and consumables. Maintenance costs are assumed to be 2 % of capital investments. Depreciation costs are taken into account based on the life span of each item (linear method). Other costs include accounting, consultation and other activities alike. See Fig. 2.4 for main operational and maintenance costs for all scenarios.

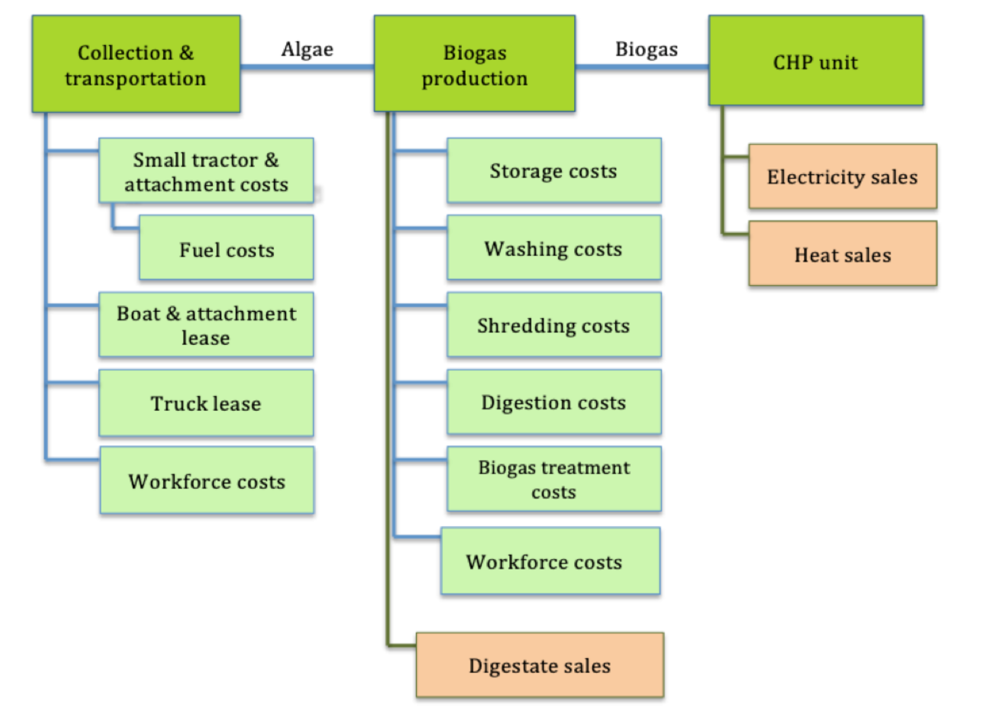

Fig. 2.4. Main operational and maintenance costs for algae scenarios.

See Table 2.3 for more detail costs and revenues for each scenario.

Table 2.3.

Costs and Revenues for each Scenario

	C. demersum	*F. vesiculosus*	*U. intestinalis*	Manure
Capital investments, EUR	2 727 750	2 732 750	2 732 750	2 635 750
Acquisition and design, EUR	81 833	81 983	81 983	79 073
Total investment, EUR	2 809 583	2 814 733	2 814 733	2 714 823
O&M				
Labor, EUR / year	32 988	35 136	30 531	29 200
Consumables, EUR / year	577	78 545	57 342	803
Lease, EUR / year	55 579	25 871	19 038	-
Maintenance, EUR / year	54 555	54 655	54 655	52 715
Depreciation, EUR / year	168 193	169 543	168 693	162 993
Other, EUR / year	2 000	2 000	2 000	2 000
Insurance, EUR / year	13 639	13 664	13 664	13 179

Table 2.3. continued

	C. demersum	*F. vesiculosus*	*U. intestinalis*	Manure
Income from electricity, EUR / year* *With feed in tariff	279 081	275 193	279 081	289 313
Income from electricity, EUR / year	65 561	64 648	65 561	67 965
Income from heat, EUR / year	150 525	150 525	150 525	150 525
Income from digestate, EUR / year	149 467	169 104	151 884	124 691
Loan amount, EUR	1 966 708	1 970 313	1 970 313	1 900 376
Loan payment, EUR / year	236 479.63	236 913.10	236 913.10	228 503.78

The revenues come from selling the excess electricity, heat and digestate. For the first 10 years of the project, electricity is sold with a feed-in tariff. More details about the analysis performed and its results can be seen in publication Pastare & Romagnoli, 2019.

2.4. Criteria Weight Determination

The criteria weights are an important part of the overall MCA as each the 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 the 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 (see Table 2.4) (Munier, 2004; Saaty, 1990).

Table 2.4.

Preference Scale Values and Explanations for AHP Pair-Wise Comparison (Saaty, 1990)

Values	Judgment of preference	Explanations
1	Both are equally important or preferred	Two factors contribute equally to the objective
3	One of the criteria is moderately important or preferred over the other (weak preference)	Experience and judgment slightly favor one over the other
5	There is a strong preference of one over the other	Experience and judgment strongly favor one over the other
7	One is very strongly important over the other	Experience and judgment very strongly favor one over the other. Its importance is demonstrated in practice.
9	One is absolutely preferred over the other, or is definitely more important	The evidence favoring one over the other is of the highest possible validity
2-4-6-8	Intermediate values	When a compromise is needed

The way to assign values of criteria comparison is to ask a question – How important is the criteria A (row) over criteria B (column)? If a criterion A is moderately important over criteria B, the rating is 3, but for criteria B over criteria A the rating is inversely proportional

1/3 or 0.33. 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.

After the pairwise comparison a table of criterion assessment is created as an asymmetric matrix from which the criteria weights are calculated. For each row calculations are carried out as described in Eq. 2.10-2.12 (Munier, 2004):

$$\prod_{i=1}^{n} C_i, \tag{2.10}$$

where
Π – the multiplication of all elements in a row;
C_i – criteria;
n – number of criteria.

The root of n is then calculated for each criterion Π value (Munier, 2004):

$$\sqrt[n]{\prod_{i=1}^{n} C_i}, \tag{2.11}$$

The final weight of criteria is calculated as a part of all criteria n-root sum, as follows (Munier, 2004):

$$W_N = \frac{\sqrt[n]{\prod_1^n C_1}}{\sum_i^n \sqrt[n]{\prod_{i=1}^n C_i}}, \tag{2.12}$$

where
W_N – weight of criteria n.

Even though the proposed methodology offers to diminish the subjectivity of the weight calculation for criteria, a single expert conducts the method.

2.5. Multi-Criteria Analysis with TOPSIS

As mentioned before, there are several techniques and methods for conducting a MCA for chosen alternatives within chosen criterion. The choice of using TOPSIS methodology has been made based on the input data needs and the outcome usability and interpretation ability.

The method TOPSIS developed by Hwang and Yoon (1981) is based on the concept that the best alternative should have the shortest distance from the positive-ideal solution and the longest distance from the negative-ideal solution. 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 requires minimal number of inputs and the output is easy to understand. (Ishizaka & Nemery, 2013; Kahraman, Yasin Ateş, Çevik, Gülbay, & Ayça Erdoğan, 2007; Lu, Zhang, Ruan, & Wu, 2007)

The 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 and positive- and negative-ideal values. Finally the closeness is given as the relation of these distances. (Ishizaka & Nemery, 2013)

The performance of *n* alternatives *a* within *m* criteria *i* are summarized in a decision matrix $X = (x_{ia})$. In order to be able to calculate the criteria values for different alternatives correctly, a normalization of these values should be carried out. The normalization allows comparing criteria with different units as well as to calculate criteria values that are in a big range (for example, the minimal value in a matrix is 0.001 but the maximum is 10 000). There are several techniques for performing the normalization. The chosen method is distributive normalization, which requires dividing each criterion value by square root of the sum of each squared element in a column (Eq. 2.13).

$$\mathrm{r_{ai}} = \frac{\mathrm{x_{ia}}}{\sqrt{\sum_{\mathrm{a=1}}^{\mathrm{n}} \mathrm{x_{ia}^2}}}, \tag{2.13}$$

(for a=1,…,n and i=1,…,m)
where
r^{-}_{ia} – normalized performance of alternative *a* with respect to criteria *i*;
x_{ia} – performance of alternative *a* with respect to criteria *i*.

This method of normalization isn't influenced whether the performance of a criterion should be maximum or minimum for best result. Other methods as ideal normalization considers the desired value (maximum if the better performance is preferred or minimum if the best performance should be lowest). There are several more methods, but the distribution normalization is the most preferred in most situations. (Ishizaka & Nemery, 2013)

The next step is to take into account the weights. Multiplying the normalized scores r^{-}_{ia} with their corresponding weights w_i creates a weighted normalized decision matrix (Eq. 2.14).

$$v_{ai} = w_i \cdot \mathrm{r_{ai}}, \tag{2.14}$$

where
v_{ai} – weighted normalized performance of alternative *a* with respect to criteria *i*;
w_i – weights of criteria *i*.

These gained weighted normalized scores are next used to determine the positive- and negative-ideal solution and to determine the distance from the weighted scores till these two points. The ideal action is described in Eq. 2.15.

$$A^{+} = (v_1^{+}, \dots, v_m^{+}), \tag{2.15}$$

where
A^{+} –– the ideal action of criteria *i*;
v_I^{+} – maximum performance value if the criterion *i* is to be maximized;
v_i^{-} – minimum performance value if the criterion *i* is to be minimized.

When the positive- and negative-ideal solution values are known the distance from each of these values for each performance value can be calculated. For the positive-ideal action, the distance calculation is described in Eq. 2.16.

$$d_a^+ = \sqrt{\sum_i (v_i^+ - v_{ai})^2}, \tag{2.16}$$

(for a=1,…,m)
where
d_a^+ – performance value distance from positive-ideal action.

And the distance calculations from negative-ideal solution is calculated in Eq. 2.17.

$$d_a^- = \sqrt{\sum_i (v_i^- - v_{ai})^2}, \tag{2.17}$$

(for a=1,…,m)
where
d_a^- – performance value distance from negative-ideal action.

This distance calculation is also called the Euclidean distance, but also other metrics can be used. The use of different technique may come from specific requirements for results or in case of fuzzy set calculations. (Ishizaka & Nemery, 2013)

The next step is the final relative closeness coefficient calculation for each of the alternatives, shown in Eq. 2.18.

$$\mathrm{C_a} = \frac{d_a^-}{d_a^+ + d_a^-}, \tag{2.18}$$

where
C_a – relative closeness to the ideal solution coefficient.

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)

3. CASE STUDY

Many Baltic See region 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) Depending on the type of coastline and the accessibility the washed-out seaweeds can't always be collected or transported away. For locations where the seaweeds can't be transported away, it's possible to bury them to lower the impact on coastline ecosystems. After collecting and transporting the seaweeds away from the coast there are several options on how to dispose of the biomass – in some cases it is composted, but mostly it is disposed in landfills.

Eutrophication in freshwater bodies is also a large problem in areas with developed agriculture. The additional amounts of 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 potential of such operations several 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. In total 4 scenarios are developed for biogas production based on type of biomass used – two marine washed out algae species, one freshwater macrophyte species and baseline scenario of biogas production with manure only.

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.

Cerathophyllum demersum is a freshwater macrophyte also called coontail. It is a submerged, free-floating aquatic plant. *C. demersum* has a cosmopolitic distribution, commonly used as aquarium plant. Commonly seen in ponds, lakes, ditches, and quiet streams with moderate to high nutrient levels. It does not produce roots, instead it absorbs all the nutrients it requires from the surrounding water. See *Cerathophyllum demersum* in Fig. 3.1.

Fig. 3.1. *Cerathophyllum demersum* (A – young sprout; B – matured spring).

This macrophyte has high biomass production and good capability of absorbing environmental contaminants (e.g. metals and industrial radionuclides). (Aravind & Prasad, 2004; Block & Rhoads, 2011; Forough, 2011; Ha & Pflugmacher, 2013; Keskinkan, Goksu, Basibuyuk, & Forster, 2004; Sinha & Singh, 2010)

Fucus vesiculosus – marine brown algae also known as Red Fucus is very common seaweed in Baltic Sea (See Fig. 3.2). Research of this species is quite extensive as it is cosmopolite species and commonly found washed out on shores of water bodies. Typical sizes of fronds are up to 90 cm in length and 2.5 cm in width. (Barbot, Falk, & Benz, 2015; Tedesco, Benyounis, & Olabi, 2013)

Fig. 3.2. *Fucus vesiculosus.*

Ulva intestinalis - marine green algae commonly known as gutweed and grass kelp (see Fig. 3.3). It is more common in European coastal countries though can be found also in Pacific Ocean. Fronds are tubular with branches and can reach 30 cm in lengths (typically 10-20 cm in lengths, 0.6-1.8 mm in width).

Fig. 3.3. *Ulva intestinalis.*

Depending on temperature and lighting, *U. intestinalis* can be reproductive the whole year. (Hayden et al., 2003)

The baseline scenario of just manure use for biogas production is based on cattle farm manure, containing both liquid and solid manure fractions.

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 as they are identical for all scenarios and are not within the main goal of the study. The construction, teardown and operations of cattle farm are also not taken into account.

In all three scenarios algae are 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 supposed to be carried out after the bloom period** (usually starting July until November). There is no specific time for when the marine algae start to be washed-out, it is dependent on the weather conditions (the more sunshine and the warmer the weather, the sooner algae starts blooming, wind direction and speed affects when algae are washed-out). For freshwater algae the collection can start then there is enough algae bloom. The end period of collections would be when there are no more algae to be collected or the water bodies start to freeze up thus restricting such actions.

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). The maximal collection capacity of the tractors is 30 tones per hour if the weather conditions are favorable. As the washed out algae sometimes is more spread out not piled up, it is assumed that the average collection capacity is 5 tones per hour (Brūniņa, 2018). The truck is owned and while not collecting algae is used on site**. A boat and a trawler attachment** are leased for collecting biomass from freshwater bodies (on average 150 days per year). In all scenarios algae are collected in piles or directly into the truck used for transportation.

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**. The location of the plant is chosen to be close to algae collection sites as well as close to cattle farm, as the manure is used in biogas production together with algae. For all transportation it is assumed that the load factor is 50 %, meaning that truck transporting the biomass from water bodies to site is doing empty returns.

In the baseline scenario the cattle farm is located next to the biogas plant in order to lower the transportation costs. It is assumed it is less than 1 km away. 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. Algae are stored in a cooled temperature to avoid biomass degradation. The temperature in the storage unit is maintained only when the outside temperature is higher than 4 °C (39 °F) based on daily average temperature. The average temperature during the months of November until March has been close to or lower than 4 °C (39 °F) in the last 5 years. Based on this information, it is assumed that the unit is cooled on average 4320 hours per year. (Central Statistical Bureau of Latvia, 2018; Graham, Eastwick, Snape, & Quick, 2012) The feedstock and digestate are stored in two separate units. Only the feedstock storage unit is cooled. It is assumed that no there are no biomass losses or emissions from storage process.

In baseline scenario the manure is stored in concrete storage units without cooling.

The algae are stored until needed for the biogas production process. **Pre-treatment** of algae is carried out shortly before adding it to digestion tank. Pre-treatment includes washing of excess salt and sand for marine algae species. As freshwater species are collected directly from water, there is no need for this step. **Washing** is carried out in water tanks with sieves using freshwater as cleaning medium. On average 5 m^3 of water are used per ton of algae. The algae are submerged in water (letting the salt dissolve) and manually stirred to help remove debris. After that water is drained, leaving the algae on sieves. Washing of salt and debris is needed as it improves the overall digestibility for marine algae species, as methanogenic bacteria are sensitive to salt. (Bruton et al., 2009)

Shredding is carried out for all algae species as part of pre-treatment. A twin shaft shredder is used. Shredding improves the digestion rate as well as helps with the feed-in of the feedstock. (Romagnoli et al., 2017)

There is no pre-treatment of manure prior to digestion process.

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_2O5) and 0.9 % of nutrient potassium (as K_2O) in digestate compared to input. (Krastina, Romagnoli, & Balina, 2017; Surendra, Takara, Hashimoto, & Khanal, 2014)

After biogas production, before biogas use it goes through a **cleaning** process to remove excess moisture, sulfur compounds and other impurities. Wet scrubbing adsorption method with activated carbon is used. As the used method removes sulfur compounds, it is assumed that al sulfur is removed and there will be no sulfur compound emissions during combustion. (Coppola & Papurello, 2018)

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). See Fig. 3.4 for the overall scheme of algae scenarios.

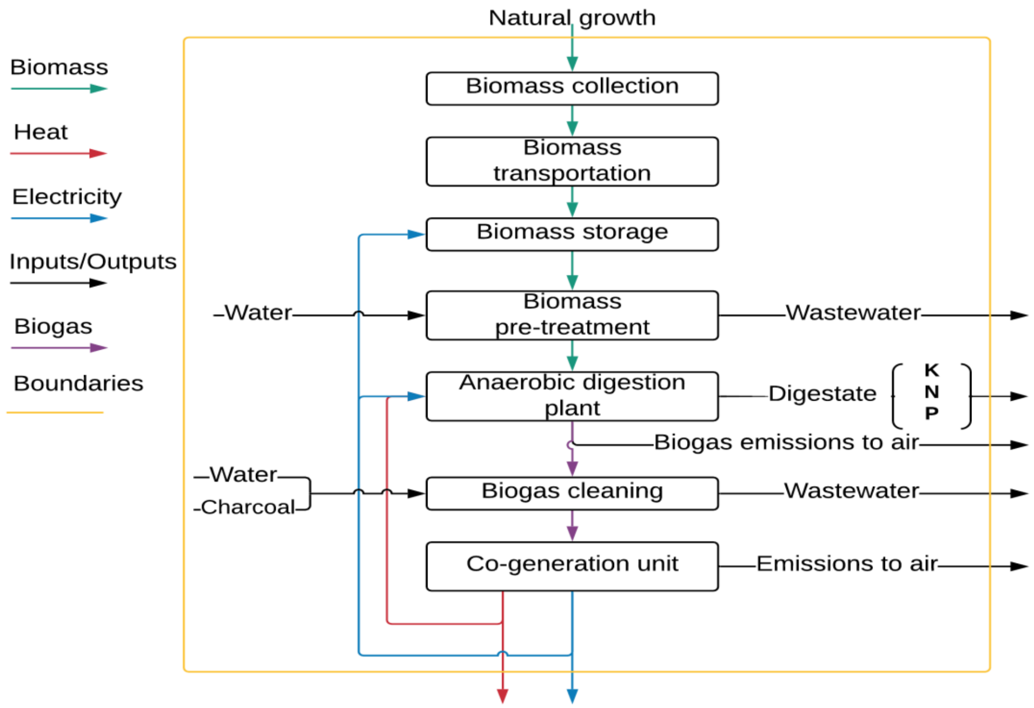

Fig. 3.4. Overall scheme of scenarios.

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 per m) and the length of available coastline (494 km in Latvia). (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, Dzene, & Kuznecova, 2014.

4. RESULTS AND ANALYSIS

4.1. Energetic Criteria

Several rounds of experiments have been carried out in order to find the best combination of factors for each of 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 of them). The results of these experiments can be found in detail in publications Pastare et al., 2016; Pastare, Romagnoli, & Blumberga, 2018; Pastare et al., 2015; Romagnoli et al., 2017.

The experiments on inoculum ratio change showed, that in samples of *C. demersum* higher ratios of inoculum produced more biogas (see Table 4.1)

Table 4.1.

Inoculum Ratio Influence on Biochemical Methane Potential in *C. demersum*

Ratio	Replicate BMP, L CH_4 / kg_{VS}			Average	SD	SD %
1 : 3	428	353	353	378	35.4	9.4 %
1 : 5	416	405	373	398	18.2	4.6 %
1 : 10	421	471	471	454	23.6	5.2 %

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. 4.1 for BMP values of scenarios with influences from pre-treatment options. 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} ($T_{test} = 0.1700$, $p = 0.434$) and from cutting + 8 L CH_4 / kg_{VS} ($T_{test} = 0.196$, $p = 0.424$), there is no interaction between factors.

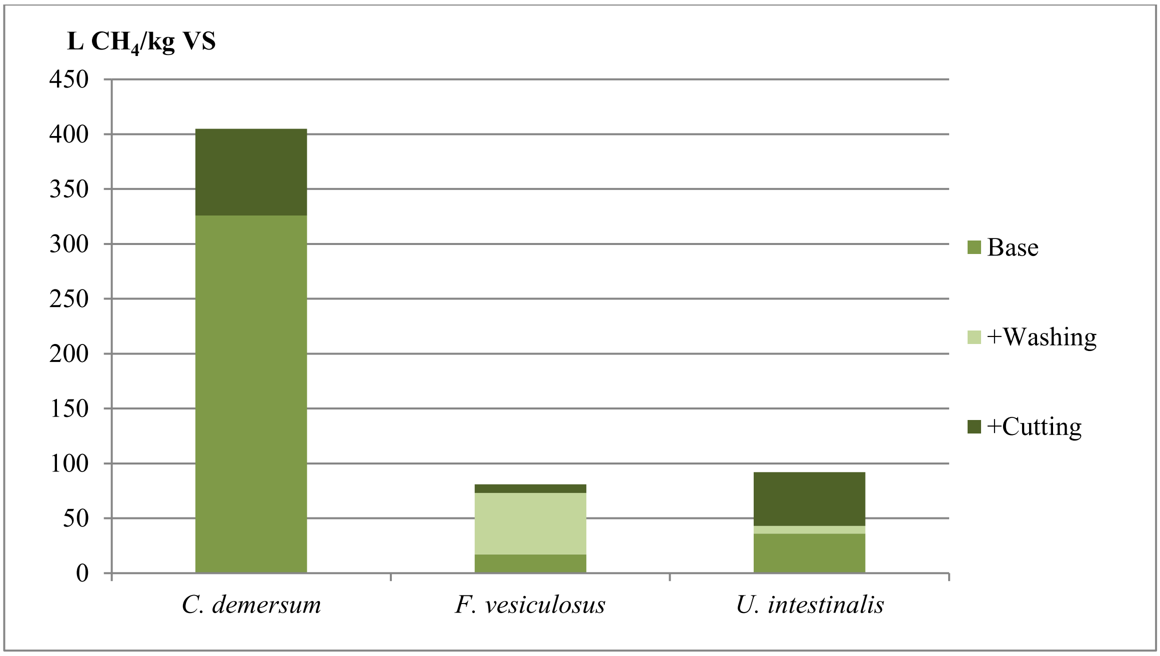

Fig. 4.1. BMP values of scenarios with influence from washing and cutting as pre-treatment.

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 4.2. 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 4.2.

Biomass Parameters for Biogas Production

Parameter	Unit	*C. demersum*	*F. vesiculosus*	*U. intestinalis*	Manure
Biochemical methane potential	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

As mentioned in scenario descriptions, algae are co-digested with cattle farm manure. Manure biochemical methane potential is based on literature review. The biogas plant operational inputs can be seen in Table 4.3. Based on experimental values and literature analysis it is assumed, that biogas contains 65 % of methane.

Table 4.3.

Operational Inputs for Biogas Production

Parameter	Unit	*C. demersum*	*F. vesiculosus*	*U. intestinalis*	Additional manure	Manure only
Inputs	t / year	6 328	9 055	6 663	14 432	17 318
Biogas produced	m^3 / year	157 862	157 862	157 862	789 311	947 173
Methane produced	m^3 / year	102 610	102 610	102 610	513 052	615 663
Electricity produced	MWh / year*	2 190	2 190	2 190	-*	2 190
Heat produced	MWh / year*	3 942	3 942	3 942	-*	3 942

* Total produced heat and electricity from co-digestion of algae and manure

Based on the BMP values, chosen biogas plant and 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 4.4.

Table 4.4.

Criteria Energy Input/Output Ratio Calculation

Process	*C. demersum*	*F. vesiculosus*	*U. intestinalis*	Manure
	MWh	MWh	MWh	MWh
Total input	**1 407.93**	**1 435.31**	**1 407.93**	**1 335.9**
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	153.3	153.3	153.3	153.3
Heat for digestion	1 182.6	1 182.6	1 182.6	1 182.6
Total output	**6 132**	**6 132**	**6 132**	**6 132**
Electricity output	2 190	2 190	2 190	2 190
Heat output	3 942	3 942	3 942	3 942
Ratio	**0.2296**	**0.2341**	**0.2296**	**0.2179**

As it can be seen in the table, while producing the same amount of energy per operational year, the amount of used energy is different. Scenario with highest amount of spent energy is with use of *F. vesiculosus*, algae with the smallest BMP value.

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

4.2. Environmental criteria

Environmental impacts are calculated in the *SimaPro* program using *IMPACT2002+* as the calculation method. The results are in 4 damage categories further divided into mid-point impact categories (see Table 4.5. for the main results in damage categories).

Table 4.5.

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
Recourse 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 by-product of cattle farming. The highest impact is for *F. vesiculosus*, as the BMP value is the lowest and higher amounts of algae are needed to produce the same amount of biogas as other scenarios, the overall impact is higher in all the categories. 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.

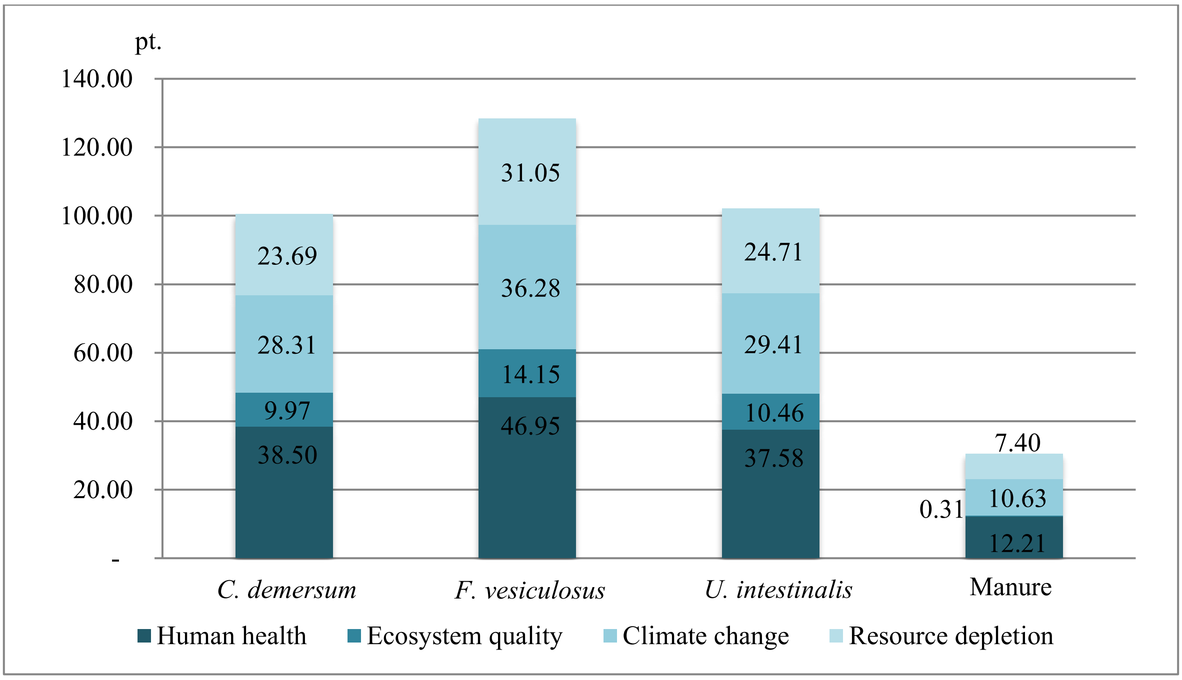

Fig. 4.2. Normalized environmental impact per damage categories in each scenario in points.

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). As it can be seen in Fig. 4.2, the biggest damage is from 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.

4.3. Economic Criteria

Cash flow was modeled based on the assumptions mentioned before. The NPV, BP and DPB values can be seen in Table 4.6.

Table 4.6.

NPV, BP, DPB Values for Scenarios

	C. demersum	*F. vesiculosus*	*U. intestinalis*	Manure	Unit
Net present value	51 008,87	-505 683	-219 061	916 864	EUR
Biogas price	355	389	373	304	EUR / t. m^3
Discounted payback period	11	20	11	2	Year

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. 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. See Fig. 4.3. for revenue structure of scenarios.

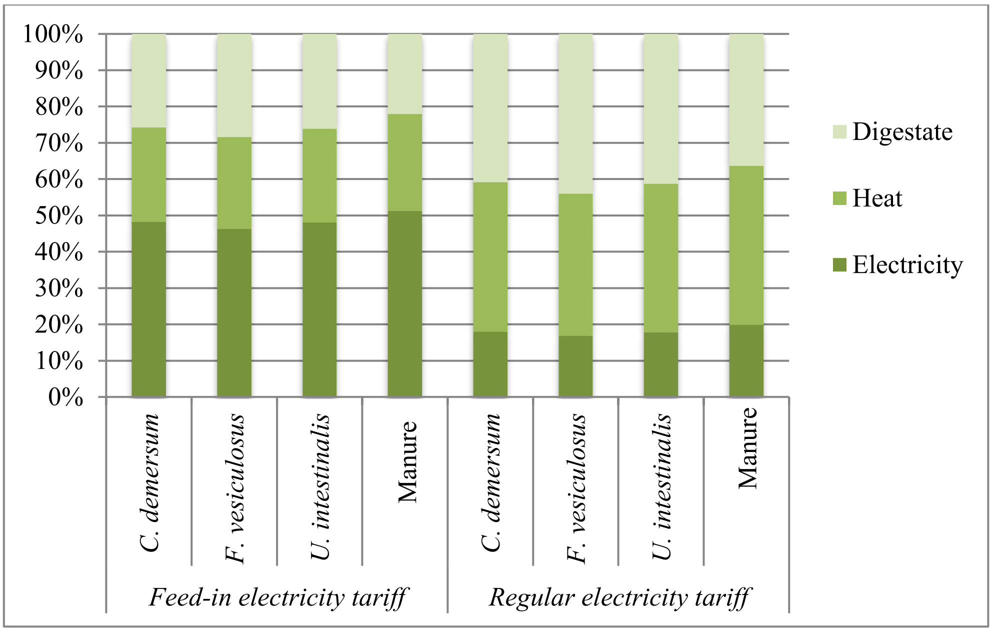

Fig. 4.3. Revenue structure of scenarios.

As there are a lot of capital investments associated with having biogas production site and CHP unit, one of the options to cut down costs would be to sell the treated biogas as an end product. By eliminating big part of capital and operational costs, it is possible that with reduced revenues NPV, BP and DPB would be more favorable. By eliminating the CHP unit on site and selling the cleaned biogas to another biogas production site or CHP unit, capital investments for the unit can be avoided. As no longer either electricity or heat will be produced on site, additional costs for electricity and heat use arise. It is assumed there are no additional costs for transporting the produced biogas to another site; all costs related are covered by the selling price. For a NPV of 0 for projects the biogas prices are in the range of 304 EUR / t.m^3 biogas to 389 EUR / t.m^3 biogas. Recalculated as price per cubic meter of methane (65 % of biogas is methane), not taking into account upgrading costs, the price range is from 467 EUR / t.m^3 methane to 599 EUR / t.m^3 methane. 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 of production is not competitive enough for a project to be viable.

4.4. Criteria Weights

The values assigned within this study for the selected criteria are compiled in Table 4.7. The criteria comparison values have been based on authors' opinion of the criterion correspondence. 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 with choosing between similar alternatives.

Table 4.7.

Assigned Criteria Ranking based on AHP Methodology

	BMP	ER	EQ	CC	HH	RD	NPV	BP	DPB
BMP	1	3	3	3	3	5	0.33	3	2
ER	0.33	1	3	0.33	3	0.33	0.50	0.33	2
EQ	0.33	0.33	1	0.33	3	0.33	0.33	0.33	2
CC	0.33	3	3	1	0.33	3	0.50	0.50	2
HH	0.33	0.33	0.33	3	1	2	0.33	0.33	2
RD	0.20	3	3	0.33	0.50	1	0.33	1	1
NPV	3	2	3	2	3	3	1	3	3
BP	0.33	3	3	2	3	1	0.33	1	2
DPB	0.50	0.50	0.50	0.50	0.50	1	0.33	0.50	1

As it can be seen the maximum given value is 5 out of 9 and most common assigned value is 3 that corresponds to moderate correspondence. As some of the criteria are indirectly dependent on each other, the assigned weights should be use with caution on its limitations.

Further the criteria weights have been calculated based on the methodology described in Chapter 2.4. See the results in Table 4.8.

Table 4.8.

Weights Assigned by Author with 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.

4.5. 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 costs analysis and calculating weights for the chosen criteria, MCA can be carried out. The compiled results for each criterion can be seen in Table 4.9.

Table 4.9.

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 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). See Table 4.10. for data after normalization step.

Table 4.10.

Criteria Values for each Scenario after Normalization Step

	C. demersum	*F. vesiculosus*	*U. intestinalis*	Manure	Goal
BMP	10.00	1.00	0.34	6.75	MAX
ER	7.25	10.00	7.25	1.00	MIN
EQ	6.98	10.00	7.34	1.00	MIN
CC	6.89	10.00	7.32	1.00	MIN
HH	7.57	10.00	7.30	1.00	MIN
RD	6.88	10.00	7.32	1.00	MIN
NPV	3.91	1.00	2.01	10.00	MAX
BP	6.00	10.00	8.12	1.00	MIN
DPB	5.00	10.00	5.00	1.00	MIN

Based on the inputs in Table 4.10 and the weights determined by AHP methodology in Table 4.8, the ranking of alternatives was calculated with TOPSIS methodology (see Fig. 4.4). The ranking shows closeness to 1, where 1 is the ideal solution that comprises the desirable values of each criterion based on the inputs.

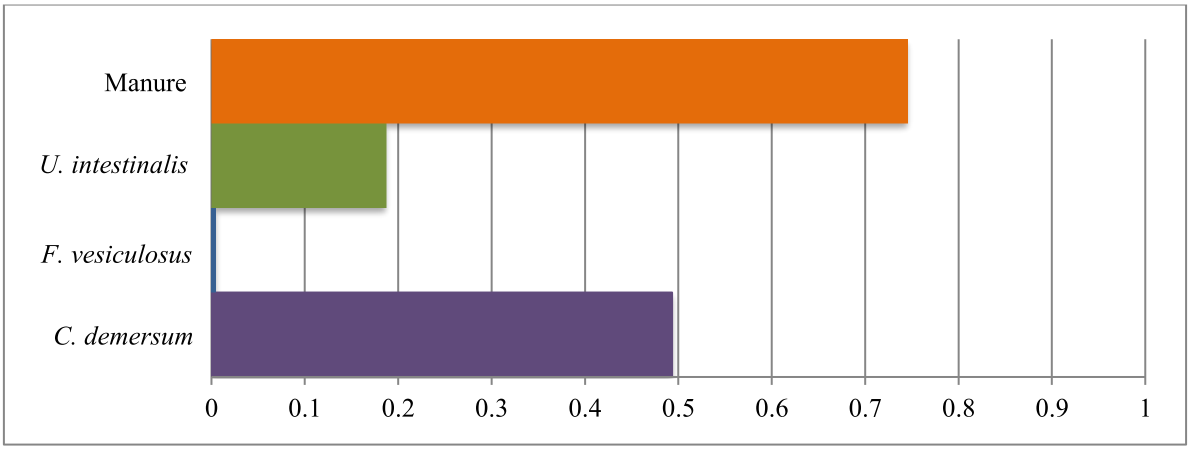

Fig. 4.4. Ranking of alternatives with TOPSIS with AHP weights.

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 by AHP methodology, it is also important to compare the ranking in case of equal assigned weights for all criteria as a base of all rankings (see Fig. 4.5).

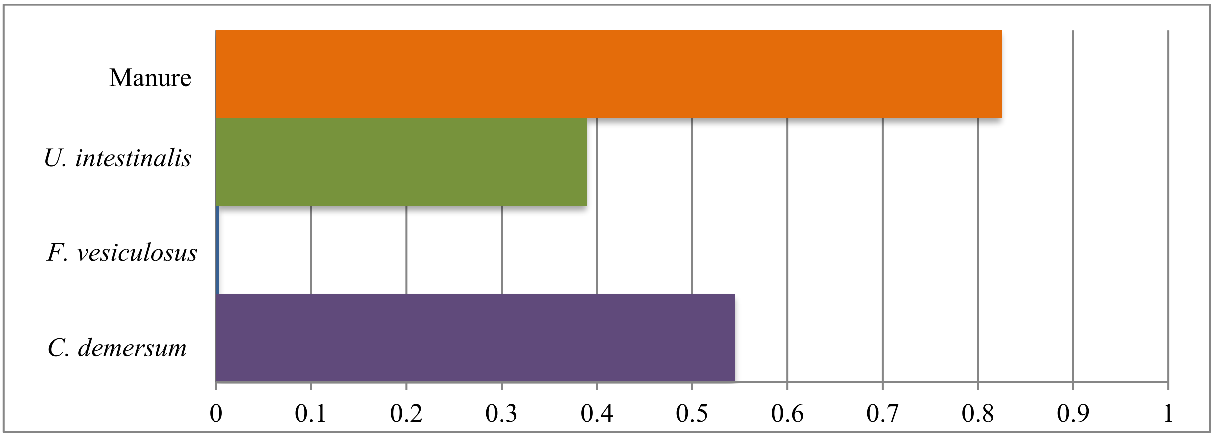

Fig. 4.5. Ranking of alternatives with TOPSIS with equal weights for criteria.

The order of ranking of alternatives with equal weights doesn't change, but their individual closeness to ideal solution does change, 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 with sensitivity analysis.

4.6. 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 the 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. See Table 4.11 for detailed tested weight values.

Table 4.11.

Sensitivity Analysis Value Changes of Weights for Criteria

Criteria groups	Energetic		Environmental				Economic		
Tested weights	BMP	ER	EQ	CC	HH	RD	NPV	BP	DPB
AHP	21.59	7.1	5.13	9.83	6.42	7.01	25.33	12.75	4.84
Equal criteria weights	11.11	11.11	11.11	11.11	11.11	11.11	11.11	11.11	11.11
Equal criteria group weights	16.67	16.67	8.33	8.33	8.33	8.33	11.11	11.11	11.11
Energetic criteria group 50 %	**25**	**25**	7.14	7.14	7.14	7.14	7.14	7.14	7.14
Environmental criteria group 50 %	10	10	**12.5**	**12.5**	**12.5**	**12.5**	10	10	10
Economic criteria group 50 %	8.3	8.3	8.3	8.3	8.3	8.3	16.7	**16.7**	**16.7**
BMP 50 %	**50**	6.25	6.25	6.25	6.25	6.25	6.25	6.25	6.25
ER 50 %	6.25	**50**	6.25	6.25	6.25	6.25	6.25	6.25	6.25
EQ 50 %	6.25	6.25	**50**	6.25	6.25	6.25	6.25	6.25	6.25
CC 50 %	6.25	6.25	6.25	**50**	6.25	6.25	6.25	6.25	6.25
HH 50 %	6.25	6.25	6.25	6.25	**50**	6.25	6.25	6.25	6.25
RD 50 %	6.25	6.25	6.25	6.25	6.25	**50**	6.25	6.25	6.25
NPV 50 %	6.25	6.25	6.25	6.25	6.25	6.25	**50**	6.25	6.25
BP 50 %	6.25	6.25	6.25	6.25	6.25	6.25	6.25	**50**	6.25
DPB 50 %	6.25	6.25	6.25	6.25	6.25	6.25	6.25	6.25	**50**

The results of weight impact sensitivity analysis are compiled together and averaged with standard deviation error bars in Fig. 4.6.

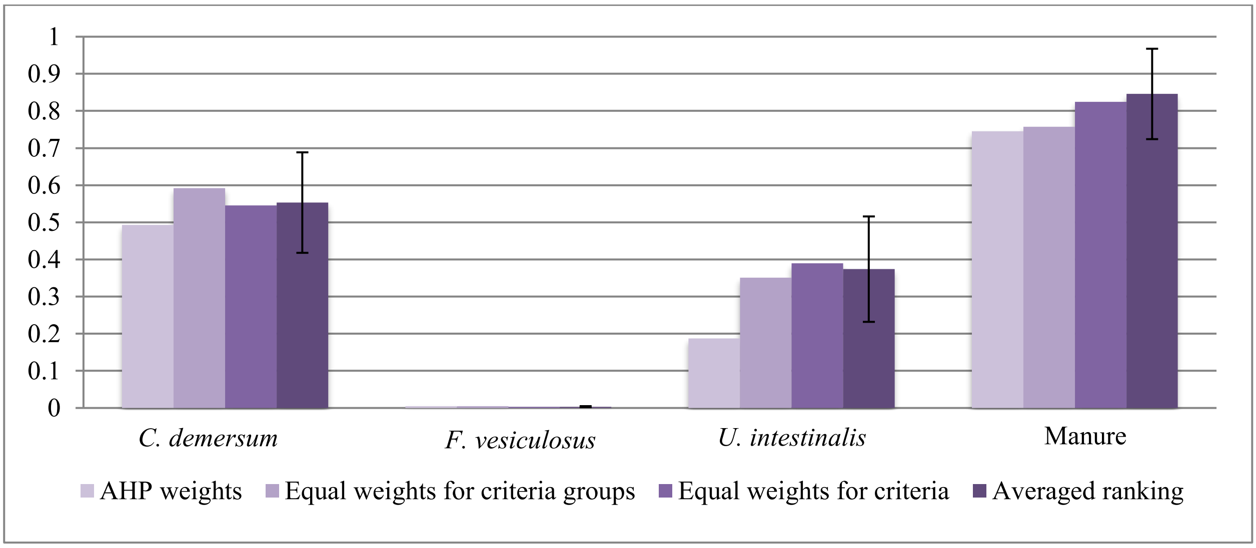

Fig. 4.6. Sensitivity analysis of criteria weights.

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 can be 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 with a single step in-between the current value and the minimum or maximum value (see Table 4.12.).

Table 4.12.

Sensitivity Analysis Inputs for Criteria NPV and DPB Value Changes

Value type	Minimal value Criteria – 100 %	In-between value Criteria – 50 %	Actual value Criteria	In-between value Criteria + 50 %	Maximal value Criteria + 100 %
DPB	1	3	5	7.5	10
NPV	1	2.45	3.9	6.95	10

See Fig. 4.7 for results of criteria DPB changes impact on ranking of alternatives and see Fig. 4.8. for criteria NPV changes impact to ranking of alternatives.

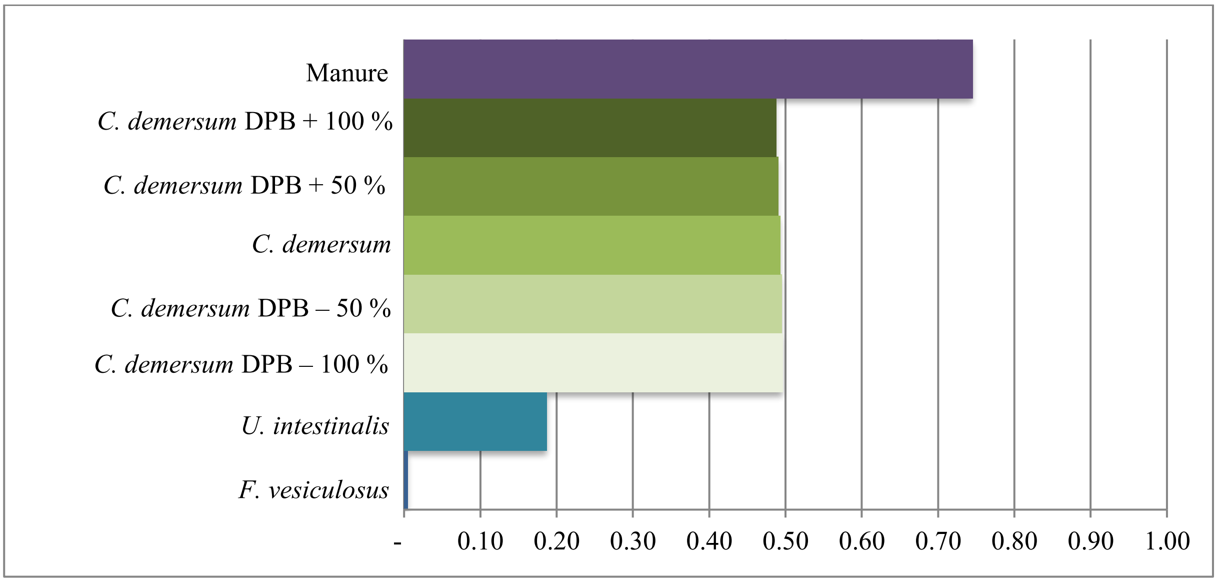

Fig. 4.7. Criteria DPB changes impact to ranking of alternatives.

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

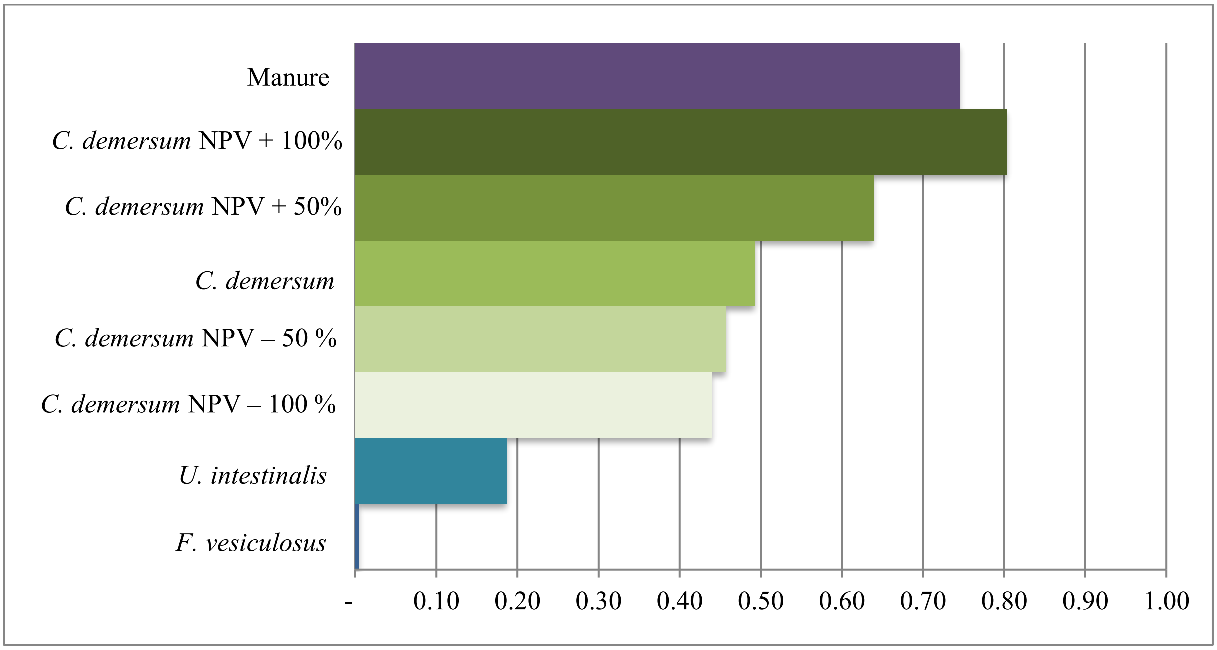

Fig. 4.8. Criteria NPV changes impact to ranking of alternatives.

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 methodology can adapts to the changes within accordingly to the expectations of it. 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 intestinali*s) 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 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 al 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 are 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 by 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 model is very flexible and allows for changes according to the goal of the study. The structure of using a LCA analysis and then a 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 allow 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.

REFERENCE LIST

Althaus, H. J., Bauer, C., Doka, G., Dones, R., Hischier, R., Hellweg, S., … Nemecek, T. (2007). *Implementation of Life Cycle Impact Assessment Methods. Ecoinvent report No.3 v2.0.* (R. Frischknecht & N. Jungbluth, Eds.). Retrieved from http://www.ecoinvent.org/fileadmin/documents/en/03_LCIA-Implementation.pdf

Aravind, P., & Prasad, M. N. . (2004). Zinc protects chloroplasts and associated photochemical functions in cadmium exposed Ceratophyllum demersum L., a freshwater macrophyte. *Plant Science*, *166*(5), 1321–1327. https://doi.org/10.1016/j.plantsci.2004.01.011

Aurora Liquefied Natural Gas Ltd. (2013). *Natural Gas Demand and Supply Forecast to 2050*. Calgary, AB, Canada.

Balina, K., Romagnoli, F., Pastare, L., & Blumberga, D. (2017). Use of Macroalgae for Bioenergy Production in Latvia: Review on Potential Availability of Marine Coastline Species. *Energy Procedia*, *113*, 403–410. https://doi.org/10.1016/j.egypro.2017.04.022

Barbot, Y. N., Falk, H. M., & Benz, R. (2015). Thermo-acidic pretreatment of marine brown algae Fucus vesiculosus to increase methane production—a disposal principle for macroalgae waste from beaches. *Journal of Applied Phycology*, *27*(1), 601–609. https://doi.org/10.1007/s10811-014-0339-x

Block, T. A., & Rhoads, T. A. (2011). *Aquatic Plants of Pennsylvania: A Complete Reference Guide Book*. University of Pennsylvania Press.

Brūniņa, L. (2018). *Jūras aļģu sanesumu izvērtēšanas un apsaimniekošanas plāna Latvijas piekrastei izstrāde*.

Bruton, T., Lyons, H., Lerat, Y., Stanley, M., & Rasmussen, M. B. (2009). *A Review of the Potential of Marine Algae as a Source of Biofuel in Ireland*. https://doi.org/10.1016/j.envint.2003.08.001

Central Statistical Bureau of Latvia. (2017). Average prices of energy resources for end-users (value added tax exempt). Retrieved December 4, 2018, from https://data1.csb.gov.lv/pxweb/lv/vide/vide__energetika__ikgad/ENG190.px/table/tableViewLayout1/

Central Statistical Bureau of Latvia. (2018). The average air temperature monthly. Retrieved December 4, 2018, from GZG070 website: https://data1.csb.gov.lv/pxweb/en/vide/vide__geogr__isterm/GZ010m.px/table/tableViewLayout1/

Coppola, G., & Papurello, D. (2018). Biogas Cleaning: Activated Carbon Regeneration for H2S Removal. *Clean Technologies*, *1*(1), 40–57. https://doi.org/10.3390/cleantechnol1010004

Crowe, A. (2005). *The PMP Exam: How to Pass on Your First Try*. Velociteach Press.

Demirbaş, A. (2001). Biomass resource facilities and biomass conversion processing for fuels and chemicals. *Energy Conversion and Management*, *42*(11), 1357–1378. https://doi.org/10.1016/S0196-8904(00)00137-0

Eriksson, L., Johansson, E., Wold, N. K.-, Wikstrom, C., & Wold, S. (2001). Design of Experiments, Principles and Applications. *Journal of Chemometrics*, *15*(5), 495–496. https://doi.org/10.1002/cem.686

European Commission. *Directive 2006/7/EC concerning the management of bathing water quality and repealing Directive 76/160/EEC.* , (2006).

European Commission. (2019). Climate Strategies and Targets. Retrieved from https://ec.europa.eu/clima/policies/strategies_en

Forough, M. (2011). Investigation of the influence of Ceratophyllum demersum to refine diluted compost latex. *Journal of Applied Sciences and Environmental Management*, *15*(2), 371–374.

Fuller, S. K., & Petersen, S. R. (1995). *Life-Cycle Costing Manual for the Federal Energy Manegement Program*. US Department of Commerce.

Gallagher, T. J., & Andrew, J. D. (2003). *Financial Management (Principles and Practice)* (Third Edit). Prentice Hall.

Gluch, P., & Baumann, H. (2004). The life cycle costing (LCC) approach: a conceptual discussion of its usefulness for environmental decision-making. *Building and Environment*, *39*(5), 571–580. https://doi.org/10.1016/j.buildenv.2003.10.008

Goedkoop, M., Oele, M., de Schryver, A., & Vieira, M. (2008). SimaPro 7 Database Manual: Methods library. In *Distribution* (2.2). PRe Consultants.

Goedkoop, M., Oele, M., Leijting, J., Ponsioen, T., & Meijer, E. (2013). *Introduction to LCA with SimaPro*.

Graham, S., Eastwick, C., Snape, C., & Quick, W. (2012). Degradation of biomass fuels during artificial storage in a laboratory environment. *International Journal of Low-Carbon Technologies*, *7*(2), 113–119. https://doi.org/10.1093/ijlct/cts029

Guinée, J., & Heijungs, R. (2017). Introduction to Life Cycle Assessment. In W. Klopffer & B. Grahl (Eds.), *Life Cycle Assessment: A guide to best practice* (pp. 15–41). https://doi.org/10.1007/978-3-319-29791-0_2

Ha, M.-H., & Pflugmacher, S. (2013). Time-dependent alterations in growth, photosynthetic pigments and enzymatic defense systems of submerged Ceratophyllum demersum during exposure to the cyanobacterial neurotoxin anatoxin-a. *Aquatic Toxicology*, *138–139*, 26–34. https://doi.org/10.1016/j.aquatox.2013.04.007

Hagen, K. N. (2009). *Algae: Nutrition, Pollution Control and Energy Sources* (K. N. Hagen, Ed.). Nova Science Publishers.

Hansen, T. L., Schmidt, J. E., Angelidaki, I., Marca, E., Jansen, J. la C., Mosbæk, H., &

Christensen, T. H. (2004). Method for determination of methane potentials of solid organic waste. *Waste Management*, *24*(4), 393–400. https://doi.org/10.1016/j.wasman.2003.09.009

Hayden, H. S., Blomster, J., Maggs, C. A., Silva, P. C., Stanhope, M. J., & Waaland, J. R. (2003). Linnaeus was right all along: Ulva and Enteromorpha are not distinct genera. *European Journal of Phycology*, *38*(3), 277–294. https://doi.org/10.1080/1364253031000136321

Holden, J. J., Kingzett, B. C., MacNeill, S., Smith, W., Juanes, F., & Dudas, S. E. (2018). Beach-cast biomass and commercial harvesting of a non-indigenous seaweed, Mazzaella japonica, on the east coast of Vancouver Island, British Columbia. *Journal of Applied Phycology*, *30*(2), 1175–1184. https://doi.org/10.1007/s10811-017-1321-1

Humbert, S., Schryver, A. De, Bengoa, X., Margni, M., & Jolliet, O. (2014). *IMPACT 2002 + :User Guide*.

Ishizaka, A., & Nemery, P. (2013). *Multi-Criteria Decision Analysis: Methods and Software*. https://doi.org/10.1002/9781118644898

ISO. (2006). *ISO 14040:2006 Environmental management - Life cycle assessment - Principles and framework*.

Jolliet, O., Margni, M., Charles, R., Humbert, S., Payet, J., Rebitzer, G., & Rosenbaum, R. (2003). IMPACT 2002+: A new life cycle impact assessment methodology. *The International Journal of Life Cycle Assessment*, *8*(6), 324–330. https://doi.org/10.1007/BF02978505

Kahraman, C., Yasin Ateş, N., Çevik, S., Gülbay, M., & Ayça Erdoğan, S. (2007). Hierarchical fuzzy TOPSIS model for selection among logistics information technologies. *Journal of Enterprise Information Management*, *20*(2), 143–168. https://doi.org/10.1108/17410390710725742

Kauliņš, D. (2019). *Nacionālais enerģētikas un klimata plāns 2021.-2030.gadam*. Retrieved from https://www.norden.lv/Uploads/2018/10/24/1540377527_.pdf

Kelly, M. S., & Dworjanyn, S. (2008). *The potential of marine biomass for anaerobic biogas production: a feasibility study with recommendations for further research*. The Crown Estate.

Kepp, U., Machenbach, I., Weisz, N., & Solheim, O. E. (2000). Enhanced stabilisation of sewage sludge through thermal hydrolysis - three years of experience with full scale plant. *Water Science and Technology*, *42*(9), 89–96. https://doi.org/10.2166/wst.2000.0178

Keskinkan, O., Goksu, M. Z. L., Basibuyuk, M., & Forster, C. F. (2004). Heavy metal adsorption properties of a submerged aquatic plant (Ceratophyllum demersum). *Bioresource Technology*, *92*(2), 197–200. https://doi.org/10.1016/j.biortech.2003.07.011

Krastina, J., Romagnoli, F., & Balina, K. (2017). SWOT analysis for a further LCCA-based techno-economic feasibility of a biogas system using seaweeds feedstock. *Energy Procedia*, *128*, 491–496. https://doi.org/10.1016/j.egypro.2017.09.065

Lakaniemi, A. M., Tuovinen, O. H., & Puhakka, J. A. (2013). Anaerobic conversion of microalgal biomass to sustainable energy carriers - A review. *Bioresource Technology*, *135*, 222–231. https://doi.org/10.1016/j.biortech.2012.08.096

Latvijas Republikas Saeima. (2010). *Latvijas ilgtspējīgas attīstības stratēģija līdz 2030. gadam*.

Latvijas Republikas Zemkopības Ministrija. (2017). *Latvijas Bioekonomikas stratēģija 2030*.

Lewis, J., Salam, F., Slcak, N., Winton, M., & Honson, L. (2011). *Product options for the processing of marine macro-algae*.

Lu, J., Zhang, G., Ruan, D., & Wu, F. (2007). *Multi-Objective Group Decision Making*. https://doi.org/10.1142/p505

Mankiw, N. G. (2017). *Principles of Macroeconomics* (8th Editio). Cengage Learning.

Møller, H. B., Sommer, S. G., & Ahring, B. K. (2004). Methane productivity of manure, straw and solid fractions of manure. *Biomass and Bioenergy*, *26*(5), 485–495. https://doi.org/10.1016/j.biombioe.2003.08.008

Munier, N. (2004). *Multicriteria Environmental Assessment*. https://doi.org/10.1007/1-4020-2090-2

Pastare, L., Aleksandrovs, I., Lauka, D., & Romagnoli, F. (2016). Mechanical Pre-treatment Effect on Biological Methane Potential From Marine Macro Algae: Results from Batch Tests of Fucus Vesiculosus. *Energy Procedia*, *95*, 351–357. https://doi.org/10.1016/j.egypro.2016.09.021

Pastare, L., & Romagnoli, F. (2019). Life Cycle Cost Analysis of Biogas Production from Cerathophyllum demersum, Fucus vesiculosus and Ulva intestinalis in Latvian Conditions. *Environmental and Climate Technologies*, *23*(2), 258–271. https://doi.org/10.2478/rtuect-2019-0067

Pastare, L., Romagnoli, F., & Baltrenaite, E. (2014). 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,"* *5*, 1–8.

Pastare, L., Romagnoli, F., & Blumberga, D. (2018). Comparison of biomethane potential lab tests for Latvian locally available algae. *Energy Procedia*, *147*, 277–281. https://doi.org/10.1016/j.egypro.2018.07.092

Pastare, L., Romagnoli, F., Lauka, D., Dzene, I., & Kuznecova, T. (2014). Sustainable Use Of Macro-Algae For Biogas Production In Latvian Conditions: A Preliminary Study Through An Integrated Mca And Lca Approach. *Environmental and Climate Technologies*, *13*(1), 44–56. https://doi.org/10.2478/rtuect-2014-0006

Pastare, L., Romagnoli, F., Rugele, K., Dzene, I., & Blumberga, D. (2015). Biochemical

Methane Potential from Anaerobic Digestion of the Macrophyte Cerathophyllum Demersum: A Batch Test study for Latvian Conditions. *Energy Procedia*, *72*, 310–316. https://doi.org/10.1016/j.egypro.2015.06.045

Pham, C. H., Triolo, J. M., Cu, T. T. T., Pedersen, L., & Sommer, S. G. (2013). Validation and Recommendation of Methods to Measure Biogas Production Potential of Animal Manure. *Asian-Australasian Journal of Animal Sciences*, *26*(6), 864–873. https://doi.org/10.5713/ajas.2012.12623

Pragya, N., Pandey, K. K., & Sahoo, P. K. (2013). A review on harvesting, oil extraction and biofuels production technologies from microalgae. *Renewable and Sustainable Energy Reviews*, *24*, 159–171. https://doi.org/10.1016/j.rser.2013.03.034

Raposo, F., De La Rubia, M. A., Fernández-Cegrí, V., & Borja, R. (2012). Anaerobic digestion of solid organic substrates in batch mode: An overview relating to methane yields and experimental procedures. *Renewable and Sustainable Energy Reviews*, *16*(1), 861–877. https://doi.org/10.1016/j.rser.2011.09.008

Romagnoli, F., Pastare, L., Sabūnas, A., Bāliņa, K., & Blumberga, D. (2017). Effects of pre-treatment on Biochemical Methane Potential (BMP) testing using Baltic Sea Fucus vesiculosus feedstock. *Biomass and Bioenergy*, *105*, 23–31. https://doi.org/10.1016/j.biombioe.2017.06.013

Saaty, T. L. (1990). How to make a decision: The Analytic Hierarchy Process. *European Journal of Operational Research*, *48*, 9–26.

Sialve, B., Bernet, N., & Bernard, O. (2009). Anaerobic digestion of microalgae as a necessary step to make microalgal biodiesel sustainable. *Biotechnology Advances*, *27*(4), 409–416. https://doi.org/10.1016/j.biotechadv.2009.03.001

Singh, A., & Olsen, S. I. (2011). A critical review of biochemical conversion, sustainability and life cycle assessment of algal biofuels. *Applied Energy*, *88*(10), 3548–3555. https://doi.org/10.1016/j.apenergy.2010.12.012

Sinha, R. K., & Singh, S. (2010). *Green Plants and Pollution: Natures Technology for Abating and Combating Environmental Pollution*. Nova Science Publishers.

Smalheiser, N. R. (2017). ANOVA. In *Data Literacy* (pp. 149–155). https://doi.org/10.1016/B978-0-12-811306-6.00011-7

Surendra, K. C., Takara, D., Hashimoto, A. G., & Khanal, S. K. (2014). Biogas as a sustainable energy source for developing countries: Opportunities and challenges. *Renewable and Sustainable Energy Reviews*, *31*, 846–859. https://doi.org/10.1016/j.rser.2013.12.015

Tedesco, S., Benyounis, K. Y., & Olabi, A. G. (2013). Mechanical pretreatment effects on macroalgae-derived biogas production in co-digestion with sludge in Ireland. *Energy*, *61*, 27–33. https://doi.org/10.1016/j.energy.2013.01.071

Triantaphyllou, E., & Mann, S. H. (1995). Using the analytic hierarchy process for decision making in engineering applications: Some challenges. *International Journal of Industrial Engineering: Applications and Practice*, *2*(1), 34–44.

US Environmental Protection Agency. (2001). *Method 1684: Total, Fixed and Volatile Solids in Water, Solids, and Biosolids*.

VDI. (2006). VDI 4630: Fermentation of organic materials, characterisation of the susbtrates, sampling, colection of material data, fermentation test. In *VDI-Handbuch Energietechnik* (pp. 44–59). VDI-HAndbuch EnergieTechnik.

Vergara-Fernández, A., Vargas, G., Alarcón, N., & Velasco, A. (2008). Evaluation of marine algae as a source of biogas in a two-stage anaerobic reactor system. *Biomass and Bioenergy*, *32*(4), 338–344. https://doi.org/10.1016/j.biombioe.2007.10.005

Wellinger, A. (2009). *Algal Biomass: Does it save the world? Short reflections*. Retrieved from http://www.iea-biogas.net/files/daten-redaktion/download/publi-task37/AlgaeBiomass8-09.pdf

Wiley, P. E., Campbell, J. E., & McKuin, B. (2011). Production of Biodiesel and Biogas from Algae: A Review of Process Train Options. *Water Environment Research*, *83*(4), 326–338. https://doi.org/10.2175/106143010X12780288628615

Zamalloa, C., Vulsteke, E., Albrecht, J., & Verstraete, W. (2011). The techno-economic potential of renewable energy through the anaerobic digestion of microalgae. *Bioresource Technology*, *102*(2), 1149–1158. https://doi.org/10.1016/j.biortech.2010.09.017

PUBLICATIONS ARRISING FROM THESIS

Paper 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.

Paper 2: Pastare, L., Romagnoli, F., Blumberga, D. Comparison of biomethane potential lab tests for Latvian locally available algae. "Energy Procedia", 2018, Vol 147, pp.277.–281. Available: doi: 10.1016/j.egypro.2018.07.092.

Paper 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.

Paper 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.

Paper 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.

Paper 6: Pastare, L., Romagnoli, F., Lauka, D., Dzene, I., Kuznecova, T. Sustainable Use of Macro-Alagae for biogas Production in Latvian Conditions: a Prelimenary 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.

Paper 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, Nr.5, pp. 1-8. eISBN: 978-609-457-538-9

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Life Cycle Cost Analysis of Biogas Production from *Cerathophyllum demersum*, *Fucus vesiculosus* and *Ulva intestinalis* in Latvian Conditions

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***Abstract* – Life cycle costs of co-digestion plant of cattle farm manure and locally available freshwater macrophyte *C. demersum*, marine brown algae *F. vesiculosus*, and marine green algae *U. intestinalis*; ratio 5:1) are analysed based on Latvian climatic and economic conditions. Biomass collection from nature and pre-treatment of biomass, biogas production, biogas treatment and utilization in combined heat and power plant are included in the boundaries. The weak points of scenarios are large capital investments, electricity sale price (and the application of feed-in tariff). As naturally grown algae and macrophytes are used, they are also sensitive to weather conditions each year as available amounts of biomass might change and decrease. Net Present Value is positive only for *C. demersum* with Internal Rate of Return of –14 % and Discounted Payback Period of 11 years.**

***Keywords* – Algae; biogas; LCCA; Life Cycle Cost Analysis**

1. INTRODUCTION

As the carbon-intensive activities are still posing different risks to the environment and is threatening sustainability, the search for alternative fuel sources has become an important topic for world leaders as well as regular citizens. In search of the best solution (application, costs, availability, etc.) many different alternative energy production technologies and fuels are examined more closely [1]. Biogas as a replacement fuel offers easy application in already existing infrastructure for natural gas use. It can be cleaned to standards of natural gas and injected into existing natural gas streams as well as directly used in the same energy generation applications. Biogas production process itself is also versatile as different set-ups can be used based on type of biomass available as well as specific climatic conditions. As biogas can be produced from a variety of different biomasses it is very versatile and could be used globally with ease, as the technological advancement is faster as compared to other similar technologies [2].

The search for the best biomass for biogas production is still ongoing as there are many aspects to be taken into account. First generation biofuels (rapeseed, wheat, etc.) were food crops that raised ethical questions of food sources being used for energy production as well as using fertile arable lands. Second-generation fuels tried to pass by the food vs. fuel debate by using non-food crops (straw, wood, crop waste). Both of these generations struggled with net energy gains – using more energy for the production process than actually producing.

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Third generation fuels have improved the weak spots of previous generations, as algae do not require arable lands and have fast growing rates [3]. It is considered as viable input for biogas production [4], [5]. As algae species availability differs from region to region, deeper analysis should be carried out for each region separately to determine the best solutions of real life, large-scale applications. Despite the promising potential, algae use is still not commercialized, as many constraining factors exist [6]. Thus, deeper examination and solutions should be found.

Algae can be either grown in pond systems (open or closed) or collected directly from nature. Cultivating algae adds another step of costs and limitations to the whole process. Collection from nature, even though unreliable, in the long term offers an opportunity of reduced costs and possible environmental benefits. Depending on water body proximity, their condition and other restrictions (protected zone limitations) it is important to collect a choice of species. All species of algae have different growing and reproducing conditions as well as their biogas yields, volatile solids, totals solids are different. A preliminary analysis of available species in each region as well as experimental research is needed to find the best available opportunities [6].

Study by Balina et al. [5] determined three potential marine algae species available and usable for Latvian conditions (*Fucus vesiculosus, Furcellaria lumbricalis* and *Ulva intestinalis*). As *F. vesiculosus* and *U. intestinalis* have been reported to regularly be washed out on shore along Latvian coastline [5]. They are chosen to be evaluated in more details in this study. Study by Pastare et al. [7] determined that *Cerathophyllum demersum* is a potentially viable algae species used for biomass production due to its availability as well as reported biogas yields. Further experimental analysis of locally collected algae and their biochemical methane potential have already been performed [5], [7]–[9]. Based on those results, all species can be considered usable for biogas production. The aim of this study is to perform a full life cycle costs analysis for the three chosen algae species (*F. vesiculosus, U. intestinalis* and *C. demersum*) in order to compare them and find the most suitable species for biogas production locally. Environmental aspects as well as aspects relating to licensing and protection limitations are not considered at this time.

2. DESCRIPTION OF SCENARIOS

Within this study 3 different scenarios for algae use for biogas production and use in combined heat and power (CHP) units are compared. Based on previous studies [5], [7] the selected species are *Cerathophyllum demersum* (freshwater macrophyte), *Fucus vesiculosus* (marine brown algae) and *Ulva intestinalis* (marine green algae), see Fig. 1. Even though *C. demersum* is a macrophyte, based on the characteristics (growing rates, digestion rate and availability) it is analysed together with algae as part of this study.

Fig. 1. Species selected for study: a) *Cerathophyllum demersum*; b) *Fucus vesiculosus*; c) *Ulva intestinalis*.

In all three scenarios the algae are naturally grown and collected either directly from water bodies (in case of *C. demersum* – from lakes) or from shores (in case of *F. vesiculosus* and *U. intestinalis* – from shores of the Baltic Sea and Gulf of Riga). The collection is carried out only after the bloom period, usually starting July until November, when the water bodies start freezing over or all of the available washed-out algae has been collected. A boat and a comb-type attachment (attachment that catches the grown algae itself) are leased for collecting *C. demersum* for 150 days per year on average. Both marine algae species (*F. vesiculosus* and *U. intestinalis*) are collected using a small tractor and a comb-type attachment.

In all scenarios, the average distance from algae collection to the site is 100 km. After collection the algae are transported to site, where it is stored in 4 °C before being treated and used for biogas production. Algae are stored in a cooled temperature to avoid biomass degradation. The temperature in the storage unit is maintained only in the summertime and partially throughout spring and autumn when needed as the average temperature in Latvia during the months of November until March has been around or lower than 4 ºC in the last 5 years [10], [11].

The algae are stored in the storage unit until needed for the biogas production process. Pre-treatment of algae is carried out shortly before adding it to the digestion tank. Pre-treatment includes washing of salt and debris for marine algae species (*F. vesiculosus* and *U. intestinalis*). Washing out is carried out in water tanks with sieves using freshwater as a cleaning medium. The algae are submerged in the water, letting the salt dissolve in the water, as well as it is manually stirred to help remove sand and debris. After algae have been submerged in the water, the tank is drained, leaving the algae on sieves. Washing of salt and debris improves the overall digestibility of algae as salt is an inhibiting factor for methanogenic bacteria [12].

As part of pre-treatment, shredding is also carried out in all scenarios. A twin shaft shredder is used. Shredding improves the digestion rate as well makes it easier to feed-in the feedstock [9].

Algae are co-digested with cattle farm manure (ratio 1:5 based on VS) to improve the overall feasibility and digestion rate. See Table 1 for details of anaerobic digestion details per algae species. The inputs are based on previous experiments [7]–[9] as well as literature analysis [12], [13].

TABLE 1. BIOMASS PARAMETERS FOR BIOGAS PRODUCTION

Biomass	*C. demersum*	*F. vesiculosus*	*U. intestinalis*	Cattle farm manure
Biogas yield, 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

As algae are growing naturally and are collected directly from nature, there are limits in the amounts available each year for collection. The limit is assumed based on the average washed out algae load size per meter of coastline per year (25 kg/m) and the length of the coastline (494 km) [14]. Based on that information, the biogas yields and the chosen algae-manure ratio a digestion tank with a capacity of 1 500 m^3 and a CHP unit with 250 kW electrical capacity are chosen. As each of the algae has a different biogas yield, volatile solids and total solids content, the amount of feedstock needed to operate the CHP unit to get the same outcome differs (Table 2).

TABLE 2. OPERATIONAL INPUTS FOR SCENARIOS

	C. demersum	Manure	*F. vesiculosus*	Manure	*U. intestinalis*	Manure
Inputs, t/year	6 328	14 432	9 055	14 432	6 663	14 432
Methane produced, m^3/year	102 610	513 052	102 610	513 052	102 610	513 052
Methane produced in total, m^3/year	615 663		615 663		615 663	
Electricity produced in total, MWh/year	2 190		2 190		2 190	
Heat produced in total, MWh/year	3 942		3 942		3 942	

All calculations are based on generating 2 190 MWh electricity and 3 942 MWh heat per year.

3. DESCRIPTION OF COSTS

Life cycle costs analysis is a cost-effectiveness approach and requires detailed inventory (or estimations) of overall costs as well as benefits [15]. The 4 main phases of any project are – acquisition and design phase, construction phase, operation, maintenance and repair phase and residual phase [16]. Residual phase is not considered in this study.

The main relevant costs are design & licensing, capital investments and O&M (operation and maintenance). Design and licensing costs are estimated to be 3 % of total capital investments [17].

The capital investment costs are the sum of costs of equipment for algae collection and transportation (small tractor with an attachment), storage units for feedstock and digestate, container units for pre-treatment, pre-treatment equipment (washing tank, shredder), biogas digestion plant (reactor, pumps and mixers, network connections, feeding system, measurement and control system, heat system), biogas treatment equipment (compressor, condensator), CHP plant (co-generation engine, input ventilator, cooler, emergency cooler). Land acquisition costs are not included.

Operational and maintenance costs are directly based on the scenarios and can be divided into 2 major groups – collection and transportation and biogas production (Fig. 2).

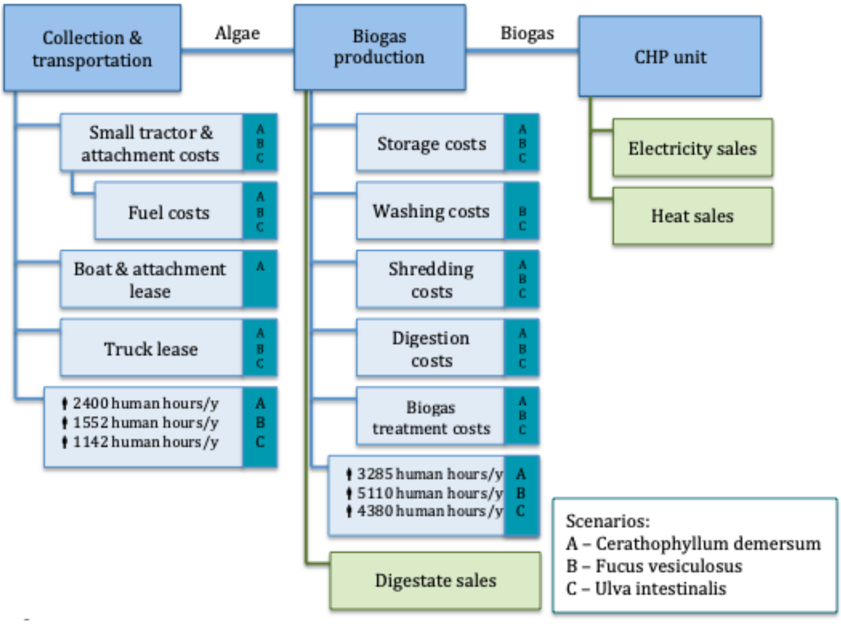

Fig. 2. Main operational costs.

Operation and maintenance include labour for operating algae collection machinery, overseeing pre-treatment, digestion, treatment and CHP plant operations. Consumables include diesel for collection transportation, electricity for cooling storage units, water and wastewater costs for pre-treatment, and electricity for pre-treatment. Lease includes water transportation lease for algae collection and land transportation lease for moving algae to site. Maintenance and replacement of other goods in cash flow are presented in O&M position. Digestion, treatment and CHP unit electricity and heat needs are included in the parasitic electricity consumption. Maintenance costs are assumed as 2 % of capital investments [18], [19].

Depreciation depends on the estimated life span for each item (linear method). Other costs include activities like accounting, consultations and alike. Insurance costs are 0.05 % of capital investment [17]. Loan is calculated as 70 % of total investments. Inflation rate is 2 %, rate on loan is 3.5 %. Income tax is 15 % [17]. The study period is 20 years; discount rate is 5 %. Post financing is 70 % debt capital and 30 % equity capital with a loan period of 10 years and interest rate of 3.5 % [19]. See Table 3 for more detailed information of costs and revenues of scenarios.

TABLE 3. TOTAL COSTS AND REVENUES FOR SCENARIOS

	C. demersum	*F. vesiculosus*	*U. Intestinalis*
Capital investments, EUR	2 727 750	2 732 750	2 732 750
Acquisition and design, EUR	81 833	81 983	81 983
Total investment, EUR	2 809 583	2 814 733	2 814 733
O&M			
Labour, EUR/year	32 988	35 136	333 778
Consumables, EUR/year	803	78 545	30 531
Lease, EUR/year	55 579	25 871	58 011
Maintenance, EUR/year	54 555	54 655	19 038
Depreciation, EUR/year	168 193	169 543	54 655
Other, EUR/year	2 000	2 000	169 543
Insurance, EUR/year	13 639	13 664	13 664
Income from electricity, EUR/year*	279 081	594 822	581 491
Income from electricity, EUR/year	65 561	384 277	367 971
Income from heat, EUR/year	150 525	275 193	279 081
Income from digestate, EUR/year	149 467	64 648	65 561
Loan amount, EUR	1 966 708	1 970 313	1 970 313
PMT, EUR/year	236 479.63	236 913.10	236 913.10

*With feed in tariff.

Revenues come from selling the excess electricity, heat and digestate. For the first 10 years of a project, electricity is sold with a feed-in tariff. In accordance with Latvian Cabinet Regulation No. 221, electricity producers upon production of electricity in cogeneration can apply for the sale of electricity within the framework of the mandatory procurement. For the first 10 years of operation, the price for electricity produced is determined based on trader electricity price, the natural gas tariff and differentiation coefficient, which depends on the electric capacity installed in a cogeneration unit [19], [20]. See Table 3 for main total costs and revenues of each scenario.

More detailed information about the inputs for LCCA can be found in Annex 1. It should be taken into account that only the major costs of projects are taken into account. All cost estimations are subject to reference. All cost estimations are made with consideration of the time value of money and currency rates. To convert prices into today's gross domestic product deflator was used as price index. Eq. (1) was used to convert past prices to price level for a specific year by using GDP deflator value for a specific year [21].

$$\text{Price}_{\text{Specific year}} = \frac{\text{GDP Deflator}_{\text{Specific year}}}{\text{GDP deflator}_{\text{Base year}}} \cdot \text{Price}_{\text{Base year}}, \tag{1}$$

where

$\text{Price}_{\text{Specific year}}$	Price level in a specific year;
$\text{Price}_{\text{Base year}}$	Price level in a past year;
$\text{GDP Deflator}_{\text{Specific year}}$	GDP deflator index in a specific year;
$\text{GDP Deflator}_{\text{Base year}}$	GDP deflator index in a past year [18].

4. METHODOLOGY OF LCC

The following section presents the methodology of Life Cycle Cost Analysis (LCCA). LCCA is an economic method that uses a structured approach to address all different costs occurring during a lifetime (or a set period) of a project. It also offers an evaluation of economic consequences (costs, revenues, cash flows etc.) and monetary trade-offs. This analysis allows for comparisons of alternative scenarios to optimize the costs in a given time period. For projects needing both environmental and economic analysis, LCCA is a great tool as it can cover project stages in the same way as Life Cycle Analysis (LCA) [22]–[24].

LCCA is widely used (starting from US and EU governments, businesses, scientists etc.) due to many advantages. Main advantages are projection of relevant cash flows, time value of money taken into account, comparisons possible, can assist in decision making process and main critical costs points are easily determined. Of course, there are some constraints as well – indirect costs usually are out of boundaries, it is time consuming, lack of reliable data may lead to unreliable results and comparison with different benefits are impossible [16].

For all projects 4 main categories of costs exist – Acquisition and design costs (research, design, rent and licensing, other), Construction costs (materials, construction), Operation, maintenance and repair costs (Resources as energy, water, other consumables; Maintenance as repairs, planned maintenance and waste management; Operational as labour and others) and residual costs (Disposal costs and benefits). Depending on the type of project being analysed, the distribution of these costs can vary greatly [16]. For this study the total costs are comprised of:

1. Capital Investments;
2. Acquisition and Design;
3. Operation and Maintenance:
   - Labour,
   - Consumables,
   - Lease,
   - Maintenance,
   - Depreciation,
   - Other;
4. Insurance;
5. Loan.

The viability of scenarios is determined based on several economic factors like net present value (NPV), internal rate of return (IRR) and discounted payback (DPB). Used discount rate for NPV calculation is 2 per cent. NPV is the sum of discounted values in the flow until a specific reference date. NPV shows how the cash flow is affected by time. It helps determine and compare the value of an investment [25]. Discount rate is used for discounting the cash flow to the present.

Internal Rate of Return (IRR) is also used in determining the viability of a project. IRR estimates the profitability of potential investments by calculating the discount rate by which the NPV of all cash flow in a project are equal to zero. Or in other words, IRR shows the maximum value of the interest rate with which it is acceptable to borrow money for the project development. Discounted Payback measures how long recovery of initial investment will take place. These values can be used to accept or reject a certain project. IF NPV value is greater than 0, then the project can be accepted, if it’s smaller than 0; it should be rejected. In case of several positive NPV values, the project with the highest value should be chosen.

In case of IRR, positive values – accept project, negative – reject. DPB should be shorter than the study period (which is 20 years) [21].

5. Results

Cash flow is modelled based on the inputs and assumptions mentioned before. NPV, IRR and DPB values can be seen in Table 4.

TABLE 4. NPV, IRR, DPB OF SCENARIOS

	C. demersum	*F. vesiculosus*	*U. intestinalis*
NPV	51 009	–505 683	–219 061
IRR	–14 %	Undefined	–20 %
DPB	Year 11	After 20 years	Year 11
Evaluation	Reject	Reject	Reject

As it can be seen from NPV, only use 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 internal rate of return is too high to be accepted as viable. Based on this information alone – all of the projects should be rejected, as the IRR values are negative or undefined. Even with a positive NPV value, the *C. demersum* scenario would not be a good investment.

Cost structure of all scenarios can show the most critical cost positions. All costs are expressed as a percentage of total costs per year for operation of the biogas plant and CHP unit (including algae collection and pre-treatment). The yearly costs of capital goods are estimated in terms of depreciation and insurance costs. The yearly costs of other positions are estimated according to previously described inventory.

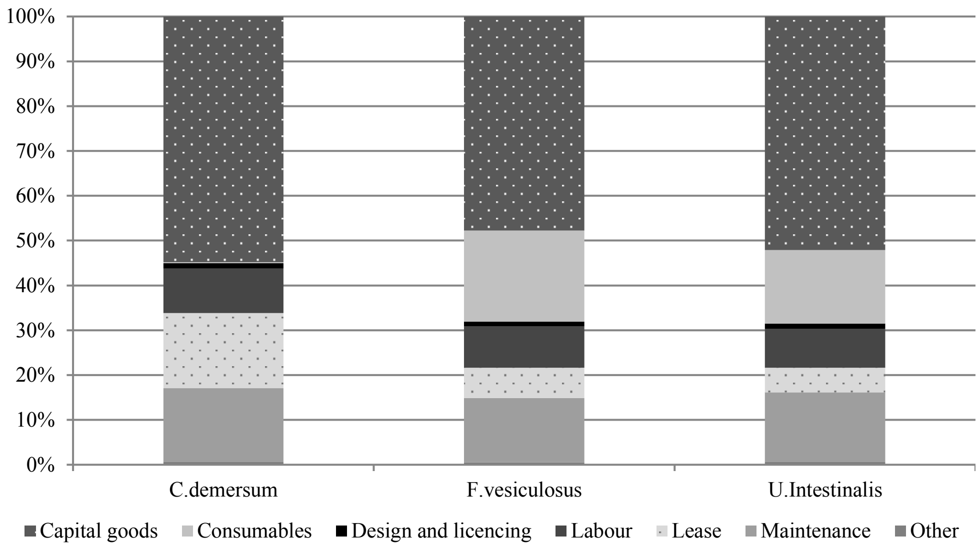

Fig. 3. Costs structure of scenarios.

As it can be seen in Fig. 3, the most critical costs are capital goods and maintenance for all scenarios and either consumable (for *F. vesiculosus* and *U. intestinalis*) or lease (for *C. demersum*) costs. As *C. demersum* does not require washing of salt and debris, consumable costs are significantly smaller, but as it requires boat rental for extraction from water, lease costs are significantly higher. Besides, the cost structure it is important to evaluate the revenue structure (Fig. 4).

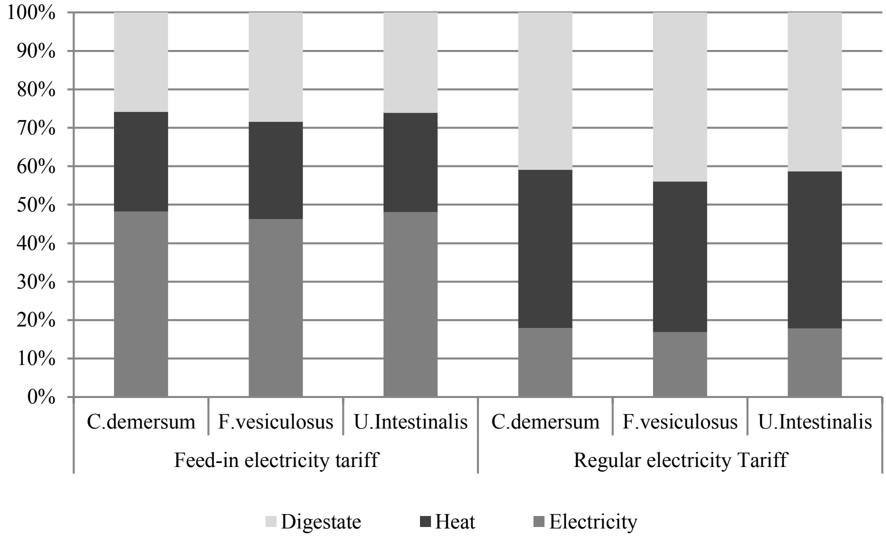

Fig. 4. Revenue structure of scenarios.

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

As there are a lot of capital investments associated with having a biogas production site and CHP unit, one of the options to cut down costs would be to sell the treated biomethane as an end product. By eliminating a big part of capital and operational costs, it is possible that, with reduced revenues, NPV, IRR and DPB would be more favourable.

By eliminating the CHP unit on site and selling the cleaned biogas to another biogas production site or CHP unit capital investments for the unit can be avoided. As no longer either electricity or heat will be produced on site, additional costs for electricity and heat use arise. It is assumed there are no additional costs for transporting the produced biogas to another site; all costs related are covered by the selling price. For each scenario, there is different break-even price for NPV (Table 5). For a positive NPV for projects the biogas-selling price is in the range of 547 to 599 EUR/t.m^3. The average natural gas sale price for end-users in year 2017 was 287 EUR/t.m^3 [23]. Without any subsidies or feed-in tariffs for biogas selling, the almost-double price is not competitive enough for a project to be viable.

TABLE 5. NPV, IRR AND DPB FOR SCENARIOS DEPENDING ON BIOGAS SELLING PRICE

Biogas selling price, EUR/t.m^3	*C. demersum*			*F. vesiculosus*			*U. intestinalis*		
	NPV, EUR	IRR, %	DPB, years	NPV, EUR	IRR, %	DPB, years	NPV, EUR	IRR, %	DPB, years
287	–2 663 092	–	>20	–3 198 554	–	>20 years	–2 940 103	–	>20
300	–2 529 699	–	>20	–3 065 160	–	>20 years	–2 806 710	–	>20
400	–1 503 994	–	11	–2 039 056	–	>20	–1 780 605	–	11
500	–477 490	–10 %	11	–1 012 951	–13 %	11	–754 501	–11 %	11
547	0	–7 %	11	–530 682	–10 %	11	–272 232	–8 %	11
574	281 827	–6 %	11	–253 634	–8 %	11	0	–7 %	11
599	538 353	–5 %	11	0	–7 %	11	261 343	–6 %	11
600	548 615	–5 %	11	13 153	–7 %	11	271 604	–6 %	11
700	1 574 719	–1 %	11	1 039 257	–3 %	11	1 297 708	–2 %	11
800	2 600 823	1 %	2	2 065 362	0 %	4	2 323 812	1 %	2
900	3 626 928	4 %	2	3 091 466	3 %	2	3 349 917	4 %	2

Also for projects using naturally grown algae, it must be taken into account that the amounts of biomass available each year might fluctuate due to weather conditions. As the total project timeline is 20 years, it must be taken into account that during this period the general condition of water bodies might change (eutrophication, pollution) as well as legal aspects of biomass collection from nature. In order to approve a project like this, alternative plans should be considered for obtaining biomass as well as adjusting the digestion process accordingly.

6. CONCLUSIONS

As the study shows, based on experimental analysis of locally available algae as well as life cycle costs analysis, the use of algae for biogas production in current Latvian conditions is not viable. There are several weak points of such scenarios – the low biochemical methane potential, high investment costs, low electricity prices as well as possibly inconsistent source of biomass. In order to make algae use viable at least one of these factors should be resolved and even then, it might not be enough.

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ANNEX

Parameter	Value			Unit	Source
	C. demersum	***F. vesiculosus***	***U. intestinalis***		
Algae collection and transportation					
Skid steer loader price	17 000	17 000	17 000	EUR/unit	[26]
Skid steer loader life span	20	20	20	Years	[26]
Skid steer loader attachment price	5 000	5 000	5 000	EUR/unit	[26]
Skid steer loader attachment life span	20	20	20	Years	[26]
Skid steer loader daily usage in base	2	2	2	Litres/day	Assumption
Skid steer loader usage for collection	–	194	143	Days/year	Calculation
Skid steer loader diesel consumption while collecting	–	10	10	Litres/day	[26]
Diesel price	0.79	0.79	0.79	EUR/litre	[27]
Boat with mechanical motor and attachment lease (including diesel consumption)	200 + 50	–	–	EUR/day	[28]
Boat with mechanical motor and attachment lease	150	–	–	Days	Assumption
Truck (10 t with self-loader) lease	200	200	200	EUR/day	[29]
Truck daily capacity	70	70	70	t/day	Assumption
Truck lease	90	129	95	Days/year	Calculation
Collection labour worker need	2	1	1	People/day	Assumption
Days needed	150	194	143	Days/year	Calculation
Hours per day worked	8	8	8	h/day	Assumption
Wage	5	5	5	EUR/h	Assumption
Storage					
Feedstock storage unit price	15 000	15 000	15 000	EUR/unit	[18]
Feedstock storage unit life span	20	20	20	Years	[18]
Digestate storage unit price	7 500	7 500	7 500	EUR/unit	[18]
Digestate storage unit life span	20	20	20	Years	[18]
Cooling unit power	4	4	4	kW	[18]
Operation hours for cooling	4320	4320	4320	h/year	[18]
Pre-treatment					

Parameter	Value			Unit	Source
	C. demersum	***F. vesiculosus***	***U. intestinalis***		
Pre-treatment container unit price	75 000	75 000	75 000	EUR/unit	[18]
Pre-treatment container unit life span	20	20	20	Years	[18]
Feedstock washing tank price	–	5 000	5 000	EUR/unit	[18]
Feedstock washing tank life span	–	10	10	Years	[18]
Freshwater need for pre-treatment	–	5	5	m^3/t algae	Assumption
Freshwater price	–	0.88	0.88	EUR/m^3	[30]
Effluent discharge price	–	0.79	0.79	EUR/m^3	[30]
Feedstock shredder price	12 000	12 000	12 000	EUR/unit	[19]
Feedstock shredder life span	10	10	10	Years	[19]
Feedstock shredder power	25	25	25	kW	[19]
Feedstock shredder usage daily	6	9	6	h/day	Calculation
Labour worker need per day	1	2	2		Assumption
Hours worked per day	5	5·2	4·2	h/day	Assumption
Labour worker wage	3.5	3.5	3.5	EUR/hour	Assumption
Digestion – biogas treatment – CHP plant					
Digestion tank capacity	1 500	1 500	1 500	m^3	Assumption
Algae input	6 328	9 055	6 663	T ww/year	Calculations
Manure input	14 432	14 432	14 432	T ww/year	Calculation
Algae: Manure ratio	1:5	1:5	1:5	–	Assumption
Digestion reactor	1 937 500	1 937 500	1 937 500	EUR/unit	[19] (adapted)
Digestion reactor life span	20	20	20	Years	[19]
Pump and mixer	56 250	56 250	56 250	EUR/unit	[16] (adapted)
Pump and mixer life span	10	10	10	Years	[19]
Network connections	25 000	25 000	25 000	EUR/unit	[19] (adapted)
Network connections life span	20	20	20	Years	[19]
Feeding system	50 000	50 000	50 000	EUR/unit	[19] (adapted)
Feeding system life span	7	7	7	Years	[19]
Measurement and control system	18 750	18 750	18 750	EUR/unit	[19] (adapted)

Parameter	Value			Unit	Source
	C. demersum	***F. vesiculosus***	***U. intestinalis***		
Measurement and control system life span	10	10	10	Years	[19]
Heating system	31 250	31 250	31 250	EUR/unit	[19] (adapted)
Heating system life span	10	10	10	Years	[19]
Electricity usage	Included in parasitic electricity use				Assumption
Heat usage	Included in parasitic heat use				Assumption
Labour need	4	4	4	Human hours/day	Assumption
Labour wage	10	10	10	EUR/h	Assumption
Leftover digestate	16 607	18 789	16 876	t/year	Calculations
Desulphurization compressor	100 000	100 000	100 000	EUR/unit	[19]
Desulphurization compressor life span	10	10	10	Years	[19]
Electricity usage	Included in parasitic electricity use				Assumption
CHP unit electrical capacity	250	250	250	kW	Assumption
Produced electricity	2 190	2 190	2 190	MWh/year	Calculations
Produced heat	3 942	3 942	3 942	MWh/year	Calculations
Parasitic electricity usage	7 %	7 %	7 %	% of production	[19]
Parasitic heat usage	30 %	30 %	30 %	% of production	[19]
Feed in electricity sales tariff	142.05	142.05	142.05	EUR/MWh	[20]
Electricity sales tariff	33.37	33.37	33.37	EUR/MWh	[20]
Heat sales tariff	54.55	54.55	54.55	EUR/MWh	[19]
Digestate sales tariff	9	9	9	EUR/t	[19]
Additional inputs					
Inflation rate	2 %	2 %	2 %	%	[20]
Rate on loan	3.5 %	3.5 %	3.5 %	%	[19]
Loan amount of total investment	70 %	70 %	70 %	%	[19]
Loan time	10	10	10	Years	[19]
Income tax	15 %	15 %	15 %	%	[19]

References

[1] Elegbede I., Guerrero C. Algae biofuel in the Nigerian energy context. *Environmental and Climate Technologies* 2016:17(1):44–60. doi:10.1515/rtuect-2016-0005

[2] Kelly M. S., Dworjanyn S. The potential of marine biomass for anaerobic biogas production: a feasibility study with recommendations for further research. UK: The crown estate, 2008.

[3] Matemilola S., Elegbede I. O., Kies F., Yusuf G. A., Yangni G. N., Garba I. An Analysis of the Impacts of Bioenergy Development on Food Security in Nigeria: Challenges and Prospects. *Environmental and Climate Technologies*, 2019:23(1):64–83. doi:10.2478/rtuect-2019-0005
[4] Chiaramonti D., Prussi M., Buffi M., Casini D., Rizzo A. Thermochemical conversion of microalgae: Challenges and opportunities. *Energy Procedia* 2015:75:819–826. doi:10.1016/j.egypro.2015.07.142
[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. *Energy Procedia* 2017:113:403–410. doi:10.1016/j.egypro.2017.04.022
[6] Chia S. R., et al. Sustainable approaches for algae utilization in bioenergy production. *Renewable energy* 2018:129(B):838–852. doi:10.1016/j.renene.2017.04.001
[7] Pastare L., Romagnoli F., Rugele K., Dzene I., Blumberga D. Biochemical methane potential from anaerobic digestion of the macrophyte *Cerathophyllum demersum*: a batch test study for Latvian conditions. *Energy Procedia* 2015:72:310–316. doi:10.1016/j.egypro.2015.06.045
[8] Sabunas A., Romagnoli F., Pastare L., Balina K. Laboratory algae cultivation and BMP test with *Ulva intestinalis* from the Gulf of Riga. *Energy Procedia* 2017:113:227–284. doi:10.1016/j.egypro.2017.04.066
[9] Romagnoli F., Pastare L., Sabunas A., Balina K., Blumberga D. Effects of pre-treatment on Biochemical Methane Potential (BMP) testing using Baltic Sea *Fucus vesiculosus* feedstock. *Biomass and Bioenergy* 2017:105:23–31. doi:10.1016/j.biombioe.2017.06.013
[10] Graham S., Eastwick C., Snape C., Quick W. Degradation of biomass fuels during artificial storage in laboratory environment. *International Journal of Low-Carbon Technologies* 2012:7(2):113–119. doi:10.1093/ijlct/cts029
[11] Central Statistical Bureau of Latvia. The average air temperature monthly.
[12] Sustainable Energy Ireland. A review of the potential of marine algae as a source of biofuel in Ireland. Dublin: SEI, 2009.
[13] Hagenkamp-Korth F., Ohl S., Hartung E. Effects on the biogas and methane production of cattle manure treated with urease inhibitor. *Biomass and Bioenergy* 2015:75:75–82. doi:10.1016/j.biombioe.2015.02.014
[14] Holden J. J., Kingzett B. C., MacNeill S., Smith W., Juanes F., Dudas S. E. Beach-cast biomass and commercial harvesting of non-indigenous seaweed, Mazzaella japnocia, on the east coast of Vancouver, British Columbia. *Journal of Applied Phycology* 2018:30(2):1175–1184. doi:10.1007/s10811-017-1321-1
[15] Dhanushkodi S., Wilson V. H., Sudhakar K. Life cycle cost of solar biomass hybrid dryer systems for cashew drying of nuts in India. *Environmental and Climate Technologies* 2015:15(1):22–33. doi:10.1515/rtuect-2015-0003
[16] Dhilon B. S. Life Cycle Costing for engineers. US: CRC Press, 2009.
[17] Ekodoma SIA. Informative material for biogas project developers in Latvia about licensing and financial procedures [Online]. [Accessed 04.12.2018]. Available: http://www.biogasin.org/files/pdf/WP3/D.3.8.5_EKODOMA_LV.pdf
[18] van Djik W., van der Schoot J. R. Public output report of the EnAlgae project: An economical model for offshore cultivation of macroalgae. Swensea, 2015.
[19] Krastina J., Romagnoli F., Balina K. SWOT analysis for a further LCCA-based techno-economic feasibility of a biogas system using seaweeds feedstock. *Energy Procedia* 2017:128:491–496. doi:10.1016/j.egypro.2017.09.065
[20] Ministry of Economics. Methodological guidelines of IRR calculations in order to decrease overcompensation for merchants selling electricity in the mandatory procurement program. Riga, 2016
[21] Mankiw N. G. Principles of macroeconomics Cengage Learning. US: South Western College Pub, 2014.
[22] Fabrycky W. J., Blanchard B. S. Life-cycle cost and economic analysis. Englewood Cliffs: Prentice Hall, 1991.
[23] Asiedu Y., Gu P. Product life cycle cost analysis: state of the art review. *International Journal of Production Research* 1998:36:883–908. doi:10.1080/002075498193444
[24] Reidy R., Davis M., Coony R., Gould S., Mann C., Sewak B. Guidelines for life cycle costs analysis. Stanford: Stanford University, 2015.
[25] Potkany M., Hitka M., Krajcirova L. Life Cycle Cost Calculation at the transport company in the supply of production of wooden houses – Case study. *MATEC Web of conferences* 2017:134:00049. doi:10.1051/matecconf/201713400049
[26] Skid steer pricing [Online]. [Accessed 28.08.2018]. Available: https://www.alibaba.com/product-detail/Chinese-Bobcat-700kg-mini-skid-steer_60756404107.html?spm=a2700.7724838.2017115.72.6def 6d98He0jUZ
[27] Central Statistical Bureau of Latvia. Average prices of energy resources for end-user (value added tax exempt).
[28] Boat rental pricing [Online]. [Accessed 28.08.2018]. Available: https://www.ss.com/msg/lv/transport/transports-rent/freight-of-water-transport/blhpgl.html
[29] Truck rental pricing tool [Online]. [Accessed 28.08.2018]. Available: http://www.storent.com/lv/EquipmentCatalog /Equipment Catalog.aspx?open=2&itemNumber=1bc23f56-ef18-4457-9533-317b7025ca30&n ame=Kravas%20mašīna, %20pašizgāzējs,%2012m3
[30] Freshwater and affluent pricing [Online]. [Accessed 28.08.2018]. Available: https://www.rigasudens.lv/pakalpojumi/ tarifi-un-cenas/

Paper 2: Comparison of biomethane potential lab tests for Latvian locally available algae

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Comparison of biomethane potential lab tests for Latvian locally available algae

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Abstract

The aim of this study is to evaluate locally available algae *Fucus vesiculosus*, *Ulva Intestinalis* and *Cerathophyllum demersum* using biomethane potential laboratory tests. Mechanical pre-treatment (cutting) and washing are applied to study the effects on cumulative biogas yield. *Fucus vesiculosus* (cut and washed) produced 81.8 l CH_4/kg VS, *Ulva intestinalis* (cut and washed) produced 92.1 l CH_4/kg VS and *Cerathophyllum demersum* (untreated) produced 405.3 l CH_4/kg VS. For marine algae, the effect of pre-treatments varies from 17 % to 44 %, for freshwater algae it varies between –12 % and 5 %. Best t-test and p values are for washed *Ulva intestinalis*. Results show that from three tested algae species, *Cerathophyllum demersum* is the most suitable algae for biogas production in Latvia, but more detailed analysis of environmental, economical and legal aspects is needed.

Keywords: biomethane potential; algae; biogas

1. Introduction

The growth of energy demand and its impact on the environment is one of the key issues recognized within the European Union (EU). The EU has set targets for the year 2020 (also known as 20-20-20 targets) to tackle this issue

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by increasing the renewable energy share in gross final consumption [1]. New solutions and novel technologies are encouraged.

Biogas production from anaerobic digestion (AD) process is one of the solutions with most applications as different types of biomass can be used (adapted to locally available resources). The primary production of biogas in Latvia has increased tenfold over the last decade (317 TJ in year 2006 and 3762 TJ in year 2016). The biogas primary production in the EU has a similar trend – increasing from 186,771 TJ in 2006 up to 695,011 TJ in 2016 [2].

Biogas production systems are well known, effective and flexible in the use of different substrates. Types of resources used for biogas and other biofuel production have changed as the search for economically feasible and sustainable resources continues [3]. So called first generation biofuels were produced from food crops (corn, wheat, soybeans, etc.). The issue with them is fuel versus food choice [4]. The second-generation food crops are non-edible crops like grass, wood and other organic wastes. Even though the ethical issue is no longer topical, large areas of arable farmland are needed [5]. The third-generation biomass is derived from the aquatic environment. In recent years algae are presented as a viable solution and have gained considerable scientific interest [6].

The use of algae represents several key points – high growth rates and productivity (species specific parameters), adaptations to all water mediums (freshwater, marine water, brackish water) and high carbon content [7, 8]. Also the overall carbon neutrality is a crucial point when evaluating the algae use for biogas production, especially in the Baltic Sea region [4, 5]. Algae can be cultivated both on-shore and offshore as well as collected from natural water bodies. As cultivation has an energy demand that impacts the overall feasibility of algae use, it should be considered carefully.

Within this perspective, the aim of this work is to evaluate different locally available algae in Latvia for biogas production potential. The results of biomethane potential (BMP) lab tests are compared in the search for most suitable algae as biogas substrate.

Nomenclature

AD	anaerobic digestion
BMP	biomethane potential, L CH_4/kg VS
EU	European Union
TS	total solids, %
VS	volatile solids, %

2. Materials and methods

The comparison is made for *Fucus vesiculosus* (marine water brown algae, native in Gulf of Riga, Baltic sea), *Ulva intestinalis* (marine water green algae, native in Gulf of Riga, Baltic Sea) and *Cerathophyllum demersum* (freshwater macrophyte, native in freshwater bodies around Latvia). These three algae are chosen based on literature analysis of native species and availability for experimental analysis.

The evaluation of BMP values has been carried out from batch tests. For all algae the implemented pre-treatment methods are mechanical (cutting) and washing.

2.1. Substrate and inoculum

All algae were kept frozen between harvesting and performing experiments to avoid biodegradation of matter. Before freezing, no pre-treatments were applied.

The washing of algae was performed in order to see the effect of salt and debris inhibition on BMP value. Algae were washed in running tap water until no debris was visible in the excess water.

The mechanical pretreatment of algae was manual chopping of biomass until the maximum fraction size of 5 mm was achieved.

The volatile solid (VS) and total solid (TS) content was determined for algae and the used inoculum (see Table 1) prior to the BMP experiments adopting EPA standards [9]. The used inoculum was sewage sludge from a wastewater plant in the Riga region. Prior to experiments, it was degassed for 5 days at a temperature of 37 °C in order to minimize possible influences on the experiment results. No other pre-treatment methods were applied to inoculum.

Table 1. Volatile and Total Solid content of algae and respective inoculum.

Substrate	VS, %	TS, %
Fucus vesiculosus	78.50	17.80
Inoculum	60.01	3.00
Ulva intestinalis	78.50	21.30
Inoculum	60.40	2.77
Cerathophyllum demersum	78.30	5.11
Inoculum	59.79	1.92

2.2. Batch tests

The BMP tests were carried out in mesophilic conditions (37 °C) in 100 ml serum bottles with maximum loading volume of 60 ml. Batches contained 20 ml inoculum, algae (with ratio 1:5 based on VS), 30 ml water and buffer (3M $NaHCO_3$ solution, 3 g L^{-1} concentration). After filling of bottles, prior to incubation, they were flushed with nitrogen gas for 2 minutes, as methanogenic bacteria are anaerobic. At the start of and during the experiment and during, the bottles were shaken on average once every 3 days.

The biogas production was measured using syringes filled with 5 ml of 3M NaOH solution in order to determine only the methane and not the overall biogas content. BMP levels were measured until no more biogas was produced for a period no longer than 30 days.

3. Results

The results of BMP tests are calculated as liters of CH_4 per kilogram of VS (see Table 2).

Table 2. BMP yield comparison, L CH_4/kg VS.

Algae	Type	Washing	Mechanical pre-treatment	
			+1	–1
Fucus vesiculosus	Marine	+1	81.8	73.1
		–1	67.3	16.6
Ulva intestinalis	Marine	+1	92.1	42.8
		–1	67.1	36.0
Cerathophyllum demersum	Freshwater	+1	377.5	398.4
		–1	326.4	405.3

The maximum yield of 81.8 L CH_4/kg VS for *Fucus vesiculosus* was achieved by combining both factors – mechanical pre-treatment and washing of salt. The same conditions yielded 92.1 L CH_4/kg VS from *Ulva intestinalis*. In case of *Cerathophyllum demersum* the maximum yield of 405.3 L CH_4/kg VS was achieved without applying any factor. The BMP values were approximately 4 times bigger for freshwater macrophyte than marine water algae.

The influence of each factor on BMP values was calculated and statistical analysis (t-test and p value) was applied (see Table 3). T-test values were determined as paired with 1 tail. Influence of washing and mechanical pre-treatment for each alga is different. Washing has a positive influence (on average +25 L CH_4/kg VS) in all cases while mechanical pre-treatment only for marine algae (on average +35 L CH_4/kg VS). Relative influence in percentage has been calculated based on maximum score. For marine algae the relative influence is higher than for freshwater algae.

As marine algae have thicker cell walls and is harder to break down for bacteria – the effect of mechanical pre-treatment is more visible [10]. The higher the relative influence, the higher t-test and p values. The lowest t-test and corresponding p value is for washed *Ulva intestinalis* meaning that it is most likely that the factor influence on results is not a statistical error.

Based on chemical composition and the Buswells equation [11], the maximum theoretical methane potential for biomass can be calculated. In case of *Fucus vesiculosus*, the maximum value is 320 L CH_4/kg VS meaning only a third of the maximum yield has been achieved. For *Ulva intestinalis* the maximum yield is 370 L CH_4/kg VS thus approximately a third of the maximum yield has been achieved. The maximum yield of *Cerathophyllum demersum* is 430 L CH_4/kg VS meaning more than 90 % of the maximum yield has been achieved.

Table 3. Pre-treatment factor influence on BMP analysis.

Algae	Type	Factor	Influence, L CH_4/kg VS	Influence, %	T-test value	p value
Fucus vesiculosus	Marine	Washing	35.5	43 %	0.17	0.44
		Mechanical pre-treatment	29.7	36 %	0.19	0.43
Ulva intestinalis	Marine	Washing	15.9	17 %	0.16	0.07
		Mechanical pre-treatment	40.2	44 %	0.44	0.47
Cerathophyllum demersum	Freshwater	Washing	22.1	5 %	0.29	0.16
		Mechanical pre-treatment	–49.9	–12 %	0.41	0.44

This is also confirmed by measuring the total volatile acids and total inorganic carbon. The ratio of these two parameters after the 30 days of AD was measured for *Cerathophyllum demersum*. Results showed values between 0.23 and 0.30 meaning that the active methane production phase is over.

4. Conclusion

Results show that from three tested algae species *Cerathophyllum demersum* is the most suitable algae for biogas production in Latvia as the cumulative biogas yield was the highest (405.3 L CH_4/kg VS) and without the need of pre-treatment. The yield was close to maximum thus the algae could be used as is available in nature. Even though for marine algae only approximately a third of its potential was achieved, its availability in nature (washing out of sea during summer and fall seasons) should be reasonably used. Thus, further experiments on pre-treatment can be carried out to improve the digestibility of biomass. Of course, aspects like energy used for collecting algae and pre-treatment should be considered. Also, the distance from the collecting site and actual biogas plant should be taken into account both as an economical and environmental aspect. For algae collection from nature, legal aspects also should be considered. Large parts of water bodies in Latvia have special Nature Reserve status that makes collection of biomass directly from them more complicated as in case of algae from the seashore and the sea itself. As there are many aspects that should be considered, a multi-criteria analysis should be carried out to determine whether freshwater alga is also the better option regarding these aspects.

References

[1] Europe 2020. A strategy for smart, sustainable and inclusive growth. European Commission, 2010.

[2] Eurostat database: Supply, transformation, consumption – renewable energies – annual data. Available: http://ec.europa.eu/eurostat/en/web/products-datasets/-/NRG_107A

[3] Alaswad A, Dassisti M, Prescott T, Olabi AG. Technologies and developments of third generation biofuel production. Renewable and Sustainable Energy Reviews 2015;51:1446–60.

[4] Olabi AG. Developments in sustainable energy and environmental protection. Simul Model Pract Theory 2011;19(4):1139–42.

[5] UN Report. Sustainable bioenergy: a framework for decision makers. Available: http://www.fao.org/tempref/docrep/fao/010/a1094e/a1094e00.pdf

[6] Demirbas A. Biomass resource facilities and biomass conversion processing for fuels and chemicals. Energy Conversion and Management 2001;24:1357–78.

[7] Debowski M, Zielinski M, Grala A, Dudek M. Algae biomass as an alternative substrate in biogas production technologies – Review. Renew. Sust. Energ. Rev. 2013;27:596–604.

[8] Rajiv S. Air, water and soil pollution science and technology: green plants and pollution. USA: Nova science publisher; 2010.

[9] Regulations of the United States. EPA Method 24e Determination of Volatile Matter Content, Water Content, Density, Volume Solids and Weight Solids of Surface Coatings, Appendix A-7, Part 60, Chapter 1 of Title 40 of the Code of Federal.
[10] Jard G, Jackowiak D, Carre H, Delgenes JP, Torrijos M, Steyer JP, Dumas C. Batch and semi-continuous anaerobic digestion of *Palmaria palmata*: comparison with *Saccharina latissima* and inhibition studies. Chem. Eng. J. 2012;209:513–19.
[11] Symons GE, Buswell AM. The methane fermentation of carbohydrates. Journal of American Chemical Society 1933;55:2028–36.

Paper 3: Effects of pre-treatment on Biochemical Methane Potential (BMP) testing using Baltic Sea *Fucus vesiculosus* feedstock

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Research paper

Effects of pre-treatment on Biochemical Methane Potential (BMP) testing using Baltic Sea *Fucus vesiculosus* feedstock

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ABSTRACT

Seaweeds are considered a viable feedstock for producing energy through the anaerobic digestion conversion process. Its exploitation and use as an alternative renewable energy source; however, remains marginal in the EU. This study aims to evaluate BMP in batch tests of the brown algae *Fucus vesiculosus* from the Baltic Sea and collected from the Latvian coast.

The lab scale BMP tests were oriented towards the evaluation of the effects of mechanical and microwave pre-treatment methods, as well as the impact of a different algae-to-inoculum (A/I) ratio using: i) cutting blades together with mortar and pestle (C&PM) in combination with the use of a 700 W capacity microwave, ii) 1:3 and 1:5 A/I ratios. The cumulative CH_4 yields show a value in the range of 68 ± 21 mL CH_4/g_{VS} – a trial with no microwave treatment and A/I of 1:3) and 144 ± 28 mL CH_4/g_{VS} – a trial including a microwave treatment for 3 min, and A/I ratio of 1:3.

The results show effectiveness in the range of 7.8%–43.7%, when the microwave pre-treatment is applied for 1.5 min, and a range of 37.2%–45.2% when the pre-treatment is applied for 3.0 min. The results of this study suggest promising potential for *F. vesiculosus* for biogas production, especially in the Baltic region.

1. Introduction

The Sustainable Biofuel Directive 2009/28/EC by the European Commission set a target to reach a 20% share of energy from renewable sources in gross energy consumption in the EU, as well as 10% of biofuel share for transportation by the year 2020 [1]. Biomass is expected to contribute to about 50% of the target [2]. However, issues related to land use and sustainability, particularly for first generation biofuels, have also drawn considerable attention. Within this perspective, seaweed has become a promising sustainable biomass option [2]. It has been estimated that the energy potential of marine biomass can be five times higher than land-based biomass (22 EJ yr^{-1}) in the EU [3]. Seaweeds have higher carbon capturing capability and approximately three times higher primary productivity rates than terrestrial crops, with a value of around 470 g $Cm^{-2}y^{-1}$ [4]. These aspects represent a strong background for enhancing the sustainable exploitation of marine biomass from various EU shores, while offering valuable economic, environmental, and societal benefits [2]. Seaweeds represent a valuable feedstock within the production of biogas through anaerobic digestion due to their high concentration of carbohydrates [5], high fractions of hemicellulose favourable for enzymes activity onto the substrate [6], and low lignin content [7].

While eutrophication is one of the most severe environmental problems in the Baltic Sea [8–10], growing and harvesting macroalgae reduce nutrient loading, resulting in the conditions for eutrophication [11]. Furthermore, there has been a sharp increase of nitrogen and phosphorus concentrations over the last five decades [10]. A study by Seghetta et al. [12] found three main strategies for lowering the effect of macro-algae green tides: i) prevention, ii) increasing water circulation, and iii) direct harvesting.

Biogas production from seaweeds has shown potential in terms of biogas yields [13,14]. Several research studies have highlighted the essential part played by the proper co-digestion of seaweed

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biomass with other substrates for optimizing and producing higher and more sustainable CH_4 yields [15,16].

Research from Biochemical Methane Potential (BMP) trials present methane yields of around 100–500 mL CH_4 g^{-1}_{VS} for macroalgae [17–19]. This includes up to 134 mL CH_4 g^{-1}_{VS} for *Ulva intestinalis* [20], 132 ml CH_4 g^{-1}_{VS} for *Gracillaria vermiculophylla*, 152–271 ml CH_4 g^{-1}_{VS} for *Ulva lactuca*, 166 ml CH_4 g^{-1}_{VS} for *Chaetomorpha linum* and 340 ml CH_4 g^{-1}_{VS} for *Saccharina latissima*. In a study by Gunaseelan [21], methane yields of 480 mL CH_4 g^{-1}_{VS} for *Ulva* sp., *Cladophora* sp., *Chaetomorpha* sp. and 310 mL CH_4 g^{-1}_{VS} for *Macrocystis pyrifera* were observed.

Studies from marine sediments of *M. pyrifera* in a seawater system obtained biogas yields in the range of 282 and 383 ml/g_{VS} [22]. Findings from Asian studies assessed biogas yields of 170–200 ml/g_{VS} [23]. A study by Oliveira et al. assessed biogas production from macroalgae *Gracilaria vermiculophylla* with values of around 481 ml/g_{VS} [24]. Published results report a *Sargassum* ssp BMP ranging from 120 to 190 mL ml/g_{VS}

Raw algae biomass collected from the Trelleborg shore (Sweden) shows a BMP in the range of 118–192 ml/g_{VS} [25]. BMP yields of different seaweeds' biomass (*U. lactuca, A. nodosum, L. digitata, S. polyschides, S. latissima*), based on the VS added to the anaerobic digestion process, were detected in a wide range, varying from 186 to 423 ml/g_{VS}.

A study by Montingelli at al [26]. provide a detailed summary of methane production, as well as macroalgal biomass. The results of the batch test were: *Saccharina latissima* – with a range of 223–326 ml/g_{VS}, *Ulva lactuca* – ranging from 150 to 180 ml/g_{VS}, macroalgae mix (*Laminaria digitata* + *L. hyperborea* + *L. Saccharina*) – 277 ml/g_{VS}; *Gracilaria vermiculophylla* – 132 ml/g_{VS}, *Chaetomorpha linum* – 277 ml/g_{VS}.

However, there are several constraining factors for the large-scale exploitation of marine algae biomass and, more specifically, for biogas or methane production. These include resistance to cell wall degradation due to a high level of cellulose or hemicellulose, the capability of algae to release compounds inhibiting the activity of the anaerobic bacteria (i.e. alkaline metals), high levels of heavy metals that decrease the quality of the digestibility [2], an improper C:N ratio in the biomass subjected to the fermentation processes [27,28] and overly high levels of sulphur resulting in higher concentration levels of hydrogen sulphide (H_2S) in the biogas. As a result, specific pre-treatment methods are needed [29]. Co-digestion with other substrate helps attain higher CH_4 yields [15,16]. One available option is to use a waste water treatment sludge [16]. Research by Oliveira et al. demonstrated that the co-digestion of sewage sludge (85% TS) and *Ulva* sp. (15% TS) ensured the biodegradability of a substrate and increased methane yield by 26% [5].

It is therefore necessary to have a preliminary evaluation of the biogas (and biomethane) potential of available local substrates, and one of the ways to do so is via BMP tests. A BMP test is a well-known method used to evaluate the anaerobic biodegradability of a specific substrate, and thus assess the associated specific methane yield [30–32].

The aim of this study is then oriented towards determining the potential of local seaweeds in the Baltic Sea for CH_4 production using a BMP test co-digested with Waste Water Treatment Plant (WWTP) sludge. The biomethane yield evaluation is conducted for the brown algae *Fucus vesiculosus*, one of the most common species found in the Gulf of Riga, using WWTP as inoculum. The tests are essential to evaluate seaweed degradability to methane. Initial findings evaluate local seaweeds as a new promising biomass while ensuring a low-carbon economy in the Baltic region. Moreover, the tests evaluate the impact of mechanical and microwaving pre-treatment, as well as a different algae-to-inocula (A/I) ratio for the biomethane yield in the BMP test. Finally, the cumulative CH_4 potential determined using the results of the BMP tests is utilized to calibrate the Gompertz mathematical model [33].

2. Materials and methods

2.1. Substrate (collection, pre-treatment, and storage)

The algal biomass of *Fucus vesiculosus* used within the batch tests for the BMP evaluation was freshly collected from washed-out algae during one green tide in October 2014 in the Gulf of Riga, Jūrmala beach, Central Latvia (56°59′ N and 23°51′ E). The site is characterised by shallow depths (0.5 – 1 m), a low salinity level, and high nutrient levels. The marine macroalgae sample was transported with plastic bags to the Biosystem Laboratory at the Riga Technical University, washed, screened, and identified. The seaweed biomass was then frozen at −18 °C, and defrosted a day before the start of the analysis and BMP tests. Freezing was chosen as freeze-thawing algae has been observed to be more favourable for anaerobic digestion than cooling [34]. Additionally, the biomass underwent two types of pre-treatment: mechanical and physical (microwaving).

F. vesiculosus was chopped with a simple cutting blade up to a size of 2 cm in length. The size was then reduced using a pestle and mortar to <2 mm, to be easily added to the reactor. A fraction of the mechanically treated sample then underwent microwave pre-treatment in a 700 W capacity microwave.

The microwave method has the capability to increase the kinetic energy of water contained in the biomass until the boiling point. The process creates changes in the structure of proteins, and a rapid generation of heat and pressure in the biological system favouring cell hydrolysis, forcing out compounds from the biological matrix [35]. Microwave pre-treatment is used in different types of biomass, such as lignocellulosic plants [36] or organic waste [37], in order to improve the biogas yield [38–41]. This occurs even though research has shown a negligible effect on the cumulated volume of biomethane [42]. The biomass was exposed to a microwave treatment for 1.5 min (Type A) and 3.0 min (Type B). The moisture losses during the microwave treatment were accounted for by a weight comparison completed before and after the treatment.

Volatile solids' (VS) and total solids' (TS) values were determined prior to the experiments based on EPA Standards [43,44]. VS was obtained by placing a sample into an oven for 24 h at 104 °C, while the solids were subsequently placed in an oven at 550 °C for 2 h to be able to obtain the VS content as a fraction of the total solid (%TS). The results are presented in Table 1 and Table 2.

2.2. Inoculum

WWTP was collected from the Daugavgrīva plant (Riga district, Latvia), from two different stages of sludge formation: the first just after the denitro/nitrification processes (hereafter named pre-final sludge, *PFS*) and the second in the last sludge management process (hereafter named final sludge, *FS*). Prior to the BMP experiment, the inoculum was incubated for 5 days at 37 °C, with no other pre-treatment method applied. Both types of inoculum were

Table 1
TS and VS content of *Fucus vesiculosus* and inoculum.

Substrate	VS, % of TS	TS, %
Fucus vesiculosus	80.1%	21.6%
PFS inoculum	67.8%	2.9%
FS inoculum	67.8%	2.8%

Table 2
Fucus vesiculosus chemical composition.

Organic elements	% TS	Macroelements	mg kg-1 TS	Microelements	mg kg^{-1} TS	Heavy metals	mg kg^{-1} TS
Carbon (C)	36.98	Potassium (K)	11000	Iron (Fe)	490	Selenium (Se)	0.11
Hydrogen (H)	5.12	Phosphorous (P)	1400	Manganese (Mn)	1680	Lead (Pb)	11
Oxygen (O)	35.98	Calcium (Ca)	21500	Chromium (Cr)	9.6	Zinc (Zn)	89
Nitrogen (N)	2.02	Magnesium (Mg)	9300	Strontium (Sr)	930	Copper (Cu)	12.7
Sulphur (S)	2.82	Sodium (Na)	6300				
Ash	18.40						

evaluated for specific methanogenic activity and VS content using EPA standards [43,44].

2.3. BMP tests method

BMP tests were used to define the amount of methane produced per gram of VS for different algae to inocolum (A/I) ratios (i.e. 1:3 and 1:5). The BMP test is mainly based on mixing a specific organic substrate with an aerobic inoculum at different operative conditions, and evaluating the produced biomethane using volumetric quantitative methods.

BMP methods need measurements to be carried out by liquid displacement [31] or the displacement of a piston with a syringe inserted into the batch [45]. In order to evaluate the fraction of biomethane produced, an alkaline solution for cleaning the biogas (by absorbing the CO_2 fraction) is added in both methods. The method is a well-known approach, but still lacking true standardization [31].

The methods require the maintenance of a constant temperature for the batches. This condition can be obtained with a water bath, or with an incubation chamber [46]. An incubation chamber with a constant temperature of 37 °C has been used in this study.

It is important to guarantee a near neutral pH within the batches to optimize the bacterial activity. A pH range between 6.5 and 8.2 [31,47,48] is optimal for most anaerobic bacteria, including methanogens. A lower pH value can inhibit methanogenesis due to the formation of volatile fatty acids (VFA) [48]. Therefore, an alkaline compound is normally added within the solution as a buffer capacity (i.e. sodium hydroxide, sodium (bi)carbonate and sodium sulphide) [3].

Anaerobic biodegradation is a complex process, thus BMP is a sensitive method, influenced by the conditions for the anaerobic bacteria to grow [49].

In this light, the analysis of the results from the BMP approach can be difficult due to the amount of potentially influential factors, resulting in the likely possibility of error and/or inaccuracy [50]. Meanwhile, the same substrates did not show the same BMPs based on the tests' conditions [46].

2.4. Experimental set-up

The BMP test was conducted in a batch mode using 100 ml media bottles with a working volume of 60 ml. A volumetric measuring method was used consisting of measuring the biomethane fraction through the displacement of a syringe piston inserted into a bottle using an alkaline solution for absorbing the CO_2 in the biogas mix within the syringe.

Each bottle was then filled with 30 ml of distilled water, 20 ml of inoculum and *Fucus vesiculosus*. To keep a constant pH, the bottles were also filled with a buffer basal solution of 3 mol of $NaHCO_3$ in a concentration of 3 g L^{-1}.

To determine the methane concentration without the CO_2 fraction, a 3-mol NaOH solution was filled into the measuring syringe. Consequently, the measured biogas values pertain to the methane content produced.

Batch tests were prepared in triplicates considering the ratios of the VS of A/I 1:3 and 1:5. Additionally, reference samples containing only inoculum were prepared in triplicates, to account for the methane production solely from the macroalgae biodegradation. The batches were sealed and the headspace flushed with N_2 for 2 min before sealing them with rubber stoppers and metal cramps. The tests were carried out at a mesophilic temperature (37 °C) in the ECOCell © incubator and lasted for 22 days. The batches were manually shaken one time per day on average. All trials with algae were made in 4 replicates, and the average results of successful samples were further analysed (i.e., results with standard deviation larger than 20% were taken out). The result was 14 × 3 sets of batches being prepared (see Table 3) for 14 laboratory experimental conditions.

2.5. Theoretical BMP according to Buswell formula

Depending on the type of biomass, the assessment of BMP can eventually require an incubation time of up to 90 days; almost all the methane potential would be achieved in the process [30,51,52]. Furthermore, it enables the acquisition of preliminary information on the biomethane potential of a specific substrate. For a more rapid estimation, a theoretical biomethane potential (BMP_{theo}) comes to the forefront.

BMP_{theo} is the amount of biogas produced from a specific biomass, if all possible elements are digested completely. As such, it can be considered a theoretical maximum biogas yield with the methane content calculated accordingly [50]. Once the chemical composition of C, N, O is known, it is possible to calculate the BMP_{theo} [49] using the Buswell equation [53]. The Buswell equation (1952) can be reported in terms of a stoichiometric value represented as CH_4 and CO_2 volumes theoretically produced once the substrate is fully digested by the bacteria within the digester. The CH_4 fraction thus represents BMP_{theo} as written in Formula 1.

$$C_nH_aO_b + \left(n - \frac{a}{4} - \frac{b}{2}\right)H_2O \rightarrow \left(\frac{n}{2} + \frac{a}{8} - \frac{b}{4}\right)CH_4 + \left(\frac{n}{2} - \frac{a}{8} + \frac{b}{4}\right)CO_2 \quad (1)$$

Where: n – carbon atoms in biomass; a – hydrogen atoms in biomass; b – oxygen atoms in biomass.

The methane yield (BMP_{theo}) from the Buswell equation can be recalculated with a reference to the unit of VS [54] (Formula 2).

$$BMP_{theo,yield} = \frac{\left(\frac{n}{2} + \frac{a}{8} - \frac{b}{4}\right) \cdot 22.4}{12n + a + 16b} \cdot \left(STP \frac{lCH_4}{g - VS}\right) \quad (2)$$

Using Formula 2, it is possible to calculate not only the theoretical biogas yield from the process, but also the CH_4:CO_2 ratio within the produced biogas. Experimental yields are usually lower, but knowing the theoretical yield value can show how well the digestion occurs, and to what extent the yield values could be increased.

Table 3
Batch tests with experimental conditions listed and a cumulative biomethane yield from BMP tests for *Fucus vesiculosus* are depicted. An experiment plan applying: i) microwaving treatment for 1.5 min. (called Type A microwave treatment) and 3 min. (called Type B microwave treatment) min and no treatment (type 0); ii) mechanical treatment using a cutting blade with mortar and pestle treatments (C&PM); iii) type of inocula (i.e. PFS or FS).

Batch experimental condition	*Fucus vesiculosus*	Inoculum		Pre-treatment		Algae-to-inoculo ratio (A/I)	Inoculum type	Methane yield [ml CH_4/g_{VS}]
Trial No.	TS, [g]	Volume, [ml]	TS, [g]	Physical	Mechanical			
01_FS_0_1/3	0.185	20	0.554	0	C&PM	1:3	*FS*	68.4 ± 21.7
02_PFS_0_1/3	0.192	20	0.576	0	C&PM	1:3	*PFS*	76.4 ± 15.4
03_FS_A_1/3	0.185	20	0.554	A	C&PM	1:3	*FS*	99.0 ± 35.6
04_PFS_A_1/3	0.192	20	0.576	A	C&PM	1:3	*PFS*	82.9 ± 22.7
05_FS_B_1/3	0.185	20	0.554	B	C&PM	1:3	*FS*	125.1 ± 24.7
06_PFS_B_1/3	0.192	20	0.576	B	C&PM	1:3	*PFS*	146.9 ± 28.1
07_FS_0_1/5	0.111	20	0.554	0	C&PM	1:5	*FS*	84.3 ± 28.3
08_PFS_0_1/5	0.115	20	0.576	0	C&PM	1:5	*PFS*	73.2 ± 33.6
09_FS_A_1/5	0.111	20	0.554	A	C&PM	1:5	*FS*	78.9 ± 14.9
10_PFS_A_1/5	0.115	20	0.576	A	C&PM	1:5	*PFS*	130.1 ± 11.5
11_FS_B_1/5	0.111	20	0.554	B	C&PM	1:5	*FS*	143.4 ± 38.3
12_PFS_B_1/5	0.115	20	0.576	B	C&PM	1:5	*PFS*	116.6 ± 40.7
13_FS (only sludge)	–	20	0.554	–	–	–	*FS*	19.1 ± 3.0
14_PFS (only sludge)	–	20	0.576	–	–	–	*PFS*	19.8 ± 3.2

2.6. Data analysis

First-order kinetic model types can be utilized to provide a good visualization of the BMP results [51], and to assess the specific cumulated methane production over time as well as the hydrolysis effect on the rate-limiting step with the associated lag phase [55]. An exponential equation is used to describe the progress of cumulative methane production for data processing, based on the modified Gompertz equation [33].

Within data processing and analysis, the modified Gompertz equation [16,33] (see equation (3)) was fitted to the observed cumulative CH_4 to determine the maximum CH_4 production potential called P, the CH_4 production rate R_{max} in mL $CH_4/g_{VS}\ d^{-1}$, and the lag phase (i.e. the minimum time taken to produce biogas or taken for bacteria to acclimatize to the environment, λ) according to equation (3):

$$M(t) = P \cdot exp\left\{ -exp\left[\frac{R_{max} \cdot e}{P}(\lambda - t) + 1\right]\right\} \tag{3}$$

where, M(t) is the methane cumulative production from the Gompertz equation and e is the exp of 1 (i.e. 2.71828).

The three parameters P, Rmax, and λ were estimated by curve-fitting, using MS Excel 2007 Solver and then plotted with the measured methane yields (see Fig. 3). To evaluate the model's statistical indicators the coefficient of determination (R2) and the relative root mean square error (rRMSE) based on Eq. (4) were calculated:

$$rRMSE = \left(\frac{1}{m}\sum_{j=1}^{m}\left(\frac{d_j}{Y_j}\right)^2\right)^{\frac{1}{2}} \tag{4}$$

where d_j = the deviation between the j_{th} measured, and the predicted values, m = the number of experimental values, Yj = the j_{th} measured value.

3. Results and discussion

3.1. Inoculum and substrate characterization

VS and TS values were determined before the experiments. VS and TS for both types of inoculum were similar, while *F. vesiculosus* had higher rates of both VS and TS. VS constitutes a significant part of the macroalgal biomass with a value of approximately 80% (Table 1). The *F. vesiculosus* sample used for this experiment had a significant TS value, compared to the range suggested by Montingelli et al. [26], making it promising among macroalgae.

The chemical composition of *F. vesiculosus* analysed by a certified Latvian Institute of Organic Synthesis is listed in Table 2. The presence of heavy metals, such as selenium, lead, zinc and copper, was also observed.

3.2. Biochemical methane potential

The principle that the biomethane fraction from inoculum should not exceed 20% of the total gas production in the BMP test [50] was respected for all batches in the experiment (Fig. 1). This also includes the batch trial *01_FS_0_1/3* where the FS inocula fraction constituted 19.4%.

Three main zones (the initial, the intermediate, and the final phases) can be distinguished. According to Wellinger et al. [50], 3 types of BMP curves can be observed: the normal degradation curve, the delayed degradation curve, and the slightly inhibited degradation curve.

The selection of the retention time of 22 days was decided upon based on the general trends presented by almost all the trials during the degradation period. In fact, except for 09_FS_A_1/5 and 12_PFS_B_1/5, all the trials already showed a "plateau" on the cumulative bio-methane curve before the 22nd day. This is also in line with a retention time for BMP tests involving WWTP sludge and algae biomass according to the literature [56]. Moreover, accounting for the results as a preliminary step for a continuously fed biogas plant design, it could be assumed that a retention time of 20 days using seaweeds as feedstock is reasonable.

Literature shows values of BMP for the inocula in the range of 120–400 CH4/gVS [57,58]; therefore, this is in line with results obtained from the trials (i.e. 13_FS and 14_PFS).

The cumulative curve of the trials *06_PFS_B_1/3* and *05_FS_B_1/3* can be defined as normal degradation curves, while the *09_FS_A_1/5* enters the condition of slightly inhibited degradation. The other curves can be considered delayed degradation, exhibiting typical S shape behaviour (Fig. 1).

Different behaviours of cumulative biomethane curves can be related to the size of the substrate particles (for this study within a range up to 1, using a pestle and mortar). The more complex the organic matter of the feedstock, the lower the steepness of the biomethanisation curve in the first phase. This mainly means that hydrolysis processes need a longer time to occur, thus creating a

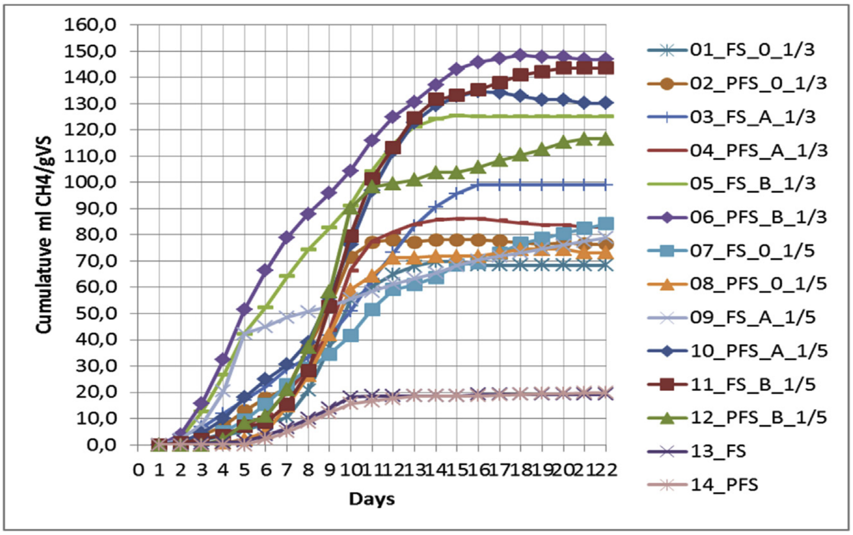

Fig. 1. Cumulative biomethane yields for all implemented trials.

bottle neck effect for optimal biomethanisation. Even more so, the decomposition of undissolved compounds like cellulose, proteins, or fats into monomers might require even more time [59,60]. Table 3 summarizes the final experimental cumulated biomethane potentials using a BMP test.

The cumulative CH_4 yield obtained from the trial *06_PFS_B_1/3* was the highest for *F. vesiculosus*, with a value of 146.9 ± 28.14 ml CH_4/g $_{VS}$, while the lowest yield was observed for the trial *01_FS_0_1/3* with a value of 68.4 ± 21.7 CH_4/g $_{VS}$. The methane yield of reference samples (inoculum only) was 19.1 ± 3.0 ml CH_4/g for the FS inoculum and 19.1 ± 3.0 ml CH_4/g for the PFS inoculum, thus rather close.

Other recent studies put *F. vesiculosus* methane potential varying from 47 mL CH_4 g^{-1} $_{VS}$ (unwashed biomass) to 113 mL CH_4 g^{-1} $_{VS}$ for pre-treated biomass [61] or 71.5 ± 4.9 mL CH_4 g^{-1} $_{VS}$ to 126.3 ± 11.4 mL CH_4 g^{-1} $_{VS}$ [53], depending on different constraint factors. A C:N ratio lower than 20 is observed as an inhibiting environment for the methanogenic bacteria [61,62]. That could eventually lead to higher ammonia levels and a failed conversion process.

Table 4 shows biomass composition of *F. vesiculosus* used for this study (sample 1), a second analysed *F. vesiculosus* biomass (sample 2), and two other references from other seas (sample 3, 4). The C:N proportion is lower than the ideal range for all samples.

Nevertheless, Bucholc et al. [65] reports a C:N ratio of 26:1 for *F. vesiculosus*, thus potentially suitable for methanogenesis activity for which a range of 20:1–30:1 is recommended [50]. However, a high inoculum to algae ratio might not support this assertion as a variation. In fact, an excessively high C:N may result in increased volatile fatty content leading to an overall pH decrease, and a further inhibition of methanogen bacteria [66]. Moreover, there could be two additional factors, such as light and heavy metal ions, that can become inhibitory, values in a range of 20–150 mg/l can already be sensitive benchmarks [50]. The variation of the BMP evaluated within the trials can also suggest that inhibition could have occurred due to H_2S production, although it was not verified.

With reference to Table 3 and the results summarized in Fig. 2a, a generally positive effect of the microwave pre-treatment on BMP was observed, except for the trial *09_FS_A_1/5* (where the physical treatment A was implemented – i.e. 1.5 min in a microwave) and partly for the trial *12_PFS_B_1/5* (where the physical treatment B was implemented – i.e. 3.0 min in a microwave). The latter sample exhibited significantly improved results, compared to the untreated biomass, even though a microwaving pre-treatment of 3.0 min. resulted in lower yields than those with 1.5 min. Overall, the A scenario improved the yield by 7.8%–43.7%, in respect to the trials without a physical pre-treatment (trial 0), while the B scenario improved it by 37.2%–45.2%.

The effect of the algae-to-inoculum ratio (Fig. 2b) on the cumulative biomethane yield does not draw any clear correlation with the BMP yields, as the results for the 02_PFS_0_1/3 and 08_PFS_0_1/5 trials showed similar yields, while the results diverge for the trial 05_FS_B_1/3 compared to the trial 11_FS_B_1/5, and for the trial 06_PFS_B_1/3 compared to the trial 12_PFS_B_1/5.

The results showed a general tendency for the co-digestion of macroalgae with WWTP sludge representing a potentially strong choice from an integrated and biorefinery-based perspective. This contrasts to significantly lower yields for the trials where only sludge was used (Table 3). According to the Buswell formula, and the chemical composition of *F. vesiculosus*, the theoretical methane yield was 465 L CH_4 kg_{VS}^{-1} (the theoretical CH_4 share of 52.5% $_{vol}$ and 47.5% $_{vol}$ of CO_2). This is in line with other BMP_{theo} calculated from other types of macroalgae [45]. To more effectively increase the overall BMP test efficiency, other pre-treatment methods on the biomass need to be explored. The possibility to extend the retention time could be one of the solutions towards this direction.

Table 4
Organic element content (% TS), C/N ratios in *Fucus vesiculosus*.

Sample	Location		C	H	O	N	C/N
1	Gulf of Riga	Autumn 2014	36,98	5.12	35,98	2.05	18
2	Gulf of Riga	January 2015	36.89	5.14	34.76	1.98	19
3	South coast of England [63]	February	32.88	4.77	35.63	2.53	13
4	South coast of Ireland [64]	August	26.80	3.20	44.50	1.50	18

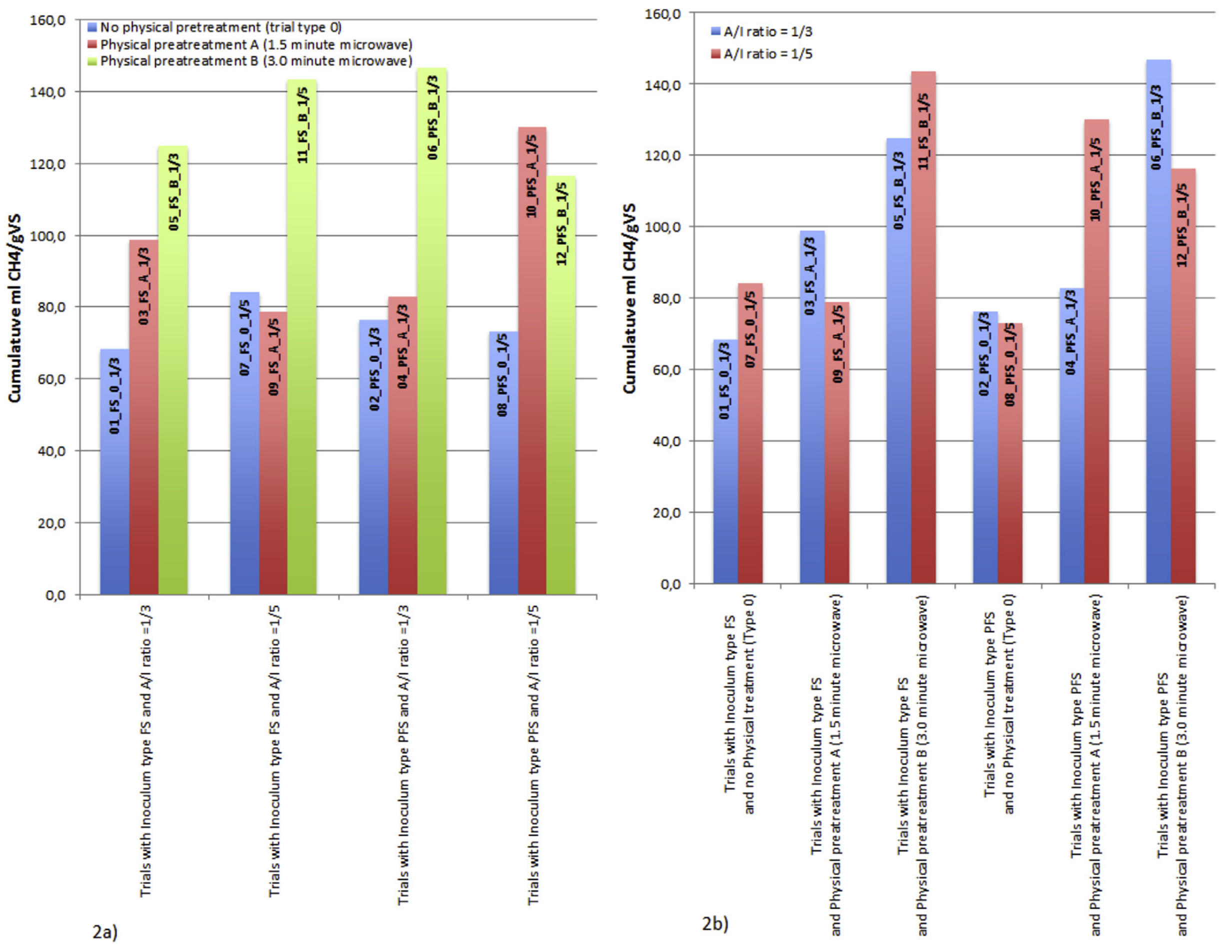

Fig. 2. Microwave pre-treatment effects and A/I ratio influences on BMP of *Fucus vesiculosus*.

The results obtained from the BMP tests were used to calibrate Gompertz mathematical model. The modelled parameters and results using the Gompertz equation are presented in Table 5 and Fig. 3. It was observed that the biomethane production was stable after 2.5–7 days lag time.

The CH_4 cumulative curves presented good, uniform behaviour for *07_FS_0_1/5* and *08_PFS_0_1/5*, followed by *01_FS_0_1/3* and *11_FS_B_1/5* (Fig. 3). The remaining ones show similar trends, except for trial *09_FS_A_1/5* which has a slightly inhibited type of anaerobic digestion, as well as *10_PFS_A_1/5* and *12_PFS_B_1/5*. Irrespective of the behaviour, all modelled Gompertz curves presented an excellent value of R^2 (Table 5). A non-uniform behaviour can be explained with the complexity of the substrates.

The Gompertz model showed rRMSE for the algae substrate in the range of 1.4–6.2%. The low deviations obtained between the theoretical and experimental values suggest that the proposed model properly predicted the behaviour within the reactors. The lag phases had a range of variation between 1.2 days (*09_FS_A_1/5*) and 6.7 days (*11_FS_B_1/5*), while the difference among the measured maximum CH_4 yields and the calculated ones were in a range of 0.3% (*11_FS_B_1/5*) and 8.12% (*03_FS_A_1/3*).

All batch tests exhibited the maximum obtainable biomethane after 22 days. Nevertheless, there were important differences with the BPM_{theo}. The differences in the biomethanisation rate depend on several factors: total amount of organic solids left, biodegradability of a substrate, presence of inhibitors and fluctuation in pH. The interaction with ammonia and VFAs can be considered one of the main reasons for a steady inhibition, resulting in a low biogas yield. An increase of the ammonia can affect the level of VFAs within the substrate, with a resulting increase of pH [26]. Furthermore, inhibition can be caused by the accumulation of different metals by seaweed. It has been observed that marine macroalgae has the ability to absorb minerals and nutrients from the surrounding environment [67]. Since the concentration of heavy metals in the Baltic Sea is up to 20 times higher than in the North Atlantic [68], it strongly affects the algal biomass composition and inhibits anaerobic digestion.

The effect of the proposed combination of the mechanical and microwaving treatments showed significant impacts on the methane yield. Seaweed biomass, washed ashore and collected after tidal movements, has the potential to be used as energy feedstock in Latvia. The distribution of seaweed, including the seaweed which is washed ashore, is not monitored in Latvia, but doing so would evaluate macroalgae as a potential source of energy. The overall potential use of macroalgae, from a bioenergy perspective, must be evaluated from the life cycle and sustainability perspectives, focussing on the advantages of macroalgae usage.

4. Conclusions

Seaweed is an alternative type of feedstock for renewable energy, namely biogas. This study estimated the biomethane potential of *F. vesiculosus* from the Baltic Sea in order to evaluate the potential use of marine biomass at a higher scope. The experimental findings

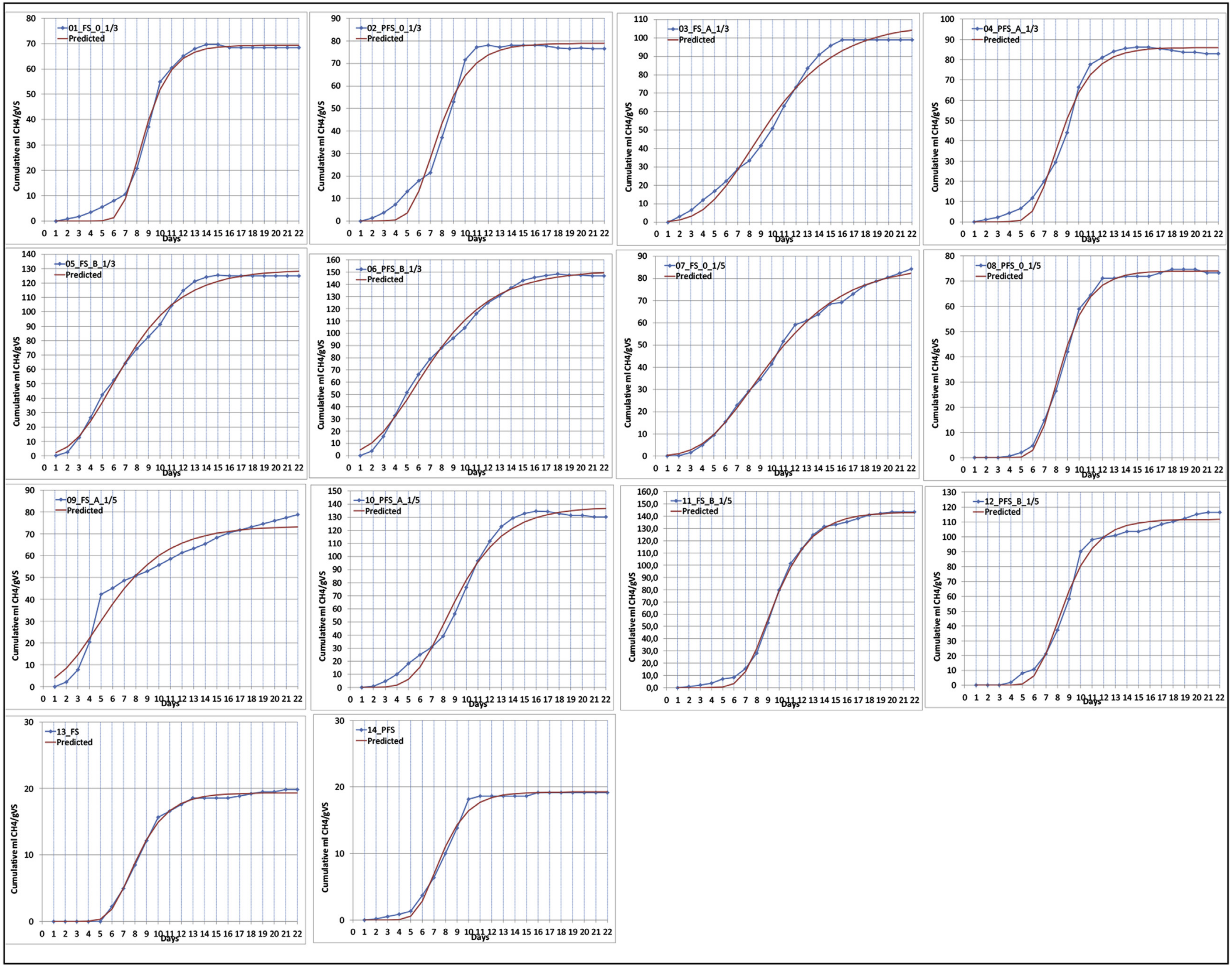

Fig. 3. Averaged measured methane yield plotted with methane yield predicted using a modified Gompertz model.

Table 5
Summary of estimated parameters from Gompertz equation and experimental CH_4 yields.

Trial	P (mL CH4/g VS)	λ (days)	R^2	CH_4 yield (mL CH_4/g $_{VS}$)
01_FS_0_1/3	69.38	6.94	0.9953	68.44 ± 21.75
02_PFS_0_1/3	78.89	5.23	0.9837	76.44 ± 15.42
03_FS_A_1/3	107.75	4.07	0.8949	99 ± 35.59
04_PFS_A_1/3	86.02	6.05	0.9918	82.94 ± 22.68
05_FS_B_1/3	129.29	2.38	0.9938	125.06 ± 24.70
06_PFS_B_1/3	151.40	1.96	0.9951	146.87 ± 28.15
07_FS_0_1/5	86.03	4.02	0.9977	84.26 ± 28.34
08_PFS_0_1/5	74.00	6.29	0.9980	73.22 ± 33.56
09_FS_A_1/5	73.64	1.24	0.9620	78.86 ± 14.95
10_PFS_A_1/5	137.66	5.38	0.9880	130.11 ± 11.49
11_FS_B_1/5	143.23	6.72	0.9986	143.64 ± 38.33
12_PFS_B_1/5	143.23	6.72	0.9986	116.56 ± 40.68
13_FS	19.34	5.73	0.9983	19.14 ± 30.03
14_PFS	19.25	5.45	0.9945	19.83 ± 3.16

were compared with the BMP_{theo} (Buswell formula) in order to estimate the efficiency and the room for improvement of the biomethane yield. The results showed that *F. vesiculosus* has the potential to be an implementable source for sustainable production of 3rd generation gaseous biofuel, thus mitigating both climate change and the eutrophication of the Baltic Sea. Results showed the maximum methane production obtained from the algal biomass fraction being 144 ± 28 mL CH_4/g_{VS} for the trial 06_PFS_B_1/3. The batch was pre-treated with microwaves for 3 min, and used PFS sludge and an A/I ratio of 1:3. Conversely, the lowest yield of the algal biomass fraction was observed in the trial 01_FS_0_1/3 (i.e. use of the FS sludge, no microwaving, and I/O of 1:3), with 68 ± 21 mL CH_4/g $_{VS}$. The effects of the microwave were generally positive for biogas production, the overall improvements compared to 0 (untreated) trials varied in a range of 7.8%–43.7% for the scenarios with pre-treatment Type A (1.5 min microwaving) and in a range of 37.2%–45,2% for the scenarios with pre-treatment Type B (3.0 min microwaving). A low correlation among the A/I ratio (Fig. 2), and the cumulative biomethane yield was identified. The analysis of the trial results confirmed that the limiting step of the anaerobic digestion process was hydrolysis. Other inhibiting factors could also influence the divergence between the practical yield and BMP_{theo}. These include organic matter loss (and thus a loss of a VS fraction) if the seaweed is washed out and remains on the beach for an extended period, high levels of absorbed metals appear as a result of the pollution of the Baltic Sea. Further study should be addressed to evaluate the effect of seasonal changes in the algae biomass composition on biomethane potential.

The results of this study are relevant within the direction of creating a full scale biorefinery concept based on the use of seaweed *F. vesiculosus*, also noted for a significant dry matter share, which can play an important role in the Baltic region context.

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References

[1] European Parliament, Directive 2009/28/EC of the European parliament and of the council of 23 April 2009, Off. J. Eur. Union 140 (16) (2009) 16–62.
[2] G. Jard, D. Jackowiak, H. Carrère, J.P. Delgenes, M. Torrijos, J.P. Steyer, C. Dumas, Batch and semi-continuous anaerobic digestion of Palmaria palmata: comparison with Saccharina latissima and inhibition studies, Chem. Eng. J. 209 (2012) 513–519.
[3] D.P. Chynoweth, J.M. Owens, R. Legrand, Renewable methane from anaerobic digestion of biomass, Renew. Energy 22 (1–3) (2000) 1–8.
[4] A.D. Hughes, M.S. Kelly, K.D. Black, M.S. Stanley, Biogas from Macroalgae: is it time to revisit the idea? Biotechnol. Biofuels 5 (1) (2012) 86.
[5] J.V. Oliveira, M.M. Alves, J.C. Costa, Design of experiments to assess pretreatment and co-digestion strategies that optimize biogas production from macroalgae Gracilaria vermiculophylla, Bioresour. Technol. 162 (2014) 323–330.
[6] X. Briand, P. Morand, Anaerobic digestion of Ulva sp. 1. Relationship between Ulva composition and methanisation, J. Appl. Phycol. 9 (6) (1997) 511–524.
[7] A. Dave, Y. Huang, S. Rezvani, D. McIlveen-Wright, M. Novaes, N. Hewitt, Techno-economic assessment of biofuel development by anaerobic digestion of European marine cold-water seaweeds, Bioresour. Technol. 135 (2013) 120–127.
[8] K. Balina, K Romagnoli, F. Pastare, L. Blumberga, Macroalgae for Bioenergy Production in Latvia: review on Potential Availability of Marine Coastline Species.
[9] Ü. Suursaar, K. Torn, G. Martin, K. Herkül, T. Kullas, Formation and species composition of stormcast beach wrack in the Gulf of Riga, Baltic Sea, Oceanologia 56 (4) (2014) 673–695.
[10] L. Kautsky, S. Svensson, Life in the Baltic Sea, Environ. Sci. Underst. Prot. Manag. Environ. Balt. Sea Reg. (2003) 148–181.
[11] A. Strunga, Mikro un makro aļģu audzēšanas un pārstrādes iespējas Baltijas jūras reģionā, in: Submariner, 2013, p. 7.
[12] M. Seghetta, H. Østergård, S. Bastianoni, Energy analysis of using macroalgae from eutrophic waters as a bioethanol feedstock, Ecol. Modell. 288 (2014) 25–37.
[13] M. Dębowski, M. Zieliński, A. Grala, M. Dudek, Algae biomass as an alternative substrate in biogas production technologies-Review, Renew. Sustain. Energy Rev. 27 (2013) 596–604.
[14] V.N. Nkemka, M. Murto, Evaluation of biogas production from seaweed in batch tests and in UASB reactors combined with the removal of heavy metals, J. Environ. Manage. 91 (2010) 1573–1579.
[15] A. Cappelli, E. Gigli, F. Romagnoli, S. Simoni, D. Blumberga, M. Palerno, E. Guerriero, Co-digestion of macroalgae for biogas production: an LCA-based environmental evaluation, Energy Procedia 72 (2015) 3–10.
[16] A. Gurung, S.W. Van Ginkel, W.C. Kang, N.A. Qambrani, S.E. Oh, Evaluation of marine biomass as a source of methane in batch tests: a lab-scale study, Energy 43 (1) (2012) 396–401.
[17] A. Bruhn, J. Dahl, H.B. Nielsen, L. Nikolaisen, M.B. Rasmussen, S. Markager, B. Olesen, C. Arias, P.D. Jensen, Bioenergy potential of Ulva lactuca: biomass yield, methane production and combustion, Bioresour. Technol. 102 (3) (2011) 2595–2604.
[18] H.B. Nielsen, S. Heiske, Anaerobic digestion of macroalgae: methane potentials, pre-treatment, inhibition and co-digestion, Water Sci. Technol. 64 (8) (2011) 1723–1729.
[19] M. Dębowski, M. Zieliński, A. Grala, M. Dudek, Algae biomass as an alternative substrate in biogas production technologies - Review, Renew. Sustain. Energy Rev. 27 (2013) 596–604.
[20] A. Sabunas, F. Romagnoli, L. Pastare, K. Bāliņa, Laboratory algae growing and BMP tests with *Ulva intestinalis* from the Gulf of Riga, Energy Procedia 113 (2017) 277–284.
[21] V.N. Gunaseelan, Anaerobic digestion of biomass for methane production: a review, Biomass Bioenergy 13 (1–2) (1997) 83–114.
[22] L. Fan, R.B. Guo, X.Z. Yuan, Y.L. Qiu, A.M. Yang, F. Wang, M.T. Sun, X.X. Zhao, Biogas production from *Macrocystis pyrifera* biomass in seawater system, Bioresour. Technol. 197 (2015) 339–347.
[23] P. Yazdani, A. Zamani, K. Karimi, M.J. Taherzadeh, Characterization of Nizimuddinia zanardini macroalgae biomass composition and its potential for biofuel production, J. Bioresour. Technol. 176 (2015) 196–202.
[24] J.V. Oliveira, M.M. Alves, J.C. Costa, Design of experiments to assess pretreatment and co-digestion strategies that optimize biogas production from macroalgae *Gracilaria vermiculophylla*, Bioresour. Technol. 162 (2014) 323–330.
[25] V.N. Nkemka, M. Murto, Evaluation of biogas production from seaweed in batch tests and in UASB reactors combined with the removal of heavy metals, J. Environ. Manag. 91 (2010) 1573–1579.
[26] M.E. Montingelli, S. Tedesco, A.G. Olabi, Biogas production from algal biomass: a review, Renew. Sustain. Energy Rev. 43 (2015) 961–972.
[27] M. Cogan, B. Antizar-Ladislao, The ability of macroalgae to stabilise and optimise the anaerobic digestion of household food waste, Biomass Bioenergy 86 (2016) 146–155.
[28] X. Wu, W. Yao, J. Zhu, C. Miller, Biogas and CH(4) productivity by co-digesting swine manure with three crop residues as an external carbon source, Bioresour. Technol. 101 (11) (2010) 4042–4047.
[29] P. Peu, J.F. Sassi, R. Girault, S. Picard, P. Saint-Cast, F. Béline, P. Dabert, Sulphur fate and anaerobic biodegradation potential during co-digestion of seaweed biomass (*Ulva sp.*) with pig slurry, Bioresour. Technol. 102 (23) (2011) 10794–10802.
[30] I. Angelidaki, I.M. Alves, D. Bolzonella, L. Borzacconi, J.L. Campos, A.J. Guwy, S. Kalyuzhnyi, P. Jenicek, J.B. van Lier, Defining the biomethane potential Batch, (BMP) of solid organic wastes and energy crops: a proposed protocol for assays, Water Sci. Technol. 59 (2009) 927–934.
[31] G. Esposito, L. Frunzo, A. Panico, F. Pirozzi, Enhanced bio-methane production from co-digestion of different organic wastes, Environ. Technol. 33 (22–24)

(2012) 2733–2740.
[32] N.R. Labatut, R.A. Angenent, L.T. Scott, Biochemical methane potential and biodegradability of complex organic substrates, Bioresour. Technol. 102 (2010) 255–2264.
[33] B. Gompertz, On the nature of the function expressive of the law of human mortality, and on a new mode of determining the value of life contingencies, Philos. Trans. R. Soc. Lond. 115 (0) (1825) 513–583.
[34] I. Angelidaki, W. Sanders, Assessment of the anaerobic biodegradability of macropollutants, Rev. Environ. Sci. Biotechnol. 3 (2) (2004) 117–129.
[35] A.C. Rodriguez, A. Alaswad, K.Y. Benyounis, A.G. Olabi, Pretreatment techniques used in biogas production from grass, Renew. Sustain. Energy Rev. 68 (2) (2017) 1193–1204.
[36] Z.H. Hu, H.Q. Yu, Optimizing and modeling the anaerobic digestion of lignocellulosic wastes by Rumen cultures, in: A. Mudhoo (Ed.), Biogas Production: Pretreatment Methods in Anaerobic Digestion, John Wiley & Sons, Inc, Hoboken, NJ, USA, 2012.
[37] Aliyu Salihu, Md. Zahangir Alam, Pretreatment methods of organic wastes for biogas production, J. Appl. Sci. 16 (2016) 124–137.
[38] C. Eskicioglu, K.J. Kennedy, R.L. Droste, Enhanced disinfection and methane production from sewage sludge by microwave irradiation, Desalination 248 (1–3) (2009) 279–285.
[39] M. Kuglarz, D. Karakashev, I. Angelidaki, Microwave and thermal pretreatment as methods for increasing the biogas potential of secondary sludge from municipal wastewater treatment plants, Bioresour. Technol. 134 (2013) 290–297.
[40] Z. Sapci, The effect of microwave pretreatment on biogas production from agricultural straws, Bioresour. Technol. 128 (2013) 487–494.
[41] S. Banik, S. Bandyopadhyay, S. Ganguly, D. Dan, Effect of microwave irradiated Methanosarcina barkeri DSM-804 on biomethanation, Bioresour. Technol. 97 (6) (2006) 819–823.
[42] D. Jackowiak, J.C. Frigon, T. Ribeiro, A. Pauss, S. Guiot, Enhancing solubilisation and methane production kinetic of switchgrass by microwave pretreatment, Bioresour. Technol. 102 (3) (2011) 3535–3540.
[43] Regulations of the United States., “EPA Method 24 – Determination of Volatile Matter Content, Water Content, Density, Volume Solids and Weight Solids of Surface Coatings, Appendix A-7, Part 60, Chapter 1 of Title 40 of the Code of Federal.”
[44] Apha, Awwa, Wef, Standard Methods for the Examination of Water and Wastewater, 2005.
[45] M. Edward, S. Edwards, U. Egwu, P. Sallis, Bio-methane potential test (BMP) using inert gas sampling bags with macroalgae feedstock, Biomass Bioenergy 83 (2015) 516–524.
[46] A. Del Borghi, A. Converti, E. Palazzi, M. Del Borghi, Hydrolysis and thermophilic anaerobic digestion of sewage sludge and organic fraction of municipal solid waste, Bioprocess Eng. 20 (6) (1999) 553–560.
[47] O.N. Ağdağ, D.T. Sponza, Effect of alkalinity on the performance of a simulated landfill bioreactor digesting organic solid wastes, Chemosphere 59 (6) (2005) 871–879.
[48] R. Chandra, V.K. Vijay, P.M.V. Subbarao, T.K. Khura, Production of methane from anaerobic digestion of jatropha and pongamia oil cakes, Appl. Energy 93 (2012) 148–159.
[49] I. Angelidaki, W. Sanders, Assessment of the anaerobic biodegradability of macropollutants, Rev. Environ. Sci. Biotechnol. 3 (2) (2004) 117–129.
[50] Arthur Wellinger, Jerry Murphy, David Baxter, The Biogas Handbook: Science, Production and Applications, A volume in Woodhead Publishing Series in Energy, 2013.
[51] G.K. Kafle, S.H. Kim, Anaerobic treatment of apple waste with swine manure for biogas production: batch and continuous operation, Appl. Energy 103 (2013) 61–72.
[52] T.L. Hansen, J.E. Schmidt, I. Angelidaki, E. Marca, J.L.C. Jansen, H. Mosbæk, T.H. Christensen, Method for determination of methane potentials of solid organic waste, Waste Manag. 24 (4) (2004) 393–400.
[53] E. Allen, J. Browne, S. Hynes, J.D. Murphy, The potential of algae blooms to produce renewable gaseous fuel, Waste Manag. 33 (11) (2013) 2425–2433, 2013.
[54] F. Raposo, et al., Biochemical methane potential (BMP) of solid organic substrates: evaluation of anaerobic biodegradability using data from an international interlaboratory study, J. Chem. Technol. Biotechnol. 86 (8) (2011) 1088–1098.
[55] P. Parameswaran, B.E. Rittmann, Feasibility of anaerobic co-digestion of pig waste and paper sludge, Bioresour. Technol. 124 (2012) 163–168.
[56] R. Wickham, B. Galway, H. Bustamante, L.D. Nghiem, Biomethane potential evaluation of co-digestion of sewage sludge and organic wastes, Int. Biodeterior. Biodegrad. 113 (2016) 3–8.
[57] S. Bellaton, et al., Estimation of the biomethane methane potential of sewage sludge's with AMPTS® II, Online source, http://www.bioprocesscontrol.com/media/1418/mocopee_bioprocess_newsletter.pdf.
[58] T. Al Seadi, D. Rutz, R. Janssen, B. Drosg, Biomass resources for biogas production. Chapter 2, in: Arthur Wellinger, Jerry Murphy, David Baxter (Eds.), The biogas handbook: Science, production and applications, A volume in Woodhead Publishing Series in Energy, 2013.
[59] D.S. Kelly MS, The potential of marine biomass for anaerobic biogas production: a feasibility study with recommendations for further research, Scotl. Scott. Assoc. Mar. Sci. (2008).
[60] P. Weiland, Biogas production: current state and perspectives, Appl. Microbiol. Biotechnol. 85 (4) (2010) 849–860.
[61] K. Bāliņa, F. Romagnoli, Chemical composition and potential use of Fucus vesiculosus from Gulf of Riga, Energy Procedia 95 (2016) 43–49.
[62] L. Pastare, I. Aleksandrovs, D. Lauka, F. Romagnoli, Mechanical pre-treatment effect on biological methane potential from marine macro algae: results from batch tests of Fucus vesiculosus, Energy Procedia 95 (2016) 351–357.
[63] A.B. Ross, J.M. Jones, M.L. Kubacki, T. Bridgeman, Classification of macroalgae as fuel and its thermochemical behaviour, Bioresour. Technol. 99 (14) (2008) 6494–6504.
[64] N. Wei, J. Quarterman, Y.S. Jin, Marine macroalgae: an untapped resource for producing fuels and chemicals, Trends Biotechnol. 31 (2) (2013) 70–77.
[65] K. Bucholc, M. Szymczak-Żyła, L. Lubecki, A. Zamojska, P. Hapter, E. Tjernstrom, G. Kowalewska, Nutrient content in macrophyta collected from southern Baltic Sea beaches in relation to eutrophication and biogas production, Sci. Total Environ. 473–474 (2014) 298–307.
[66] J. Prochazka, P. Dolejs, J. Maca, M. Dohanyos, Stability and inhibition of anaerobic processes caused by insufficiency or excess of ammonia nitrogen, Bioenergy Biofuels 93 (2012) 439–447.
[67] S. Taylor, Marine Medicinal Foods: Implications and Applications. Macro and Microalgae, Elsevier Inc, 2011.
[68] HELCOM, Heavy metal pollution to the Baltic Sea in 2004, Balt. Sea Environ. Proc. 108 (2007).

Paper 4: Mechanical pre-treatment on biological methane potential from marine macro algae: results from batch tests of *Fucus vecisulosus*s.

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Mechanical pre-treatment effect on biological methane potential from marine macro algae: results from batch tests of *Fucus vesiculosus*

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Abstract

Macroalgae have recently attracted attention as a possible feedstock for energy as well as for biogas. Macroalgae have higher productivity than terrestrial plants, and do not compete with crops for arable land but insight is still necessary on the biogas yield for an overall sustainable evaluation.

The objective of this study was addressed to evaluate the effect mechanical pre-treatment (MW) on anaerobic digestion (AD) conversion of the brown algae *Fucus vesiculosus* washed ashore in the Gulf of Riga.

The AD were carried out in batch tests at 37 °C, over an incubation time no longer than 21–25 days, in order to evaluate the biological methane potential (BMP). Two mechanical pre-treatment methods were tested including a biomass washing with TAP water and a further manual chopping up to a maximum size of 5 mm. Total solids (TS) and volatile solids (VS) tests were defined according to EPA standards [1]. The batch test-based BMP was further compared with the theoretical biological BMP from Buswell's formula.

The results show the BMP is doubling up to 200 l CH_4/kg TS if any pre-treatments method is applied. The thicker cell walls of the brown marine algae respect other macro algae types and as well respect fresh water macroalgae which inhibit the activity of fermentative bacteria during the hydrolysis process.

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Keywords: macroalgae; *Fucus vesiculosus*; Baltic sea; mechanical pretreatment; biological methane potential

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1. Introduction

As the fossil resource levels are limited, other means of energy must be found in order to offset growing energy demand. Even though the amount of resources actually available is still high, the research and development of new technologies need time to substitute the older ones and thus need to be encouraged [2]. There are many other options of energy resources that could be used instead, but their efficiency varies greatly. One of the most promising technologies worldwide is biogas production through anaerobic digestion as it is a natural process occurring in nature. The issue with this technology is the feedstock – even though almost all biomass can be used for digestion, only part of it can be used efficiently and only part of it can be acquired efficiently.

Latvia, as part of European Union (EU) is taking part in achieving the EU targets for year 2020 (known as 20-20-20). These targets are stated to reduce greenhouse gas emissions by 20 % (compared to year 1990), to comprise 20 % of energy from renewable energy sources (RES) and to increase energy efficiency by 20 % [3, 4]. Even though Latvia already has high use of renewable energy (due to hydro energy and historical high use of wood biomass) the share of RES should be increased more. The increase in RES share includes already existing technologies as well as implementation of new ones. Biogas production from traditional substrates has increased in recent years. As the field is developing, the use of third generation feedstock as algae could be implemented in a few years [5].

Algae and other water-based plants (like macrophytes) are now considered as a good and valuable option for biogas production as their growth rates exceed terrestrial plants, they do not use arable lands and can grow in a variety of conditions (salinity level, lighting, temperature, etc.). Substrates with a low level of lignin are more favourable for biomass degradation than lignocellulosic feedstock. They are easier to break down, thus saving energy for pre-treatment processes before fermentation [6–9].

In case of Latvia both the freshwater and marine water algae are available. As no governmental programs exist on monitoring the water bodies, the amount and types of available biomass is unknown as well as the macro-algal species composition and distribution. According to Balina et al. [10] the following abundant species of algae have been identified in Latvia: *Phaeophyceae* (brown algae), *Rhodophyta* (red algae), *Chlorophyta* (green algae). More in specific the authors identified in the algae genera abundant on the costline: *Fucus vesiculosus, Furcellaria lumbricalis, Ulva intestinalis*. On the coastline of open sea *Furcellaria sp.* is the most observed, while in the Gulf of Riga *Fucus vesiculosus* (brown algae) are more abundant.

Mostly in autumn large amounts of algae are washed ashore along the coast of Latvia. In some municipalities, algae are collected by residents for personal use (in gardening - used for composting, as soil supplement or as insulation layer for plants). Occasionally the collected algae biomass is disposed. No data is available on amounts washed out annually but, as reported in other studies [12–14], this biomass represents an important and valuable source of feedstock in biogas production.

The importance of algae pre-treatment and conditioning for biogas production has been reported in several studies [15, 16] mostly focused on enhancing the hydrolysis processes. Most of the pre-treatment methods for algae biomass focus on physical pre-treatment (i.e. maceration [16]) and mechanical pre-treatment (washing and grinding, or beating pre-treatment [17]).

The aim of the study is to analyse marine brown algae *Fucus vesiculosus* washed ashore as a substrate for biogas production. The study will also compare the laboratory results with the theoretical biological methane potential (BMP) given by the Buswell's formula [18]. The most suitable pre-treatment method should be found as well as most suitable co-digestion substrate based on their chemical composition.

2. Materials and methods

The evaluation of the *F. vesiculosus* BMP has been carried out by batch tests for the evaluation of BMP tests and further compared with the theoretical biological BMP from Buswell's formula. The implemented pre-treatment method involved mechanical chopping and washing. The analyses on the composition of the algae biomass and inoculum have been carried out in order to determine the influence of anaerobic digestion processes.

2.1. Substrate and inoculum

A mixture of washed out algae was harvested in autumn 2014 on the seaside of Jurmala beach (coast of Gulf of Riga). It was further kept in the freezer to avoid biodegradation of biomass prior to the laboratory tests. Before freezing, no pre-treatments were applied. The main identified specie in the harvested algae mixture was *Fucus vesiculosus*.

Two mechanical pre-treatment methods are used to analyse their impact on BMP – washing (of salt and debris) and chopping. A harvested alga was washed in running tap water until no debris (mostly sand) was visible in the excess water. Manual chopping of algae was carried out until the fraction size was a maximum of 5 mm.

Total solids (TS) and volatile solids (VS) tests were carried out prior to the experiment (using EPA methodology [1]). The tests were carried out for algae and inoculum (see Table 1). The chemical composition of algal biomass was determined in a certified laboratory.

Table 1. Total solids and volatile solids content of *F. vesiculosus* and inoculum.

Substrates	Volatile Solids	Total Solids
F. vesiculosus	17,8 %	78,5 %
Inoculum	3 %	60 %

The used inoculum was sewage sludge from a wastewater treatment plant Daugavgriva (Riga district, Latvia). Prior to the experiment, it was degassed for 5 days in an incubator at a temperature of 37 °C in order to reproduce the conditions of a co-digestion operating system and to minimise possible influences on the experiment results. No other pre-treatment methods were used for the inoculum.

2.2. Batch experiments

The biomethane potential (BMP) tests were carried out at batch test level under mesophilic conditions (37 °C) in 100 ml serum bottles with maximum loading volume of 60 ml. The used inoculum: biomass ratio was 5:1. A blank reference sample with no biomass (i.e. only sludge) was also set up. The batches contained biomass, inoculum, water and 3M $NaHCO_3$ solution as a buffer capacity (see Table 2).

Table 2. Experiment plan (where W – washed, NW – unwashed, C – chopped, NC – not chopped).

	Algae			Pre-treatment		Ratio	Inocula		Water	Buffer
Nr.	Type	Weight, g	TS, g	Washing	Chopping	Alga: inocula	ml	TS, g	ml	ml
1	-	-	-	-	-	-	20	0,55	30	1
2	*F. vesiculosus*	0,51	0,11	W	C	1:5	20	0,55	30	1
3	*F. vesiculosus*	0,51	0,11	NW	C	1:5	20	0,55	30	1
4	*F. vesiculosus*	0,51	0,11	W	NC	1:5	20	0,55	30	1
5	*F. vesiculosus*	0,51	0,11	NW	NC	1:5	20	0,55	30	1

After filling the bottles, they were flushed with nitrogen gas (oxygen free) for 2 minutes prior to incubation. The length of the experiment was set as one month or until no production of gas has been registered for 5 days in a row. A triplicate of samples were used.

Produced biogas was measured with syringes filled with 3M NaOH solution. As sodium hydroxide dissolves, the carbon dioxide within it, the measure was related only to the volume of the methane produced (excluding the information on the share of CO_2). As mentioned, this method does not provide data on the share of biogas, but represents a simple, cheap and practical method to provide preliminary information about the biomethane potential for scale-up systems.

2.3. Theoretical biomethane potential yield calculations

The first attempt to estimate the theoretical methane yield from the biogas process was done back in 1952 by Buswell, who devised a formula based on the chemical composition of substrates [17]. The formula (see Eq. 1) is based on elements like carbon, hydrogen, oxygen and nitrogen. The formula gives both the ratio of methane and carbon dioxide produced as well as the total amount of biogas produced. Based on this information further energetic gains can be calculated.

$$C_nH_aO_b + \left(n - \frac{a}{4} - \frac{b}{2}\right)H_2O \rightarrow \left(\frac{n}{2} + \frac{a}{8} - \frac{b}{4}\right)CH_4 + \left(\frac{n}{2} - \frac{a}{8} + \frac{b}{4}\right)CO_2 \quad (1)$$

where
n carbon atoms in biomass;
a hydrogen atoms in biomass;
b oxygen atoms in biomass [18].

A simple calculation tool based on the equation has been used to determine the theoretical methane potential of *Fucus vesiculosus*. The calculations are based on the chemical composition of algae (see Table 3) obtained from a certified laboratory.

Table 3. Chemical composition of washed out *Fucus vesiculosus*.

Element	C, %	H_2, %	O_2, %	N_2, %
Content	32,88%	4,77%	35,63%	2,53%

3. Results

3.1. Methane production and pre-treatment influence

Batch test level experiments of *Fucus vesiculosus* biological methane potential were carried out. Two pre-treatment methods (washing and/or chopping) were applied to analyze their influence on the BMP results. The batch experiments were carried out in triplicates; the results show an average value of successful samples (see Table 4).

Table 4. Results of biological methane potential tests, where W – washed; NW – not washed; C – chopped; NC – not chopped.

Nr.	Pre-treatment method		Total yield (including the inoculum impact), L CH_4/kg VS	Algae yield (without inoculum impact), L CH_4/kg VS
1	-	-	68,6	-
2	W	C	133,7	81,1
3	NW	C	120,1	67,3
4	W	NC	125,7	73,1
5	NW	NC	51,5	–

As it can be seen in Table 4, the highest methane yield is gained in the sample where both pre-treatment methods were applied. The second best result is for chopped and unwashed algae, yielding similar results as uncut and washed algae. The untreated algae sample shows a negative value of methane yield as it produced less methane than the reference sample with only inoculum. This can be attributed to the fact that salts in algae work as inhibitory elements. Also the marine algae usually have thicker cell walls that are harder to break down within the hydrolysis phase. The combination of these two factors represents a criticality as shown by the results of experiment.

Even though the use of pre-treatment methods shows an increase in the BMP, the results are relatively low. In general, several types of algae can produce methane content as high as 300–400 l CH_4/kg $_{VS}$ [12, 19, 20]. It should be taken into account that marine algae will be harder to break down due to changes in cell structure (influenced by the salinity of water thus unavoidable in most cases). In order to understand whether a higher biological methane yield can be achieved by different pre-treatment methods, theoretical methane yield is determined.

3.2. Theoretical methane yield

Based on the Buswell formula (see Eq. 1, chapter 2.2) and the chemical composition of *Fucus vesiculosus*, the theoretical methane yield is 320 l CH_4/kg $_{VS}$. The literature analysis is in line with this outcome (see Table 5).

Table 5. Theoretical and experimental *Fucus Vesiculosus* methane yield.

Authors	Yield	Comments	Source
Pastare, et al	81,1 l CH_4/kg $_{VS}$	Experimental; Batch; Washing + Cutting	-
Pastare, et al	320 l CH_4/kg $_{VS}$	Theoretical (Buswell equation)	-
Huili Li, et al (2013)	67 l CH_4/kg $_{VS}$	Experimental; Batch; No pre-treatment	[21]
Huili Li, et al (2013)	131 l CH_4/kg $_{VS}$	Experimental; Batch; Mechanical +1 % enzyme pre-treatment	[21]
Huili Li, et al (2013)	350 l CH_4/kg $_{VS}$	Theoretical	[21]
Tedesco, et al (2013)	71,5 l CH_4/kg $_{TS}$	Experimental; Batch; No pre-treatment	[22]
Tedesco, et al (2013)	230 l CH_4/kg $_{TS}$	Experimental; Batch; Mechanical pre-treatment;	[22]

As it can be seen, there still is the possibility to improve methane yield. One of the aspects, is the criticality related to the algae cell structure. In order to increase the overall BMP, pre-treatment methods should be aimed at breaking down easily.

Another option to increase the overall BMP would be to increase the retention time in order to give bacteria more time to break down the biomass. The problem with this solution usually is the efficiency decrease as well as the possibility of bacteria starving to the point of dying. Co-digestion of two different substrates might solve this problem. If the other substrates offers easy-to-break-down compounds as well as complies with the C:N ratio needs of existing substrate, the overall efficiency of the process could be improved.

Using the Buswells formula, several co-digestion options are compared. Traditional substrates such as cattle manure and sludge are observed as well as untraditional willow catkins (see Table 6). Willow catkins are chosen for their high carbon content (to balance out the C:N ratio to optimal 20–30 to 1 range [23]). Sludge and cattle manure are selected as substrates because they contain easy to digest compounds.

Willow catkins alone can produce lower methane content than *Fucus vesiculosus*, together their BMP is averaged to around 290 l CH_4/kg $_{TS}$ with an optimal C:N ratio of 27:1. Even though this substrate lowers the theoretical BMP, it might improve the actual methane yield by increasing the retention time without the efficiency loss.

Table 6. Theoretical methane yield based on substrate content.

Substrate	C, %	H_2, %	O_2, %	N_2, %	C:N ratio	Methane yield, l CH_4/kg $_{TS}$	Source
Fucus vesiculosus	32,88	4,77	35,63	2,53	13:1	320	-
Willow catkins	48,45	5,85	43,69	0,47	103:1	270	[24]
50 % *F. vesiculosus* + 50 % Willow catkins	40,67	5,31	39,66	1,50	27:1	292	-
Sludge	31,79	4,36	20,57	4,88	6,5:1	417	[25]
50 % *F. vesiculosus* + 50 % sludge	32,34	4,57	28,10	3,71	9:1	364	-
Cattle manure	34,79	4,83	30,32	2,51	14:1	342	[26]
50 % *F. vesiculosus* + 50 % Cattle manure	33,84	4,80	32,98	2,52	13,5:1	353	-

Both sludge and manure have similar theoretical and actual BMP yields, their co-digestion with brown marine algae offer similar results. Theoretically the yield increases, knowing the differences in digestion speed compared to *F. vesiculosus*, practically the same should be happening. As the Buswells equations do not take into account factors like inhibitors (salts), temperature changes, pH levels and so on, experiments are needed to confirm that these chosen substrates would be a good fit with *F. vesiculosus* and increase the overall BMP.

4. Conclusion and discussion

The aim of the study was to analyze algae washed ashore in the Gulf of Riga as a substrate for biogas production. The main specie of harvested algae was *Fucus vesiculosus*. Literature analysis suggest that theoretical biological methane potential is around 300–350 l CH_4/kg $_{TS}$ (depending on chemical composition and TS/VS content). Experimental yield of *F. vesiculosus* depends on the pre-treatments applied, no pre-treatment results in a lower yield under 100 l CH_4/kg $_{TS}$, while application of pre-treatment methods can increase the BMP up to 200 l CH_4/kg $_{TS}$. Due to thicker cell walls (caused by the water salinity and osmotic pressure), marine algae in general are harder to break down by methanogenic bacteria. Mechanical and enzymatic pre-treatment methods try to break down the cell walls themselves or to make them more available for bacteria.

Also costs of pre-treatment application should be taken into account when analyzing up-scaled systems of biogas production from washed-out marine algae. The costs of substrate itself only consist of the harvesting process, but pre-treatment needs have to be accounted for.

Based on the theoretical methane yield calculations, the most suitable co-digestion substrate is cattle manure. It offers easier to break-down elements thus giving time for bacteria to break down other substrates. Thus, the retention time should be longer.

More experiments are needed both for checking the compatibility of sludge and cattle manure as co-digestion substrates as well as for upscaling the systems (taking into account the energy demand for pre-treatment).

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References

[1] Environmental Protection Agency, Office of Water, Office of Science and Technology, Engineering and Analysis Division. Method 1684: Total, Fixed, and Volatile Solids in Water, Solids, and Biosolids. USA: US EPA; 2001.
[2] Nehrin R. Traversing the mountaintop: world fossil fuel production to 2050. Philos Trans R Soc Lond B Biol Sci 2009;364(1532):3067–79.
[3] Annex to cabinet order 517: Environmental policy strategy 2009-2015. Latvijas Vēstnesis; 2009:122(4108).
[4] Europe 2020. A strategy for smart, sustainable and inclusive growth. EU: European Commission; 2010.
[5] Kalns J. Biogas in Latvia. 2012. Available: http://www.lvportals.lv/likumi-prakse.php?id=251397 [23.01.2014].
[6] Bruton T, Lyons H, Lerat Y, Stanley M, Rasmussen MB. A review of the potential of marine algae as a source of biofuel in Ireland. Sustainable Energy Ireland; 2009.
[7] Wellinger A. Algal Biomass – Does it save the world? Short reflections. IEA Bioenergy Task 37 report; 2009.
[8] Roesijad G, Jones SB, Snowden-Swan LJ, Zhu Y. Macroalgae as a biomass feedstock: A preliminary analysis, PNNL 19944. Pacific Northwest National Laboratory; 2010.
[9] Kim SK. Handbook of Marine Macroalgae: Biotechnology and Applied Physology. USA: Wiley; 2011.
[10] Balina K, Romagnoli F, Pastare L, Blumberga D. Use of macroalgae for bioenergy production in Latvia: review on potential availability of marine coastline species. Proceedings from EUBCE 2015 – 23rd European Biomass Conference, Vienna, 1−4 June 2015.
[11] Burton T, Lyons H, Lerat Y, Stanley M, Rasmussen MB. A Review of the Potential of Marine Algae as a Source of Biofuel in Ireland. Sustainable Energy Ireland; 2009.
[12] Bruhn A, Dahl J, Nielsen HB, Nikolaisen L, Rasmussen MB. Bioenergy potential of Ulva lactuca: biomass yield, methane production and combustion. Bioresour Technol 2011;102(3):2595–604.
[13] Roesijadi G, Coleman AM, Judd C, Van Cleve FB, Thom RM. Macroalgae Analysis. A National GIS-Based Analysis of Macroalgae Production Potential. Summary Report and Project Plan. USA: Pacific Northwest National Laboratory; 2011.

[14] Dźbowski M, Zieliński M, Grala A, Dudek M. Algae biomass as an alternative substrate in biogas production technologies—Review. Renewable and Sustainable Energy Reviews 2013;27:596–604.
[15] Montingelli M, Tedesco S, Olabi A. Biogas production from algal biomass: A review. Renewable and Sustainable Energy Reviews 2015;43:961–72.
[16] Shultz-Jensen N, Thygesen A, Leipold F, Thomsen ST, Roslander C, Lilholt H, Bjerre AB. Pretreatment of the macroalgae *Chaetomorpha linum* for the production of bioethanol– Comparison of five pretreatment technologies. Bioresour Technol 2013;140:36–42.
[17] Tedesco S, Marrero Barroso T, Olabi AG. Optimization of mechanical pre-treatment of laminariaceae spp biomass-derived biogas. Renewable Energy 2014;62:527–34.
[18] Buswell EG, Neave SL. Laboratory studies of sludge digestion. Illinois Division of State Water Survey; 1930:30.
[19] Chynoweth DP. Renewable biomethane from land and ocean energy crops and 417 organic wastes. Hort Science 2005;40(2):283–6.
[20] Dębowski M, Zieliński M, Grala A, Dudek M. Algae biomass as an alternative substrate in biogas production technologies—Review. Renew Sustain Energy Rev 2013;27:596–604.
[21] Li H, Kjerstadius H, Tjernstrom E, Davidsson A. Evaluation of pretreatment methods for increased biogas production from macro algae. SGC Rapprot 2013:278. Sweden: SGC; 2013.
[22] Tedesco S, Benyounis KY, Olabi AG. Mechanical pretreatment effects on macroalgae-derived biogas production in co-digestion with sludge in Ireland. Energy 2013;61:27–33.
[23] Wellinger A, Murphy J, Baxter D. The Biogas handbook. Science, Production and Applications. UK: Woodhead Publishing; 2013.
[24] Sannigrahi P, Ragauskas AJ, Tuskan GA. Poplar as a feedstock for biofuels: A review of compositional characteristics. Biofuels, Bioprod, Bioref 2010;4:209–26.
[25] Werle S, Dudziak M. Analysis of Organic and Inorganic Contaminants in Dried Sewage Sludge and By-Products of Dried Sewage Sludge Gasification. Energies 2014;7(1):462–76.
[26] Meng J, Wang L, Liu X, Wu J, Brookes PC, Xu J. Physicochemical properties of biochar produced from aerobically composted swine manure and its potential use as an environmental amendment. Bioresourc Technol 2013;142:641–6.

Paper 5: Biochemical methane potential from anaerobic digestion of the macrphyte *Cerathophyllum demersum*: a batch test study for Latvian conditions

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Biochemical methane potential from anaerobic digestion of the macrophyte *Cerathophyllum demersum*: a batch test study for Latvian conditions

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Abstract

The paper focuses on determining the biochemical methane potential of macrophyte *Cerathophyllum demersum* via batch test analysis. Artificially grown samples are used. The highest gained methane yield is 471 l CH_4/kg VS with algae-inoculum ratio 1:10.

Peer-review under responsibility of Riga Technical University, Institute of Energy Systems and Environment

Keywords: biogas yield; macrophyte; batch test

1. Introduction

In the face of constant growth of the world population, the life comfort levels together with the overall energy demand, follow the same trend. Within this light, key issues like resource depletion, global warming and pollution have encouraged the European Union (EU) to set goals for the year 2020 (also known as 20-20-20 targets) [1] in order to increase the renewable energy share in its gross final consumption by 2020 [1]. Within this background,

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new research on novel technologies and solutions within the framework for renewable energy source is encouraged [1].

Anaerobic digestion (AD) for biogas production is one of the most promising conversion processes with an important role in moving toward a higher share of renewable energy source use. In fact within the last decade the production of biogas in Latvia increased from 55 TJ in 2002 [2] to 2 175 TJ in 2012 [2]. Overall in the EU there has been growth (from 128 555 TJ in 2002 to 506 186 TJ in 2012), but not as steep as in case of Latvia [2].

Biogas-based systems are involving into well-known, effective and potentially flexible (due to the use of different types of substrate) technologies. Even though issue on the use of more sustainable biomass feedstock is still a matter of research. It involves move from a first-generation biogas (i.e. using edible energy crops as feedstock) to a third type generation through non-edible energy crops cultivation (algae as biomass feedstock) [3]. Nevertheless, algae cultivation strictly related to bioenergy purposes needs improvement from a technical and environmental perspective in order to be profitable at the industrial scale [3, 4].

In recent years the use of micro- and macro-algae for energy production has been examined for several reasons – high productivity and growing rates (species-specific parameters, but can be higher than terrestrial plants), adaptation to different growing mediums (saline, brackish water) and high lipid content (for the production of biofuels). Also the overall carbon neutrality (if we consider the final combustion of biological biomass and the avoided use of arable lands) is among crucial reasons for improvement of the research field on algae and their end use. [5, 6] In this respect, extended research of alternative types of biomass can also involve biomass very similar to macro-algae like water plants (macrophytes) that can thus be potentially considered as feedstock for biogas production in the same manner as algae. The similarity of macrophytes to macro-algae is species-specific and should be evaluated in each case separately [3−6].

Within this perspective the aim of the proposed work was mainly oriented to evaluate the biochemical methane potential (BMP) of locally available macrophyte species through the implementation of a specific biogas batch test study. The experiments were carried out in several stages – species determination, experiment planning, parameter determination, actual conducting of the experiment and data analysis.

2. Materials and methods

2.1. Selection of biomass and inoculum

Latvia's territory consist of inland water to the extent of 3.7 % (2 402 km^2). Latvia has around 2700 species of freshwater algae and macrophytes, but for most of them the biogas yield (thus potential to be used in a large scale biogas production) is unknown. As Latvia has a total length of the Baltic Sea coastline equal to 498 km (including the Gulf of Riga), marine algae species are also present. Since no governmental framework program exists for on-site surveys, the amount of naturally grown algae and macrophytes is unknown, and thus the selection of potential species and the quantification of the potential exploitable algae-based biomass are key questions for Latvian research. Consequently, the evaluation of potentially usable species for biogas production in Latvia's conditions is an uninvestigated aspect that needs further and more extensive evaluations. [7]

After a preliminary literature analysis, 7 species of macro-algae and macrophytes were selected for potential use in experimental analysis (*C. demersum, L. Minor, E. Canadensis, P. natans L., Chara sp., F. vesiculosus, C. glomerata*). The choice of species was further limited by availability, and thus the macrophyte species of *Cerathophyllum demersum* was chosen for the planned biogas batch tests. *C. demersum* – also called coontail - is a submerged, free-floating aquatic plant. Coontail has a cosmopolitan distribution, commonly used as an aquarium plant (see Fig. 1). It can be easily found in ponds, lakes, ditches, and quiet streams with moderate to high nutrient levels. It does not produce roots, instead it absorbs all nutrients it requires from the surrounding water. This macrophyte has an important biomass growth rate and good capability of absorbing environmental contaminants (*e.g.* metals and industrial radionuclides). [8]

C. demersum is locally available in Latvian water bodies. This species is also used as an aquarium plant as it is not toxic for fish or other underwater life. The biomass samples used are from an aquatic center growing underwater life and thus biomass was subject to additives used to maintain the water conditions of aquariums. [8]

Specifically for the batch tests, anaerobic suspended biomass from the municipal wastewater treatment plant "Daugavgriva" (Riga, Latvia) anaerobic digester was selected as inoculum.

2.2. Preparation of substrates

For the first experiments part of the macrophytes biomass was kept in small aquariums with a room temperature water (+20 °C) and a 12 hour lighting regime while for the latter experiment, the biomass was frozen in order to avoid the biodegradation of the selected sample of biomass. In order to be used properly within the selected batches, the biomass of macrophyte was shredded using a hand blender. As it can be seen in Figure 1, this process was stopped when an average size of the particles around 2 mm was reached, thus creating biomass slurry (see Figure 1(c)). As the slurry with time segregates, a mixing of the biomass before the experiment was applied.

Fig. 1. (a) newly grown sample of macrophyte C. demersum, (b) – fully grown sample of macrophyte C. demersum, (c) – Shredded macrophyte C. demersum on milimeter paper.

In order to determine the quantities needed for the experiment, the total solids (TS) and volatile solids (VS) content of the biomass and inoculum was determined using the EPA methodology (see Table 1). [9]

Table 1. Characteristics of inoculum and macrophyte *C.demersum* biomass

	Total Solids	Standard Deviation	Volatile Solids	Standard Deviation
Inoculum	1.92 %	0.04 %	59.79 %	0.14 %
C. Demersum	5.11 %	0.28 %	78.30 %	0.86 %

In order to minimize the possible influence on the experimental results from inoculum, it was kept at 37 °C in the incubator for 5 days prior to the experiments (degassing). Filtration, dilution and other forms of pre-treatment were not applied to inoculum.

2.3. Set-up of batch experiments

The experiment was carried out under mesophilic conditions at 37 °C in 100 ml serum bottles with a maximum loading volume of 60 ml wherein macrophyte biomass in different ratios was introduced. The ratios of biomass − inoculum tested are 1:10 1:5 and 1:3. Also reference samples (with no biomass but with inoculum) were set-up to use as a benchmark for estimating biogas yield for biomass.

The serum bottles (digesters) contained biomass, inoculum, water and additive (3M $NaHCO_3$ solution was added to provide buffer-capacity) (see Table 2.).

After filling the digesters with its content, they were flushed with oxygen-free nitrogen gas for 2 min, before starting the incubation. The biogas production and gas content was controlled after each 24–48 hours during the experiments. Digesters were kept in an incubator for a month.

Biogas produced was measured in the syringes filled with 3M NaOH solution. The volume of the appeared gas was equivalent to the methane volume produced as carbon dioxide is soluble in the solution. This method does not provide data on the methane and carbon dioxide ratio, but is simple, cheap and provides the necessary data on methane yield of biomass. The methane production was measured cumulatively.

Table 2. Experiment plan, where ww – wet weight.

Sample	Inoculum		C. demersum		Ratio Algae: Inoculum	$NaHCO_3$	Water
	g ww	g TS	g ww	g TS		ml	Ml
1.1. 1.2. 1.3.	20	0.4	-	-	-	1	30
2.1. 2.2. 2.3.	20	0.4	1.3	0.039	1:10	1	30
3.1. 3.2. 3.3.	20	0.4	2.7	0.081	1:5	1	30
4.1. 4.2. 4.3.	20	0.4	4.4	0.132	1:3	1	30

2.4. Analytical methods

After the 30-day period the measurements of methane yield were finished. Standard method was applied for pH measurement (LUTRON PH-208). Determination of total inorganic carbon (TC) and total volatile acid (TVA) values were performed as a two-step endpoint titration using 0.1M sulphuric acid. [10] Determination of these values can provide insight in the biogas production process stage.

3. Results

The experiments provided a quantitative assessment of the biochemical methane potential from locally available macrophyte *C. demersum*.

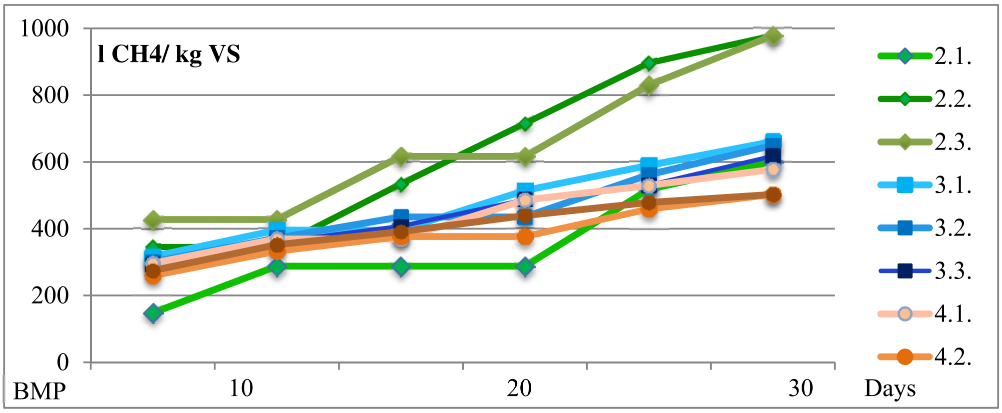

Fig. 2. Cumulative biochemical methane yield of samples containing macrophyte *C.demersum* biomass (2.x. – with ratio algae : inoculum 1:10; 3.x. – with ratio 1:5; 4.x. – with ratio 1:3).

The cumulative yield of samples (see Fig. 2.) shows the amount of biomethane produced together with the impact of inoculum. It can be clearly seen that sample 2.1 is faulty as it yields approximately half of that of samples 2.2 and 2.3. Also samples with a larger ratio (1:10 compared to 1:5 and 1:3) show a larger final yield.

When determining the total yield of biomass, faulty samples should be taken out of calculations (see Table 3). The corrections are based on the Standard Deviations (SD) of final results. It is assumed that SD should not be higher than 10 % in order to have reliable results.

Table 3. Biochemical methane yield of *C. demersum*.

	Actual yield		Corrected yield	
Sample	l CH_4/kg VS	SD	l CH_4/kg VS	SD
2.1. 2.2. 2.3.	345.16	178.21	471.18	0
3.1. 3.2. 3.3.	398.33	18.37		
4.1. 4.2. 4.3.	377.98	35.48		

As it can be seen, the highest methane yield is 471 l CH_4/kg VS followed by 398 and 377 l CH_4/kg VS depending on the algae-inoculum ratio. Previously in literature there were no mentions of the biogas or biochemical methane potential of this particular species of macrophyte. The previous experiments with this species showed a biochemical methane potential yield of 554 l CH_4/kg VS and 462 l CH_4/kg VS for larger and smaller size particles respectively. All other parameters of the experiments (algae-inoculum ratio of 1:10, additive amount, temperature regime etc.) were kept the same. [11]

The analysis of total volatile acids and total inorganic carbon shows a minor difference between the different samples (see Fig. 3).

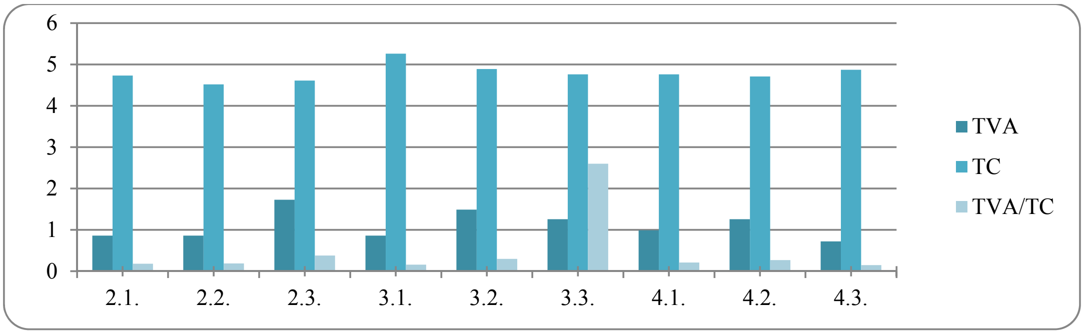

Fig. 3. Total Volatile Acid, Total inorganic Carbon and their ratio content of *C.demersum* biomass containing samples.

The ratio TVA/TC shows how much carbon is left for the bacteria to consume, meaning that the lower the value, the less available food for bacteria is left. As these measurements are made after the AD process, the low values show that the methane production phase is over.

Also the pH levels of samples after AD process were determined (see Fig.4).

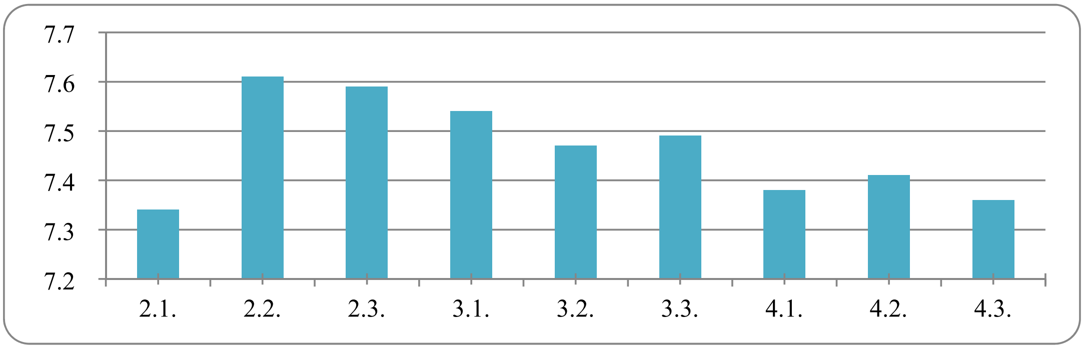

Fig. 4. pH content of C.demersum biomass containing samples.

A trend of pH level decrease with the increase of algae-inoculum ratio can be seen (though the difference is small). For sample 2.1, which provided faulty results, the pH level is lower, indicating that the process may be disturbed by dirty equipment or oxygen presence in the AD process.

4. Discussion and conclusions

The selection of macrophyte biomass for experiments raises some issues related to naturally grown algae collection and use for biogas production. The quality of inland waters in Latvia is characterized as a potentially good resource for biomass production since it would represent a potential environmental benefit in terms of eutrophication decrease. As there are no governmental programs for evaluating and estimating the amounts of macro-algae and macrophytes in the water bodies of Latvia, the information is scarce or non-existent. There are 2 256 lakes larger than 1 ha (and even more smaller ones), but, knowing the potential area or volume for algae growth mediums, does not provide qualitative information enough for potentially available amount, especially with such a large available species count (around 2 700 species). Even if the maximum potential amount in algae and macrophyte biomass in water bodies in Latvia would be know, that would not be equal to the amount available for further use. Many water bodies in Latvia are protected or contain protected species so should not be taken into account. Also the infrastructure near the water body might not support the extraction of algae from them. These are some of the issues related to the collection of naturally grown algae that can be solved, but still should be taken into account when evaluating different biomass production systems [7, 12].

In order to start to move toward a potential industrialized cultivation system, preliminary tests on the biomethane potential yield have been carried on local available macrophytes.

The experiments provided the values of biogas yield of *C.demersum* in batch tests 470 l CH_4/kg VS with algae-inoculum ratio of 1:10 and 400 and 370 l CH_4/kg VS with ratios 1:5 and 1:3, respectively. The results coincide with the previous experiments of the authors [11], but there is no other literature available for comparison. As the values depend on the algae-inoculum ratio, more experiments are needed on a larger scale to determine the biogas yield value for more realistic and larger scale use.

A greater understanding of the AD process and the input material characteristics would be useful. The chemical composition analysis of both inoculum and biomass would provide data for better understanding of the materials as well as the overall process. More tests of input chemical compositions are needed to understand the C:N ratio and other parameters and find the best option for inputs and additives.

Acknowledgements

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EIROPAS SOCIĀLAIS FONDS

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References

[1] Europe 2020. A strategy for smart, sustainable and inclusive growth. EU: European Commission. 2010.

[2] Eurostat database: Supply, transformation, consumption - renewable energies - annual data [nrg_107a]

[3] Demirbas, A. Biomass resource facilities and biomass conversion processing for fuels and chemicals. *Energy Conversion and Management* 2001; 24: 1357−1378.

[4] Alam F., Date A., Rasjidin R., Mobin S., Moria D., Baqui A. Biofuel from algae – Is it a viable option? *Procedia Engineering* 2012; 49: 221−227.

[5] Debowski M., Zielinski M., Grala A., Dudek M. Algae biomass as an alternative substrate in biogas production technologies – Review. *Renew. Sust. Energ. Rev.* 2013; 27: 596−604.

[6] Rajiv S. *Air, water and soil pollution science and technology: green plants and pollution.* USA: Nova science publisher, 2010.

[7] Latvian Biodiversity Clearing-House Mechanism. Scientific and technical co-operation and information exchange. 2014. Available at: http://biodiv.lvgma.gov.lv/cooperation/ieks_ud [Accessed: 5 April 2014]

[8] Keskinkan O., Goksu M. Z. L., Basibuyuk M.,et. al. Heavy metal adsorbtion properties of a submerged aquatic plant (Ceratophyllum demersum). *Bioresource Technology* 2004; 92 (2): 197−200.

[9] METHOD 1684: Total, Fixed, and Volatile Solids in Water, Solids, and Biosolids. Environmental Protection Agency, Office of Water, Office of Science and Technology, Engineering and Analysis Division. USA: US EPA, 2001, p. 13

[10] Lahav O; Morgan BE. Titration methodologies for monitoring of anaerobic digestion in developing countries − a review. *J Chem Tech Biotechnol* 2004; 79 (12): 1331−1341.

[11] Pastare L., Romagnoli F., Dzene I. *Multicriteria analysis of sustainable use of macro-algae for biogas production in Latvia*. Master thesis, Institute of Energy Systems and Environment, Riga Technical University 2014, p. 126.

[11] Latvian lake database. 2014. Available at: http://www.ezeri.lv/database/ [Accessed:13 May 2014]

[12] Pārskats par virszemes un pazemes udeņu kvalitāti 2013. gadā (Report of surface and groundwater quality 2013). Latvijas Vides, Ģeoloģijas un Metroloģijas Centrs (Latvian Environment, Geology and Meteorology Centre), Riga, Latvia, 2014, p. 122.

Paper 6: Sustainable Use of Macro-Alagae for biogas Production in Latvian Conditions: a Prelimenary Study through an Integrated MCA and LCA Approach

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Sustainable Use of Macro-Algae for Biogas Production in Latvian Conditions: a Preliminary Study through an Integrated MCA and LCA Approach

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Abstract **– The study focuses on sustainability evaluation of an algae-based energy system in Latvia with a holistic and integrated approach of multi-criteria analysis combined with life cycle assessment (including a practical side – biogas yield experiments of locally available algae).**

The study shows potential for sustainable use of algae in Latvian conditions and thus that algal biomass can be utilized for the production of biogas. The most sustainable and feasible scenario of using algae for biogas energy production foresees the collection of algae biomass from natural water bodies. Important beneficial effects through the use of algae are related to avoiding global warming potential (GWP) and eutrophication impacts. Biogas batch experiments carried out with the local macrophyte *C.demersum* have shown a methane yield of 554 l CH_4/kg VS.

Keywords **– macro-algae, biogas production, MCA, LCA, sustainability assessment.**

I. Introduction

Fossil fuels have been a major energy source for centuries, but as the amounts of available resources are decreasing rapidly, other means of energy production must be found [1]. There is a great variation of different renewable energy resources available that should be evaluated for efficient use within the energy sector [2, 3]. Algae and macrophytes have received increasing interest as a feedstock for biofuel and biogas production in recent years [4–7].

Algae use for energy production has been examined for several reasons. Among them the most frequently mentioned is its high productivity and growing rates [8–10]. Though these parameters are species-specific, they are considered to be higher than those of terrestrial plants [11, 12]. Other important algae-specific characteristics include: adaptation to different growing mediums like brackish and saline waters, avoiding the use of fertile agricultural lands, harmonization with the conflict of edible use of feedstock crops for energy purposes, its carbon neutral cycle (atmospheric CO_2 is sequestered in growth phase, then emitted during combustion), and high lipid content for the same species [9, 10, 12]. All these positive aspects increase the interest in algae in terms of a more efficient and sustainable use. Looking towards the use of microalgae versus the use of macro algae (or macrophytes), it is found that the latter have higher costs during cultivation and harvesting. An important issue which arises is related to marine vs. freshwater algae use due to the higher impact on desalination of the harvested algal biomass [4, 8, 12].

Depending on the desired outcome, there are several growing and harvesting technologies available. Most of the research outcomes show that the simpler systems, such as open ponds, are more economically viable than photo-bioreactors [13–16]. Also scenarios of algae collection from natural water bodies have low costs, but they are highly unpredictable due to difficult control over the growth phase [6, 8]. The impact of each of the cultivation methods should be investigated under specific criteria like land use vs. sea-surface use, consumption of freshwater, avoided use of fertilisers and nutrients, and biodiversity of ecosystems.

As there is a great variation in algae characteristics, growing mediums, sizes and availability, several methods for energy conversion may be applied. Based on available reviews of algal energy production, two technologies seem to standout – biomass trans-esterification to bio-diesel and biomass anaerobic digestion to biogas [17, 18]. Many scientists agree that anaerobic digestion shows the highest potential for successful production of bio-fuels as the conversion technology is mature, available and highlights the pros of algae use in energy production [19–21].

From the proposed literature review, the feasibility study related to scaling-up an algae-based system for biogas production is an actual key issue in different studies [12, 14–16]. Thus the overall sustainability and impact assessment is a matter that is still under study representing a gap to be offset by forthcoming research. A Life Cycle Assessment (LCA)-based study for Nordic conditions in the use of brown macro-algae [5] shows there is a promising technology to be tuned on large-scale production on off-shore-type cultivation spots.

The EU targets for 2020 (known as 20-20-20) are stated to reduce greenhouse gas (GHG) emissions by 20 % compared to the year 1990, to comprise 20 % of energy from renewables and 20 % increase in energy efficiency. As a part of EU, Latvia has also set these targets and is now working toward achieving them. Latvia has a historically high use of renewable resources (36.3 % of primary energy consumption in 2012) [22] most of it comprises wood biomass and hydro energy. Nevertheless, Latvia has set a target to increase the share of the use of renewable energy-based technologies, including biogas production [23, 24]. Within these perspectives, the third generation biofuels from alternative feedstock as algae have shown great potential in scientific research and thus could represent a potential good application for Latvian conditions that should be investigated more thoroughly.

Therefore, the aim of this study was focused on the overall evaluation of the sustainability of biogas production from macro-algae feedstock through the use of potential available cultivation techniques.

It has been found from the proposed literature review that, in connection to a relatively novel state of research, there is a lack of studies providing useful data for large scale algae cultivation and harvesting systems for biofuels production. An important part of the technical data input for this study (in fact oriented on up-scaling an algae based system for the production of biogas) was selected from existing literature. Only a specific part related to the evaluation of biomethane yield from the selected macrophyte is directly provided from a lab scale through biogas laboratory batch tests, in the same way as proposed by Merlin Alvarado-Morales et al. [5], who propose to use algae-based batch tests for the evaluation of biomethane potential within an overall LCA on use of brown macroalgae at a large production scale.

The analysis proposed within this study is executed onto the main dimensions of the sustainability aspects (i.e. economic, technical, environmental and social) and at the moment 5h3research is mostly focused on the preselected cosmopolitan freshwater macrophytes (*C. demersum*), which by its characteristics resembles macro-algae and within this study can be considered as such.

The study foresees the exploitation of both Latvian macro-algae species and also macrophytesdue to their possible biological similarity with macro algae (similarity is species specific, not general) [25, 26]. The study is aimed to understand what are the strengths and weaknesses for a reliable and feasible large-scale exploitation of macro algae as a bio-resource trying to foster the potential attractiveness for these specific technologies. At the same time, the study is the first attempt to identify the potentially useful species matching the optimal sustainable conditions at the regional level. Within the proposed and analysed scenarios, an integrated sustainable assessment approach is proposed by merging the Multi-Criteria Analysis (MCA) through the TOPSIS (Technique of Order Preference Similarity To Ideal Solution) method and the Life Cycle Assessment (LCA) framework.

II. Methodology: Conceptual Model Formulation

In order to achieve the main goal, the study focuses on the evaluation of sustainability of several algae-based biogas production scenarios through the proposed effective method based on the combination of MCA and Life Cycle Assessment (LCA). The principle steps of the methodological model formulation and the basic model concepts are shown in Fig. 1. A case study based on the selection of identified scenarios is reported in the next sections.

The MCA implemented within the sustainability evaluation is focused on overall assessment through prioritization of the selected criteria from technical, ecological, economic, and social perspectives. The MCA method focuses on both qualitative and quantitative aspects within the specific, oriented decision-making problems. Even though, a key issue towards rather quantitative assessment within the MCA is an important target, there is a need for lower subjectivity within the final rating principle outcome of the MCA. At this point, the introduction of the LCA method can be beneficially considered within the MCA structure.

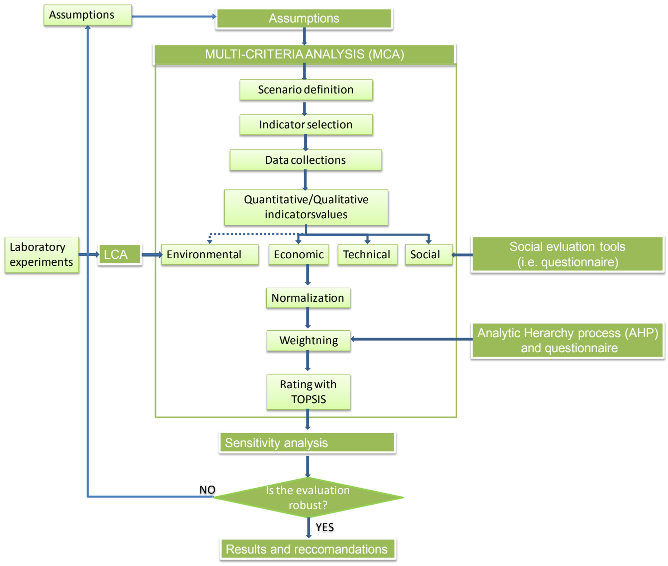

Fig. 1. Methodology concept for the sustainability analysis.

Looking towards the selection of the sustainable dimensions, the values of the economic indicators are based on data collected from literature (including scientific publications, manufacturers' information and expert opinions). The technical indicators refer to the sustainable and technical viability of a specific scenario with respect to the issues related not only to the maturity of a certain technology, but as well as to energy payback time and energy ratio (defined as the ratio among a system's produced energy and the total input energy related to the system under study). As mentioned before, environmental criteria values are based upon the main dimensions (i.e. damage categories) from the LCA framework, while social criteria values are gained from a questionnaire and economic analysis and are further used within the normalization of the indicators. Specifically for this approach, the MCA TOPSIS method has been used.

III. Insights About the Model Formulation

A. *Multi-criteria analysis using TOPSIS*

The MCA method is based on evaluation of a selected set of weighted criteria. The use of TOPSIS is well known within the sustainability evaluation and more specifically in connection to the use of renewable energy sources [27].

The mathematical principle of the whole process is set on the optimization process performed on a pre-determinate multi-objective matrix. The final result is a single score output adjusted to a weighting procedure aimed to determine the importance though the introduction of a weighting factor for each of the selected criteria.

The criteria section within the MCA is a key aspect related to the quantitative evaluation that must be carried out in connection to each of the selected indicators. The methodology represents a quantitative tool to provide the impact of specific systems or processes referred to a set of criteria [28].

Within this study, the adoption of MCA is proposed as a suitable part of the overall integrated approach for evaluation of different bioenergy scenarios under a multidisciplinary perspective.

Specifically, in order to quantify the more sustainable scenario among the selected ones, the TOPSIS technique was applied. The aim of the method proposed by Hwang and Yoon [28] is to support a decision-making process by ranking alternatives depending on their closeness to an ideal solution [29].

The basic element of TOPSIS analysis is a data matrix, where the evaluation criteria are represented by columns of the matrix. The normalization is performed to compare and thus rank the alternatives with respect to a linear normalization [30, 31]. The normalization also includes weighting of each criterion.

The Analytic Hierarchy Process (AHP) is a way to determine weights to be used in MCA. One of the principle reasons to use AHP is lying on the advantage to have a pair-wise comparison simplifying the judging of the relative importance among each criterion [32]. Determination of the weights for each criterion is based on the principle of relative importance proposed by Saaty's according to a 9-point scale [33].
The final outcome from TOPSIS is a number in the range from0 to 1 representing the distance to the ideal solution when the rating number is close to 1.

B. *Life cycle assessment*

According to the ISO Standards 14044 [34, 35], LCA is defined as an analytical, comprehensive tool that evaluates environmental burdens, benefits and performances in connection to the entire supply chain of a product, process or service. The LCA methodology is based on four main stages: (1) goal and scope definition, (2) inventory analysis, (3) impact assessment, and (4) interpretation of the results.

Within this approach, material and energy balances are defined with respect to energy consumed, resources depleted, and emissions released from all the considered life cycle processes. Thus the LCA method represents a cradle-to-grave perspective that takes into account the conversion processes from the original resource exploitation till the final disposal of the considered products and by-products.

The Life Cycle Inventory (LCI) part is focused on the evaluation of the potential environmental impacts of the analysed system in order to plan potential optimization or mitigation measures. LCI and Life Cycle Impact assessment (LCIA) are important aspects within the overall LCA approach. Within the LCI phase, all the main information about input data (i.e. material/energy flows and environmental emissions) is collected [36].

As mentioned previously, the main parameters for finalization of the LCAs for the selected scenarios have been obtained from literature reviews, expert opinions/assumptions and the inventory database eco-invent [37]. Within this specific case study, valuable data for the LCI have been evaluated through the real laboratory experimental batch studies for evaluation of potential biogas yield from macrophytes.

LCIA focuses on assessing the level and importance of the LCI result within the specific impact categories through some consecutive steps. Many LCIA methods have been developed and widely used [36] however for this specific case study the IMPACT 2002+ method [37] was selected. This method encompasses four damage categories (namely Human Health, Climate Change, Biodiversity and Resources).The same environmental categories are then reported within the proposed sustainability assessment method.

IV. Case study: Sustainability evaluation of algae- and macrophytes-based biogas scenarios

Within this section, sustainability evaluation of algae use for biogas production through the developed method is proposed.

A. *The scenario definitions*

Evaluation is carried out for 6 algae-based scenarios for a medium-large-scale biogas production. The final biogas output is then considered to feed cogeneration unit for production of thermal and electric energy.

TABLE I

Scenarios Used Within the Study

Code	Feedstock/Resource	Cultivation media and place	Harvesting technology
Nat-F	Freshwater algae	Natural growth	With trawlers
Nat-M	Marine water algae	Natural growth	With trawlers
OF-F	Freshwater algae	Open Pond (Off-shore cultivation)	Manual collection
OF-M	Marine water algae	Open Pond (Off-shore cultivation)	Manual collection
ON-F	Freshwater algae	Open Pond (On-shore cultivation)	Manual collection
ON-M	Marine water algae	Open Pond (On-shore cultivation)	Manual collection
Man	Manure	Not included	Pumping
Crop	Rapeseed oil remnants	Not included	Not included
NG	Natural gas	Not included	-

As reported in Table 1, the proposed scenarios include both marine and freshwater algae use, different cultivation methods and collection of naturally grown algae from water bodies, cultivation of algae in open-pond type artificial water body located either on land (on-shore) or in water (off-shore). The identified algae-based scenarios are evaluated in comparison with 3 identified benchmarking scenarios used in a similar cogeneration system, but using different types of sources or feedstock (namely: manure, rapeseed oil rremnants, natural gas).For the pond-based scenarios, the collection of algae was considered manual, while for the naturally-grown algae collection is assumed to be carried out with trawlers. The properties of manure are assumed to be the average of Latvian cattle farms and the biomass used is rapeseed waste. As manure and rapeseed oil remnants are considered as waste, the environmental burdens related to this product have not been taken into account.

B. The criteria selection for the sustainability analysis

As the basis of the study is to evaluate the overall sustainability of different biogas production processes, the criteria chosen for this evaluation have been selected through the identification of 4 main sustainable dimensions, namely economic, technical, environmental and social (see Table 2).

In order to be consistent with the LCA scenarios, the indicator values have been assessed in reference to 1MWh$_{el}$ produced from the cogeneration unit (i.e. common technology for all the selected scenarios). In this way this parameter has been set as the functional unit (FU) for the LCA studies and thus the base reference for all the sustainable indicators.

TABLE II

CRITERIA USED WITHIN THE STUDY

DIMENSION		INDICATOR	UNIT
A	Economic	Specific investments	€/FU
B	Economic	Revenues	€/FU
C	Economic	Operation and maintenance costs	€/FU
D	Technical	Energy ratio	-
E	Technical	Energy payback period	Months/FU
F	Technical	Maturity	(grade)
G	Environmental	Ecosystem quality	PDF/m^2 year/FU
H	Environmental	Climate Change	Kg CO_2 eq./FU
I	Environmental	Human health	DALY/FU
J	Environmental	Resource depletion	MJ primary non-renewable energy/FU
K	Social	Social acceptance	%
L	Social	Social benefits	€/FU

The economic criteria include specific investments of technologies in respect to the steps of cultivation, harvesting, transportation, pre-treatment, anaerobic digestion, biogas cleaning, digestate use and incineration: revenues are expressed as Euros gained from selling the generated 1 MWh$_{el}$ electricity; operation and maintenance costs include all the materials and energy needed including cost of labour for producing functional unit. All economic criteria are expressed as €/FU.

Energy ratio shows the relation of spent energy and produced energy, much energy is used to produce 1 MWh$_{el}$ of power; energy payback period shows the time needed to produce the same amount of energy as spent during construction phase.

Social criteria express the society's view and acceptance of the algae-based biogas production scenarios (as well as the benchmarking scenarios) as suitable technology.

Within the specific case and according to the proposed method the Criterion of Social Acceptance is expressed as a percentage among the respondents of a predefined questionnaire that support the use of a specific scenario. The questionnaire involved a sample of 100 participants – representative of different society groups of interests. The criterion of Social Benefits shows the induced financial benefit from the creation of new employments. At this stage of analysis this has not been considered.

C. Quantification of the environmental indicators through LCA

Within all the biogas-based scenarios, a further use of digestate is assumed either as a fertilizer on land or as a supplement nutrient for algae growth phase or both if amount is sufficient.

As mentioned, the identified functional unit (FU) has been set as 1 MWh$_{el}$ of electrical energy generated in a combined heat and power (CHP) unit, it is assumed that the same cogeneration unit is used for all the scenarios. For all biogas-based scenarios the same 2-stage continuous reactor is assumed. For biogas cleaning, a wet scrubbing method is applied.

The environmental impacts of the algae-based biogas have been modelled through a simplified LCA model implemented with SimaPro software and taking into account the IMPACT 2002+ as LCIA [37, 38, 39].

The benchmarking scenarios have been directly evaluated through the processes already implemented within the eco-invent database [39, 40, 41].

The data used in LCA comes from experiments, scientific publications and other literature; where data is unknown assumptions are made based on the available information about the subject. Where available, the data for Latvian specific conditions have been used. The main aspects to take into account regarding system boundaries are:

- Growth phase of scenarios of collecting biomass from natural waters is not included in the study;
- Digestate use as fertilizer included (with digestate treatment and transportation);
- The construction phase of needed plant is not included.

Limitations and assumptions regarding the LCA of algal biogas production are:

- Transportation of workers is not included;
- Feedstock quality assumed homogenous;
- No emissions arise from storage;
- Constant biogas yield and methane content for each type of input;
- Constant calorific value of produced biogas;
- Nutrient demand of the same species of algae are identical.

The freshwater algae data are based on the growth parameters and biogas yield of *C. demersum* (500 l CH_4/kg VS; 32 t TS/ha year) and for the marine algae scenarios the data of *Ulva lactuca* are used (350 l CH4.kg VS; 45 t TS/ha year) [42]. The artificial pond used for growing is 1 ha, 0.6 m deep with a water exchange rate equal to 0.2. The nutrient need and the carbon dioxide uptake and other general algae parameters are assumed to be equal for both freshwater and marine algae (see Table 3 for principal inventory data).

TABLE III

PRINCIPAL INVENTORY DATA FOR LCA MODELING

DATA	VALUE	UNIT	SOURCE
CO_2 uptake by algae	1.8	tCO_2 /t algae wow	[43, 44]
Nutrient (N_2) content in digestate compared to input	1.80	%	[46]
Nutrient (P_2O_5) content in digestate compared to input	1.00	%	[46]
Nutrient (K_2O) content in digestate compared to input	0.90	%	[46]
Biomass grinder power	38	kWh/t dry weed	[5]
Power for AD reactor mixing	0.11	kWh/kg algae	[47, 48]
Nutrient supply energy demand	4.55	MJ/kg wet algae	[49]
N demand of algae	0.26	kg/kg dw algae	[49]
P demand of algae	0.05	kg/kg dw algae	[49]
Water demand for algae cultivation	1.67	m^3/kg algae	[49, 50]
Pond mixing power demand	30	kWh/kg algae	[49]
Pump power demand (12 h a day)	6	kWh	[49]
Heat demand for AD process	32	kWh/t input	[48]
Digestate share of biomass input	0.99	t/t input	[48]
Biogas density	1.21	kg/m^3	[51]
Digestate separator capacity	500	kg/h	[52]
Digestate separator power	2	kW	[52]
Power demand for biogas upgrading	0.3	kWh/m^3 upgraded biogas	[47]
Water demand for biogas upgrading	0.33	m^3/m^3 biogas	[47]
CO_2 emissions	2.75	kg of CO_2 /kg methane	[53]
Rapeseed nutrient (N) uptake	50	kg/t biomass	[54]
Rapeseed nutrient (P) uptake	15.69	kg/ha	[54]
Rapeseed nutrient (K) uptake	90	kg/ha	[54]
Rapeseed productivity	20.5	cnt/ha	[55]
Rapeseed biogas yield	0.57	m^3 CH_4/kg VS	[56, 57]
Manure yield	0.5	m^3 CH_4/kg VS	[56, 57]
NOx emissions from methane burning	264	t NO_2/MWh	[58]

D. *Biogas yield experiments as input for the LCA*

The aim of the experiments is to determine the biogas yield of locally available algae species. The experiments were carried out in several stages – experimental planning, algae parameter examination, initial biogas yield experiments, and final biogas yield experiments and data analysis [59].

Based on a literature review, an initial list of potentially suitable species for biogas production was created. At this stage of the study a preference was given to a fresh water species over a marine species, due also to their higher capability to grow in laboratory conditions. The species called *Ceratophyllum demersum* was selected, which is a cosmopolite species widely available in nature and growing under different conditions. As it is widely used as a plant for aquariums, it's also available during wintertime when most water bodies are covered with ice. *C.demersum* grows in lakes, ponds and other water bodies with fresh water and slow-moving water and does not have roots; it can be a submerged or free-flowing macrophyte [60, 61, 62, 63, 64].

The determination of total solids (TS) and volatile solids (VS) of the selected algae was carried out by the US Environmental Protection Agency (EPA) issued methodology (see Table 4) [65].

TABLE IV

TS AND VS VALUES OF *C. DEMERSUM* WITH STANDART DEVIATION

	TS	Σ	VS	σ
Sample A	5.11 %	0.3 %	78.30 %	0.9 %
Sample B	3.70 %	0.1 %	82.01 %	0.1 %

The inoculum for batch experiments was sludge from wastewater treatment plant in Latvia, with the TS content of 3 %. The inoculum was kept at 37°C in the incubator for 5 days prior to the experiments in order to minimize any possible influence on the experimental results. No other pre-treatment (filtration, dilution) of the inoculum was performed.

Two different particle sizes in samples were obtained by using a hand blender. The bigger size particles were in range of about 2 mm to 5 mm, but the smaller size particles were smaller than 2 mm (see Fig. 2.). The tests were carried out in 100 ml glass bottles. Biomass was prepared and inserted into bottles (1.2 to 2.4 g depending on the $TS_{algae} : TS_{inoculum}$; the ratio chosen was 1:10 and 1:5),

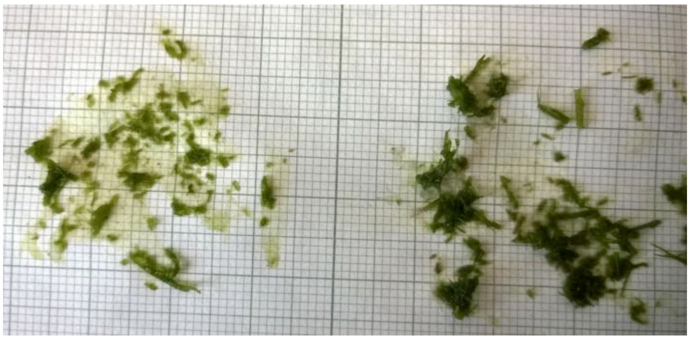

Fig. 2. Macrophyte *Ceratophyllumdemersum*, fraction sizes on mm paper (on left side smaller fractions, on right bigger fractions).

distilled water (30 ml), buffer Na-HCO_3 (3 g/l) and 20 ml of inoculum were added. Afterwards, the bottles were flushed with CO_2, rubber caps were secured with crimping tool. After the bottles were shaken and put into an incubator at 37°C. Biogas yield from the bottles are measured with syringes filled with 5 ml of NaOH solution. As the biogas bubbles through the alkali solution the CO_2 dissolves and the amount left is almost pure CH_4. The measurements are taken daily and recorded until the point at which no samples are producing biogas (1 month).

It must be noted that due to faulty bottle caps some of the samples did not produce nearly as much as the other (see Table 5). These faulty samples are excluded from any further analysis. There is no available biogas or methane yield data of *C. demersum* used in anaerobic digestion process, but the comparison of overall yield can be carried out with most popular processed algae and their yields. In general, the range of algae yield is wide, starting from 100 to 500 l CH_4/kg VS. If the algae yield is greater than 400 – 450 l CH_4/kg VS it is considered a high yield and thus such algae species are potentially viable for use in large-scale biogas production.

TABLE V

METHANE YIELD FROM MACROPHYE *CERATOPHYLLUM DEMERSUM* IN A BATCH TEST ANAEROBIC DIGESTION PROCESS, L – LARGE FRACTIONS AROUND 2 – 5 MM, S – SMALL FRACTION TILL AROUND 2 MM, * VALUES WITHOUT TAKING INTO ACCOUNT FAULTY SAMPLES

SAMPLE	BIOMASS					ADDITIVES		INOCULUM			METHANE YIELD		
	TYPE	WEIGHT, G	ALGA SIZE	TS, G	VS, G	BUFFER, ML	WATER, ML	VOLUME, ML	TS, G	$TS_A : TS_{IN}$	L CH_4/ KG VS	MEAN	σ
1.1. 1.2. 1.3.	*C. Demersum*	1.2	L	0.06	0.047	1	30	20	0.6	1:10	562.30 546.33 83.37	397.33 (554.31)*	(7.98)*
2.1. 2.2. 2.3.	C. *Demersum*	1.2	S	0.06	0.047	1	30	20	0.6	1:10	436.71 131.26 487.80	351.93 (462.25)*	(25.54)*
3.1. 3.2. 3.3.	C. *Demersum*	2.4	S	0.12	0.094	1	30	20	0.6	1:5	78.05 8.87 104.65	63.86 (91.35)*	(13.3)*

As it can be seen, the highest methane yield is for the samples with the larger particle size. This does not coincide with the information from literature and the logic behind smaller particles being easier to degrade. These results can be explained with the inconsistency of dividing the algae samples between the batches. If looking solely at the larger particle test results, literature suggests that a correctly executed experiment with smaller particles would yield even higher than that, which is a positive thing taking into account that these yields are already relatively high. Another interesting aspect is the low yield of samples with a higher algae input compared to inoculum amount. Either for these samples the bottles had small faults that partially lowered the biogas yield, or the methanogene bacteria could not process such amount of biomass. Nevertheless, these results should be omitted from any further analysis and the tests should be repeated to see whether the problem is indeed in the ratio or some technical aspects. The experiments proved that locally available macrophyte *C. demersum* has high methane yield of 554 l CH4/ kg VS and thus can be used and further analysed (the amounts available in natural waters, the possibility for artificial growing and so on) for biogas use in Latvia. It also must be noted that during the first 5 days around 50 % of biogas was already produced which is a good aspect when considering a continuous type biogas reactor (rather than a batch type).

E. *Life Cycle Assessment results*

As mentioned the results of LCA are necessary to be used and integrated within the overall MCA approach to analyse the environmental impacts of the alternatives. The final scores related to the 4 environmental damage categories and obtained by the SimaPro software are reported in Table 6.

The human health criteria values are in a narrow range for all of the alternatives, the lowest value being assigned to manure based biogas alternative, but the highest being assigned to both marine algae grown in ponds based biogas production scenarios. The difference between the highest and lowest results is around 10 %. The alternatives with a higher score are those with a higher energy and material input. The ecosystem quality criterion is similarly distributed as the human health criteria. The lowest value being assigned to manure, the highest to marine species based biomass conversion into biogas. The climate change criteria values are not equally distributed; there is a great variation of the values.

The negative criterion Climate change values for a part of the scenarios are mostly based on the avoided fertiliser impact. As in the pond-based biogas production processes, the nutrients needed for growth are taken from the digestate, and a closed cycle of these elements is created. In cases of naturally grown biomass, the nutrients found in digestate can be returned to the system as fertilizers on land avoiding the production of artificial fertilizers.

TABLE VI

ENVIRONMENTAL CRITERIA VALUES GAINED FROM LCA IN SIMAPRO

	HUMAN HEALTH	ECOSYSTEM QUALITY	CLIMATE CHANGE	RESOURCE DEPLETION
Units	[DALY/FU]	[PDF*m^2*y/FU]	[kg CO_2 eq./FU]	[MJ primary /FU]
Nat-F	0.0226	1 361	−1 612	−4 053
Nat-M	0.0231	1 924	−1 039	−444.1
OF-F	0.0245	1 831	905.0	19 024
OF-M	0.0247	2 404	980.1	19 859
ON-F	0.0246	1 832	1 127	18 935
ON-M	0.0247	2 404	980.1	19 859
Man	0.0224	1 246	−1 834	−10 155
Crop	0.0235	1 498	−408.8	1 312
NG	0.0238	1 560	−61.92	13 478

The highest beneficial effect from the avoided product is related to the climate change category. The environmental impact on resources is distributed similarly to the climate change category – 4 pond-grown algae based scenarios have the highest values, but the rest have lower or even negative values. The only exception in this case is the natural gas scenario – as natural gas is a non-renewable resource its use directly affects this criteria.

When recalculating the results of environmental performance to points (non-dimensional), the greatest impact on environment is within the criterion Human health (which is mostly comprised from the NO_x emissions from combustion process). It can be concluded that some of the data have more impact on the outcome than others. In order to evaluate the study itself, a sensitivity analysis should be applied.

The sensitivity analysis is applied to the biogas yield of algae both for marine and freshwater species. The marine algae yield is taken from species *Ulva lactuca* as 300 l of CH_4 per kg of VS. This is experimentally proven value that has been reached with several experiments. The yield for freshwater species is based on *C. demersum* and is 500 l of CH_4 per kg of VS. This is a lowered value of experimentally gained results that need to be verified with more experiments. These values depend on the quality and characteristics of the samples used. As this value directly impacts the amount of biomass needed to produce 1 MWh_{el} of power, it should be tested with sensitivity analysis. The sensitivity analysis is carried out only by diminishing the biogas yield value, as it is unlikely that the value could be higher. The values are changed in a diapason from −30 % to 0 % with a step of 10 % (see Fig. 3.).

The change of biogas yield from algae also changes the amount of algae needed, the energy needed for growth phase, pre-treatment, anaerobic digestion and so on. The only unchangeable parameters are transportation and the biogas cleaning process, as it is influenced by the biogas amount.

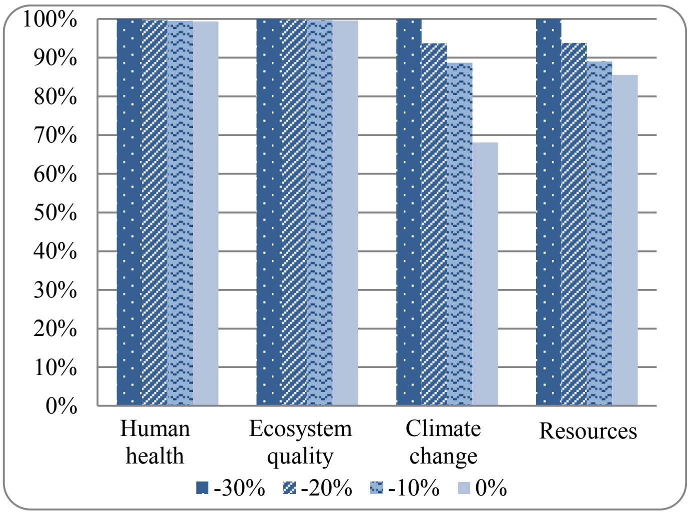

Fig. 3. Sensitivity analysis of alternative ON-F by changing biogas yield.

The figure shows how damage point value changes due to application of sensitivity analysis. As it can be seen, the biggest influence is on climate change and resources. The lower the biogas yields from biomass the bigger influence on climate changes and resources (because of the extra electrical energy needed). The same trend can be seen for the marine water species and scenarios with offshore ponds.

LCA methodology provided insight on the weak points of alternatives (the growth phase energy and material demands) as well as the sensitive points (the avoided fertilisers from digestate and the avoided heat). The sensitivity analysis showed that data are strongly interrelated. Also the choice of boundaries (as the extension of digestate use and the restricting boundaries for manure based biogas production alternative) is a major factor for the interpretation of the results.

F. Quantification of the economic, technical and social indicators

In order to gain the values for economic category, a simple economic calculation is carried out based on literature analysis about the investments, costs and revenues of the alternatives. The value of the criterion Social benefits is also based on these data.

The criterion Energy Payback Period shows the amount of time needed to produce the same amount of energy as spent on the construction phase. The boundaries might be set quite wide, including the production phase energy use for the technologies directly used in the process, or quite narrow focusing only on the energy spent directly in the construction and assembling phase of the plant.

The Total Investments for all the scenarios vary from 1217 €/FU to 2703 €/FU (see Table 7.). The revenues come from selling the generated electricity. Different tariffs apply for different types of input for energy production.

TABLE VII

ECONOMIC CRITERIA SPECIFIC INVESTMENTS, REVENUES AND OPERATION AND MAINTENANCE COST VALUES FOR MULTI-CRITERIA ANALYSIS

	SPECIFIC INVESTMENTS [€/FU]	REVENUES [€/FU]	OPERATION AND MAINTENANCE COSTS [€/FU]
Nat-F	2 180	289	1 008
Nat-M	2 203	289	1 099
OF-F	2 680	289	1 857
OF-M	2 703	289	1 923
ON-F	2 569	289	1 857
ON-M	2 592	289	1 923
Man	2 178	289	831
Crop	2 176	289	826
NG	1 217	218	409

The operation and maintenance costs vary five-fold – the lowest cost being 409 € per FU for natural gas use (as the process is highly automated and no additional materials are needed for the process) and the highest being 1 923 € per FU.

Technical criteria include the energy return ratio, energy payback period and maturity level. The data within these criteria are described further. The Energy Return ratio values are calculated based on the LCA inventory. The energy is spent in each of the stages of production, but heat is only spent for the anaerobic digestion process. The overall spent energy does not include the energy used in transportation of any kind in each alternative (see Table 8).

As it can be seen, the most energy spent is within the alternatives of pond based biogas production. As the benchmarking scenarios do not include the energy spent on growth phase or production phase, their criterion values are much lower. As the energy spent in transportation is not included, the ratio shows a good ratio of energy spent and energy gained. As the construction phase of the plants or technologies is not included in this assessment (only the production phase) the actual values of overall life cycle will be higher. As the marine algae use for energy production includes another step of salt removal, alternatives with it have a higher, less beneficial energy return ratio.

The maturity level of a technology describes the development level of said technology including the beginning levels of technology (starting from an idea that needs to be proved) and the final stages of technology (full-scale commercial production). Depending on the source, the maturity levels are different due to the variation on their descriptions. The most common type is the TRA-based (Technology Readiness Assessment) scale [62]. This scale is adapted from a more detailed 9-level scale to a more robust 4-level scale, as the boundaries between different levels are not always clear. Level 1 is a research to prove feasibility, where only experiments to proof the concept of idea are made. Level 2 is the exploratory development of a technology at a laboratory scale, while level 3 is already technology demonstration at a pilot-scale (technology validation). The last level (4) includes a system operation and production of a commercial, full-scale technology.

TABLE VIII

ENERGY SPENT IN PRODUCTION AND SCENARIO VALUES FOR CRITERIA ENERGY RETURN RATIO, SOCIAL ACCEPTANCE AND SOCIAL BENEFITS

	SPENT ENERGY, [KWH]	ENERGY RETURN RATIO	SOCIAL ACCEPTANCE [%]	SOCIAL BENEFITS [€/FU]
Nat-F	1 070	0.38	72.4	712
Nat-M	1 259	0.45	72.4	712
OF-F	1 423	0.51	72.4	1 352
OF-M	1 612	0.58	72.4	1 352
ON-F	1 423	0.51	72.4	1 352
ON-M	1 612	0.58	72.4	1 352
Man	612	0.22	78.4	656
Crop	285	0.1	78.4	672
NG	142	0.05	85.6	400

As there is more than one technology used for each of the alternatives, the maturity assessment should be performed for each of the technologies used. 4 different technology types have been acknowledged – cultivation, harvesting, anaerobic digestion and burning technologies.

The maturity level of a technology describes the development stage of it. Technology development cannot skip any of the steps, it has to be proven through all of the steps before it can be introduced to a market and produced commercially. If one of all used technologies is still in its development phases, it might mean that alternative implementation would be more difficult and more expensive. The maturity level value used in further analysis is the minimum value for all alternative assigned maturity level values (see Table 9).

TABLE IX

ASSIGNED MATURITY LEVEL VALUES FOR ALTERNATIVES

SCENARIO	CULTIVATION	HARVESTING	AD	CHP	MIN
Nat-F	–	4	4	4	4
Nat-M	–	4	4	4	4
OF-F	2	–	4	4	2
OF-M	2	–	4	4	2
ON-F	3	–	4	4	3
ON-M	3	–	4	4	3
Man	–	–	4	4	4
Crop	–	–	4	4	4
NG	–	–	–	4	4

As it can be seen, the use of marine or freshwater algae for the same technologies does not affect the maturity level of it. Cultivation of algae is used by off- and on-shore open ponds, the cultivation of algae itself is a mature technology, but as in the study large scale implementation is needed, it is considered that technology is only at level 3 out of 4, but the off-shore ponds are less mature – the technology offers some great ideas which implementation is still problematic.

The harvesting technologies used are trawlers for naturally grown algae – the technology is mature as it is used in other aquaculture farming operations. The manual harvesting from ponds is not considered a technology, so it is not given a maturity level. Other alternatives do not harvest the input for AD process. The anaerobic digestion technology is a mature technology, the applications of which do not change because of algae use in it – it is also assigned the value of 4. And the combined heat and power unit is also a mature technology, assigned a maturity level of 4.

The alternatives with lowest maturity levels are the offshore ponds due to the cultivation phase and the on-shore ponds for the same reason. If these alternatives are to be implemented in real life, a caution to these technologies should be exercised.

The maturity level assessment also shows that the weak point of the whole production process is the cultivation of algae. It is still in a laboratory scale phase for off-shore open ponds and pilot-scale production phase for on-shore open ponds. This means that time is needed for the technology to become commercially available and more feasible.

The criterion Energy payback period has been removed from the study due to its high demand of raw data as the criteria weight calculations do not allow removing or adding extra criteria without re-calculating all the relations.

Algae or any other feedstock based biogas production investments mainly consists of costs of anaerobic digestion tank, biogas-cleaning unit and the combined heat and power generation unit. The main cost for operation and maintenance are labour costs as good specialists as well as manual labour is needed. The revenues are regulated by legislation based on the inputs used for energy production process.

A social questionnaire is used for the criteria Social Acceptance value determination. The questionnaire consists of different parts – the first part is the introduction to the questionnaire, followed by general information questions of the respondent. The next section is aimed to understand the basic knowledge level on such environmental issues as environmental protection, global warming and renewable resources. The next section also determines the interest of such environmental problems as well as the opinion of the respondents. The questions are sorted from fossil fuel acceptance and support to biogas acceptance and support to finally algae-based biogas acceptance level and support determination. After answering the questions about the support of algal biogas production, additional information of the pros of using such biomass are given. This is based on the assumption that the average Latvian has no or little knowledge of such biomass use aspects (it is also assumed that the average Latvian has basic knowledge of biogas production in order to know whether he/she supports the technology or not). After the respondent has become acquainted with the given information, he/she is given a chance to change his/her answer to the question about support and acceptance of alga-based biogas production in Latvia. The results of the social questionnaire are then analysed and the criteria Social Acceptance values are assigned based on it.

The Social Acceptance values of different technologies are shown in Table 8. The results are as predicted – the more known technologies have a higher acceptance from a societies point of view. All of the algae based scenarios have the same percentage of acceptance, as the knowledge of the differences between the alternatives in society is scarce or even absent.

The value of the criterion Social Benefits is based on the economic calculations carried out for economic criteria value determination. The total amount is expressed as Euros per functional unit (see Table 8).

As it can be seen, the lowest criterion values are for natural gas scenarios use. Three-fold values are for the open pond based scenarios, as all of them need extra personal both for biogas production phase and the algae harvest and cultivation phase. There is no difference between the freshwater and marine water based scenarios, as the amount of work needed for salt removal is negligible.

G. *Weighting and final ranking*

Within this part, the AHP approach has been implemented. This numerical value assigned is still subjective, but the method of comparing them in pairs makes the decision easier and clearer. In order to reduce the subjectivity of one person assigning the weights, expert questionnaires are used. Within the scope of the questionnaire experts are considered to be people within the Institute of Energy Systems and Environment, Riga Technical University with a doctoral degree. The questionnaire consists of explanation of the subject and the study within which it would be included and the question part. The experts are asked to assign weights for both the criteria categories as well as the criteria within them. For calculating the final weight of criteria the average results of expert questionnaire are used as well as the weights from AHP methodology thus lowering the subjectivity of the data.

The values assigned by experts are more evenly distributed than values gained from AHP methodology (See Fig. 4.).

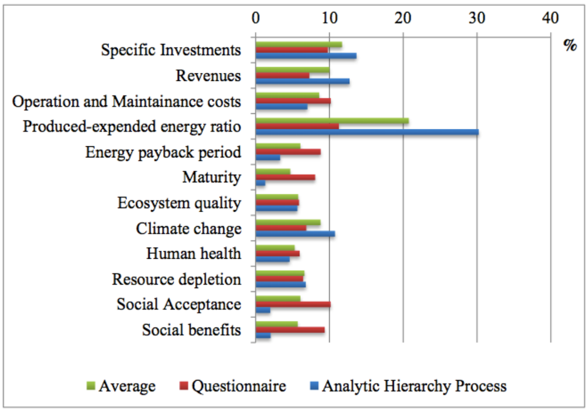

Fig. 4. Criteria weight values from Analytic Hierarchy Process methodology, expert questionnaires and the final weights.

The difference in weight values can be explained by the fact that different approaches are used in each of the methods – the pair-wise comparison allows to evaluate one criterion in comparison with another, not standing alone, thus changing the way how the criterion is perceived by the expert assigning weights.

The biggest differences in values are within the social criteria and the energy return ratio (produced-expended energy ratio). The social criteria value differences can be explained by the different perception of criteria – in general the social criteria seems to be important, but when compared to an exact economic criteria its importance in most cases is not as high. The energy return ratio value determined by AHP clearly shows that this criterion is of high importance by the authors, the expert questionnaire results also show one of the highest weights for this particular criterion, thus merging of these values provides a more balanced outlook on the weighing.

The merging of AHP methodology and expert questionnaires for weight determination methodologies has provided results with a lower level of subjectivity, as each of the methods has its advantages.

For two criteria the values are negative, there is no available literature on whether the TOPSIS methodology can successfully calculate such criteria, so values for these criteria are recalculated based on the minimum value amongst all the alternatives. The minimal value now becomes 1 (rather than 0 which may influence the results negatively) and all other values are recalculated based on this difference. This is basically a preliminary normalisation step of the data to ensure the quality of results.

When this is done, the values can be normalised (see chapter Methodology, subsection Normalisation, weighting of criteria and ranking of scenarios) and further used in TOPSIS. The results of TOPSIS show the relative closeness of an alternative to the ideal solution (see Fig. 5 only bars “Original”).

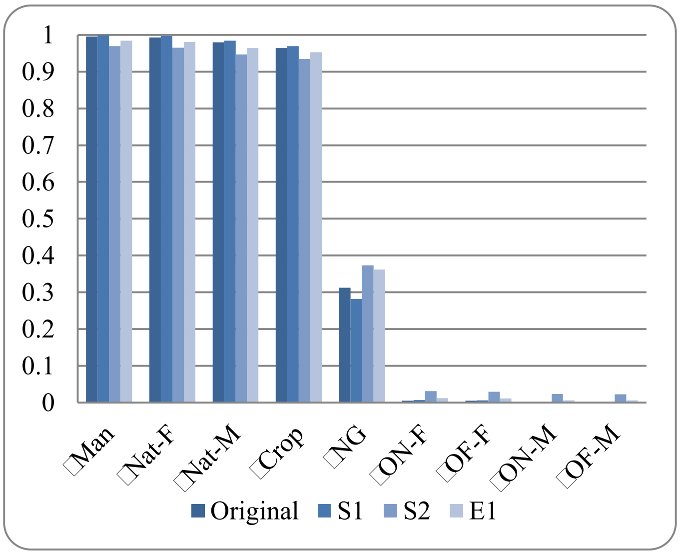

Fig. 5. Sensitivity analysis of weights within TOPSIS, where S1 – society point of view, S2 – stakeholders point of view, E1 – entrepreneurs point of view.

As it can be seen, the alternatives have formed several groups of similar results that are far away from one another. The highest ranking is to the manure based scenarios; as explained before this success might be due to the boundaries set that they do not include the production of manure, the biogas production starts with only transportation. The next part of alternatives is naturally grown and collected biomass, which has a rank really close to the ideal solution (97 % and 99 %). The other two benchmarking scenarios are ranking lower than the algae scenarios. Scenario Crop lower ranking can be explained with the differences in biomass characteristics and thus the amount needed for FU. The natural gas ranking (5th spot with the relative closeness of 31 %) is mostly due to the environmental impacts of emissions and the low number of workers required (social benefits criterion). The rest of the alternatives are ranked as less than 1 % meaning that they are not even near the ideal solution. Here again the important difference is from the avoided fertilisers impact on environmental aspects (4 of 12) as well as the economic indicators. As the cultivation requires a number of investments and operation and maintenance costs, the feasibility of such technologies is scarce. These results show that there is potential of sustainable use of algae for biogas production, but the high costs of algae cultivation should be solved. Also possibilities of using algae together with other input materials (like manure) should be considered, as this could cut the expense in half but still promote algae use and production (also allowing the technology to develop).

A sensitivity analysis of the LCA model showed its robustness, but that does not mean that the final model is robust as well. The sensitivity analysis is performed with the weights assigned by changing them according to different stakeholder group priorities. The points analyzed were a societies point of view (S1) where the environmental as social criteria are more important than environmental and economical, the stakeholders (S2) point of view where the emphasis was on economic and social criteria and the last was an entrepreneur (E1) view, where economic and technical criteria were the most important (see Fig. 6.). As it can be seen, the changes of final ranking results are negligible and the model is robust.

V. Conclusions

The study was a preliminary attempt to evaluate the potential exploitation and use of macro-algae as an alternative source for anaerobic digestion conversion processes in a Latvian context. The study is providing a preliminary insight specifically devoted to the evaluation of potential different harvesting and cultivation systems in comparison to natural-gas energy routes and production of biogas from classical feedstock (namely manure and agricultural remnants).

The results represent valuable outcomes based on a novel sustainable evaluation methodology from the integration of the MCA and LCA approaches.

The results of the study show that algae-based scenarios can achieve similar sustainability level as benchmarking scenarios (TOPSIS ranking within 5 %) under the specific assumptions of the proposed study. Meaning that algae-based scenarios of collecting biomass directly from water bodies present similar performances as benchmarking scenarios (i.e. natural gas and classical biomass feedstock from agricultural remnants).It should be reminded that although wild macro-algal harvesting seems a feasible scenario, a very sensitive management is required in order to prevent severe impact on the local ecosystem. Moreover a more in-depth analysis should be also devoted to the evaluation of the overall energy contributions during the harvesting phase that could represent a bottleneck for a massive exploitation.

The study shows that there is potential for sustainable use of algae in Latvian conditions and thus that algal biomass can be utilized for the production of biogas. Based on this study and the main assumptions on both scenarios and input data selected - the most sustainable, feasible and plausible solution of using algae for biogas energy production is the scenario related to the collection from natural water bodies (TOPSIS ranking 0.99 out of 1). The main key issues are still related to the real quantification of the viable and exploitable algal biomass, the selection of the best species (or the optimal combination) and the consequents related to a large removal of algae biomass influencing water environment.

The study proves that the important positive impact on environment is related to the use of digestate, in fact replacing the use of chemical fertilizers. The removed algae bring also a positive effect on eutrophication, but more studies are needed to understand if removals are affecting another source of nutrient consumer.

The scenarios selected for this study were assessing the use of only one biomass input at a time into biogas reactor, but recent studies show that a correct mix of inputs can increase the overall biogas yield. This would not only diminish the costs for algae growing ponds, but also increase the overall sustainability of biogas production. This is also a good option for algae collected from water bodies; as the amount is unpredictable, collected algae can be used as secondary input to increase the efficiency of a biogas plant when it is possible. The evaluation of such options is not as simple as divided input use, especially when the input amount of algae is unknown. Also regarding the collection of algae from natural waters, there is no way of ensuring that only certain species of algae are collected unless done manually. In case of Latvia there are a lot of protected species of algae and macrophytes and as well as water and coastal territories of special protection, where collection of biomass would be complicated or even forbidden.

In case of practical introduction of algae in an overall and integrated energy production system, the cultivation still represents the bottleneck of an up-scaled diffusion. A deeper evaluation of the overall sustainability should involve a more specific understanding of the real economic implications related to the diffusion of this potential novel technology. A comprehensive life cycle assessment approach interconnected with a multi-criteria analysis providing a wide and clear picture of environmental, economic and social benefits and impacts must be an important tool for guiding technology development as well as for policy decisions. Moreover a more comprehensive sensitivity analysis should be performed.

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EIROPAS SOCIĀLAIS FONDS

EIROPAS SAVIENĪBA

IEGULDĪJUMS TAVĀ NĀKOTNĒ

REFERENCES

1. **Nehrin, R.** Traversing the mountaintop: world fossil fuel production to 2050. *Philosophical transactions of the Royal Society. Biological sciences*, 2009, No. 364 (1532), pp. 3067–3079.
2. **McKendry, P**. Energy production from biomass: overview of biomass. Review paper. *Bioresource Technology*, 2002, No. 83, pp. 37–46. http://dx.doi.org/10.1016/S0960-8524(01)00118-3
3. **Demirbas, A.** Biomass resource facilities and biomass conversion processing for fuels and chemicals. *Energy Conversion and Management*, 2001, No. 24, pp. 1357–1378. http://dx.doi.org/10.1016/S0196-8904(00)00137-0
4. **Alam, F., Date, A., Rasjidin, R., Mobin, S., Moria, D., Baqui, A.** Biofuel from algae – Is it a viable option? *Procedia Engineering*, 2012, No. 49, pp. 221–227.
5. **Alvadar-Morales, M., Boldrin, A., Karakashev, B., Holdt, S. L., Angelidaki, I., Astrup, T.** Life cycle assessment of biofuel production from brown seaweed in Nordic conditions. *Bioresource Technology*, 2013, No. 129, pp. 92–99. http://dx.doi.org/10.1016/j.biortech.2012.11.029
6. **Debowski, M., Zielinski, M., Grala, A., Dudek, M.** Algae biomass as an alternative substrate in biogas production technologies – Review. *Renewable and Sustainable Energy Reviews*, 2013, No. 27, pp. 596–604. http://dx.doi.org/10.1016/j.rser.2013.07.029
7. **Singh, A., Olsen, S. I.** A critical review of biochemical conversion, sustainability and life cycle assessment of algal biofuels. *Applied Energy*, 2011, No. 88, pp. 3548–3555. http://dx.doi.org/10.1016/j.apenergy.2010.12.012
8. **Bruton, T., Lyons, H., Lerat, Y., Stanley, M., Rasmussen, M. B.** A review of the potential of marine algae as a source of biofuel in Ireland. Dublin. Ireland: *Sustainable Energy Ireland*, 2009.
9. **Wellinger, A.** Algal Biomass – Does it save the world? Short reflections. IEA Bioenergy Task 37 report. 2009, p. 13.
10. **Kim, S. K.** *Handbook of Marine Macroalgae: Biotechnology and Applied Physology*. USA: Wiley, 2011.http://dx.doi.org/10.1002/9781119977087
11. **Archer, D., Barber, J.** *Molecular to global photosynthesis*. UK:Imperial College Press, 2004. http://dx.doi.org/10.1142/p218
12. **Zamalloa, C., Vulsteke, E., Albrecht, J., Verstraete, W.** The techno-economic potential of renewable energy through the anaerobic digestion of microalgae. *Bioresource Technology*, 2011, No. 102, pp. 1149–1158. http://dx.doi.org/10.1016/j.biortech.2010.09.017
13. **Lundquist, T. J., Woertz, I. C., Quinn, N. W. T., Benemann, J. R.** A realistic Technology and Engineering assessment of algae biofuel production. USA: Energy Biosciences Institute, 2010.
14. **Resurreccion, E., Colosi, L., White, M., Clarens, A.** Comparison of algae cultivation methods for bioenergy production using a combined life cycle assessment and life cycle costing approach. *Bioresource Technology*, 2012.No. 126, pp. 298–306. http://dx.doi.org/10.1016/j.biortech.2012.09.038
15. **Richardson, J. W., Johnson, M. D., Outlaw, J. L.** Economical comparison of open pond raceways to photo bio-reactors for profitable production of algae for transportation fuels in the Southwest. *Algal Research*, 2012, No. 1, pp. 93–100.

16. **Slade, R., Bauen, A**. Micro-algae cultivation for biofuels: Cost, energy balance, environmental impacts and future prospects. *Biomass and Bioenergy*, 2013, No. 53, pp. 29–38. http://dx.doi.org/10.1016/j.biombioe.2012.12.019
17. **Demirbas, A.** Mechanisms of liquefaction and pyrolysis reactions of biomass. *Energy Conversion and Management*, 2000, No. 41 (6), pp. 633–646.
18. **Demirbas, A**. Biomass resource facilities and biomass conversion processing for fuels and chemicals. *Energy Conversion and Management*, 2001, No. 24, pp. 1357–1378. http://dx.doi.org/10.1016/S0196-8904(00)00137-0
19. **Dragone, G., Fernandes, B., Vicente, A. A., Teixeira, J. A.** Third generation biofuels from microalgae. Communicating Current Research, *Technology and Education Topics in Applied Microbiology and Microbial Biotechnology*, 2010, No. 2, pp. 1355–1366.
20. **Bahadar, A., Khan, M. B.** Progress in energy from microalgae: A review. *Renewable and Sustainable Energy Reviews*, 2013, No. 27, pp. 128–148. http://dx.doi.org/10.1016/j.rser.2013.06.029
21. **Eroglu, E., Melis, A.** Photobiological hydrogen production: Recent advances and state of art. *Bioresource Technology*, 2011, No. 102, pp. 8403–8413. http://dx.doi.org/10.1016/j.biortech.2011.03.026
22. Environmental policy strategy 2009-2015. Cabinet order 517. *Latvijas Vēstnesis* 2009, No. 122 (4108), p. 53.
23. Europe 2020. A strategy for smart, sustainable and inclusive growth. EU: *European Commission*. 2010.
24. **Kalns, J.** [Online] Biogas in Latvia. 2012. [Accessed: 23 January 2014]. Available: http://www.lvportals.lv/likumi-prakse.php?id=251397
25. **Astill, H., Walker, D., Kiliminster, K., et. al.** Macrophytes and macroalgae in the Swan-Canning estuary. *River Science*, 2010, No. 20, pp. 2–12.
26. Freshwater Ecology: Concepts and Environmental Applications. Dodds W.K. USA: Academy Press, 2002.
27. **Gül, T.** Integrated Analysis of Hybrid Systems for Rural Electrification in Developing Countries. M.Sc. Thesis. RIT Division of Land and Water and Water Resources Engineering, Stockholm, Sweden. 2004, p. 117.
28. **Hwang, C. L., Yoon, K.** Multiple Attribute Decision Making: Methods and Applications. Springer-Verlag, Heidelbeg, 1981.
29. **Tzeng, G. H., Huang, J. J.** Multiple Attribute Decision Making: Methods and Applications. United States of America: Taylor & Francis, Boca Raton, 2011.
30. **Körth, H.** Zur Berücksichtigung mehrere Zielfunktionen bei der Optimierung von Produktions planen. *Mathematik und Wirtschaft*, 1969, No. 6, pp. 184–201.
31. **Pubule, J., Blumberga, A., Romagnoli, F., Blumberga, D.** Finding an optimal solution for biowaste management in the Baltic States. In press, *Journal of Cleaner Production*, 2014. Available online on May 2014.
32. **Dong, J., Chi, Y., Zou, D., Fu, C., Huang, Q., Ni, M.** Energy environment economy assessment of waste management systems from a life cycle perspective: model development and case study. *Applied Energy*, 2014, No. 114, pp. 400–408. http://dx.doi.org/10.1016/j.apenergy.2013.09.037
33. **Saaty, T.** The analytic hierarchy process. New York: McGraw Hill, 1980.
34. ISO. ISO 14040: Environmental management-Life cycle assessment-Principles and Framework. Geneva: ISP copyright office; 1997
35. ISO 14044: Environmental management. Life cycle assessment—requirement and guidelines. International Organization for Standardization, 2006.
36. **Rodríguez R., Ruyck J. D., Díaz P. R., Verma V. K., Bram S.** An LCA based indicator for evaluation of alternative energy routes. *Applied Energy*, 2011, No. 88(3), pp. 630–635.
37. **Frischknecht, R., Jungbluth, N., Althaus, H.J., Doka, G., Dones, R., Hischier, R., Hellweg, S., Humbert, S., Margni, M., Nemecek, T., Spielmann, M.** Implementation of Life Cycle Impact Assessment Methods: Data v2.0. ecoinvent report No. 3. Switzerland: Swiss center for Life Cycle Inventories, 2007.
38. **Goedkoop, M., Oele, M., Leijting, J., Ponsioen, T., Meijer, E.** Introduction to LCA with SimaPro. The Netherlands: PRe consultants, 2013.
39. **Goedkoop, M., Oel, M., Schryver, A., Vieira, M.** SimaPro Database Manual: Methods Library. The Netherlands: Pre Consultants, 2008.
40. **Humbert, S., Schryver, A., Bengoa, X., Margni, M., Jolliet, O.** IMPACT 2002+: User Guide. Draft for version Q2.21. 2012. USA: Quantis press, 2012.
41. **Jolliet, O., Margni, M., Charles, R., Humbert, S., Payet, J., Rebitzer, G., Rosenbaum, R.** IMPACT 2002+: A New Life Cycle Impact Assessment Methodology. USA: Ecomed publishers, 2003.
42. **Bruhn, A., Dahl, J., Nielsen, H.B., et. al.** Bioenergy potential of Ulva lactuca: Biomass yield methane production and combustion. *Bioresource Technology*, 2011, No.102, pp. 2595–2604. http://dx.doi.org/10.1016/j.biortech.2010.10.010
43. **Van Iersel, S., Gamba, L., Rossi, A., Alberci, S., Dehue, B., Van de Staaij, J., Flammini, A.** Algae-based biofuels: A review of challenges and opportunities for developing countries. Italy: Food and agriculture Organization of the Unites Nations, 2009.
44. **Kumar, P.** Analysis of CO_2 capture using algae. USA: Oilgae, 2010. 24 p.
45. **Bruhn, A., Dahl, J., Nielsen, H. B., et. al.** Bioenergy potential of Ulva lactuca: Biomass yield methane production and combustion. *Bioresource Technology*, 2011, No. 102, pp. 2595–2604. http://dx.doi.org/10.1016/j.biortech.2010.10.010
46. **Surendra, K. C., Takara, D., Hashimote, A. G., et. al.** Biogas as a sustainable energy source for developing countries: Opportunities and challenges. *Renewable and Sustainable Energy Reviews*, 2012, No. 31, pp. 846–859.
47. **Collet, P., Helias, A., Lardon, L., et. al.** Life-cycle assessment of microalgae culture coupled to biogas production. *Bioresource Technology*, 2011, No. 102, pp. 207–214. http://dx.doi.org/10.1016/j.biortech.2010.06.154
48. **Frost, P., Gilkinson, S.** 27 months performance summary for anaerobic digestion of dairy cow slurry at AFBI Hillsborough. Interim Technical report. USA: Agri-Food and Biosciences Institue, 2011. p. 13.
49. **Aresta, M., Dibendetto, A., Barberio, G.** Utilization of macro-algae for enhanced CO_2 fixation and biofuels production: Development of a computing software for an LCA study. *Fuel Processing Technology*, 2005, No. 86, pp. 1679–1693. http://dx.doi.org/10.1016/j.fuproc.2005.01.016
50. **Tredici, M. R.** Energy balance of microalgae cultures in photobioreactors and ponds. The energy balance and the NER, calculated on real number as at the base of a sound LCA of algal biofules. Italy: EU workshop, Life Cycle Analysis of Algal Based Biofuels, 2012. p. 38.
51. Biogas composition from different sources [Online] [Accessed: 13 March 2014]. Available: http://www.biogas-renewable-energy.info/biogas_ composition.html
52. **Selehion, A. R., Minael, S., Razavi, S. J.** Design and performance evaluation of screw press separator for separating dairy cattle manure. *International Journal of Agronomy and Plant Production*, 2013, No. 4, pp. 3849–3858.
53. **Cuellar, A. D., Webber, M. E.** Cow power: the energy and emissions benefits of converting manure to biogas. *Environmnetal Research Letters*, 2008, No. 3(3), p. 8.
54. **Koenig, R. T., Hammac, W. A., Pan, W. L.** Canola growth, development and fertility. Fact sheet. USA: Washington state university, 2011, p. 6.
55. **Balodis, I., Balodis, O.** Winter Oilseed Rape Growing – Experience in Farm „Azaidi. Lauksaimniecības zinātne veiksmīgai saimniekošanai, 2013, No. 21, p. 4.
56. Biogāzes izmantošanas alternatīvu sistēmu efektivitātes un izmaksu salīdzināšanas sociāli-ekonomisko ieguvmu novērtējums. Izpildes tehniskais ziņojums (Biogas use alternative system efficiency and cost comparison for socio-economic gain evaluation. Technical implementation report). Latvia: *Enerģija un vide*, 2012, p. 20.
57. **Dubrovskis, V., Niklass, M., Emsis, I., Kārkliņš, A.** Biogāzes ražošana un efektīva izmantošana (Biogas production and efficienct use). Latvia: Latvijas Biogāzes Asociācija, 2013. p. 88.
58. **Frank, E. D., Han, J., Palau-Rivera, I., et. al.** Methane and nitrous oxide emissions affect the life-cycle analysis of algal biofuels. *Environmental Research letters*, 2012, No. 7, p. 10.
59. **Auziņš, J., Januševskis, A.** Eksperimentu plānošana un analīze (Experimental planning and analysis). Latvia: Riga Technical University press, 2007. p. 256.
60. **Keskinkan, O., Goksu, M. Z. L., Basibuyuk, M., et. al.** Heavy metal adsorbtion properties of a submerged aquatic plant (Ceratophyllumdemersum). *Bioresource Technology*, 2004, No. 92 (2), pp. 197–200.
61. **Aravind, P., Prasad, M. N. V.** Zinc protects chloroplasts and associated photochemical functions in cadmium exposed Cerathophyllumdemersum L., a freshwater macrophyte. *Plant Science*, 2004, No. 166 (5), pp. 1321–1327.
62. **Rajiv, K. S.** Air, water and soil pollution science and technology: green plants and pollution. USA: Nova science publisher, 2010.

63. **Block, T. A. Rhoads, A. F., Anisko, A.** Aquatic Plants of Pennsylvania: A Complete Reference Guide Book. USA: University of Pennsylvania Press, 2011. http://dx.doi.org/10.9783/9780812205046
64. **Ha, M. H., Pflugmacher, S**. Time-dependentalterations in growth, photosynthetic pigments and enzymatic defense systems of submerged Ceratphyllumdemersum during exposure to the cyanobacterial neurotoxin anatoxin-a. *Aquatic toxicology*, 2013, No.138, p. 26–34. http://dx.doi.org/10.1016/j.aquatox.2013.04.007
65. METHOD 1684: Total, Fixed, and Volatile Solids in Water, Solids, and Biosolids. Environmental Protection Agency, Office of Water, Office of Science and Technology, Engineering and Analysis Division. USA: US EPA.2001.

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Paper 7: The methodology of evaluating different macroalgae biogas production scenarios with multi-criteria analysis

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THE METHODOLOGY OF EVALUATING DIFFERENT MACROALGAE BIOGAS PRODUCTION SCENARIOS WITH MULTI-CRITERIA ANALYSIS

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Abstract

The aim of the work is to describe the methodology used in evaluation of different macroalgae biogas production scenarios in Latvian conditions. The evaluation is carried out with a multi-criteria analysis in which other methodologies as Analytical Hierarchy Process, questionnaires, experiments, modelling, life cycle assessment and more are used. The combination of said methodologies is aimed at reducing all subjectivity of evaluation as well as to give clear end-result of preferences on scenarios chosen. Even though a lot of data is needed to carry out the multi-criteria analysis most of it is based on actual objects rather than being calculated empirically. When combining described methodologies an evaluation is gained that is comprehensive, without subjectivity, with experimental data and that shows which are the weak points of each scenarios as well as giving an easy understandable and presentable results.

Key words: Biogas, Analytical Hierarchy Process, Multi-Criteria analysis, Life Cycle Assessment, macro-algae

Introduction

As it is clear that available fossil fuel amount is decreasing rapidly, other resources for energy production must be found. There is a great variation of different renewable energy resources available that should be evaluated for efficient use in energy sector. Algae and macrophytes have received an increasing interest as a feedstock for biofuel production in recent years.

Algae use for energy production has been examined for several reasons. From them most frequently mentioned is the high productivity and growing rates. Though this parameter is species specific it is considered to be higher than those of land plants. The facts, that algae growing don't use fertile agricultural lands, that it doesn't compete with human food crops, that is can grow in saline and brackish waters, that its use for energy purposes has carbon neutral cycle (atmospheric CO_2 is sequestered in growth phase then emitted during combustion), that some of the species have a high lipid content, are what contributes to increasing interest of their efficient and sustainable use. In general the use of microalgae versus the use of macro algae or macrophytes has higher costs for growing and harvesting phase. Also the use of marine algae versus use of freshwater algae usually has higher costs due to the extra expenses of salt removal of algae (costs of pre-treatment). (Zamalloa *et al*. 2011) (Sustainable Energy Ireland, 2009)

Depending on the desired outcome there are several growing and harvesting technologies available. Most of the research done shows that the simpler systems as open ponds are more economically viable that those of higher complexity and efficiency, e.g. photo-bioreactors. Also scenarios of alga collection from natural water bodies' have low costs, but they are highly unpredictable due to no control over the growth phase. For macro algae physical harvesting can be carried out, but microalgae requires chemical involvements (i.e. flocculants, flotation etc.) as well as extra amount of energy to separate the solid fraction from the liquid fraction. (Sustainable Energy Ireland, 2009) (Debowski *et al*. 2013)

As there is a great variation in algae characteristics, growing mediums, sizes and availability, there are several methods for energy conversion. Theoretically there are several conversion technologies that could be applied for algae conversion to fuel. Based on available reviews of algal energy production two technologies seem to stand out – biomass trans-esterification to bio-diesel and biomass anaerobic digestion to biogas. If the lipid content does not exceed 40 % anaerobic digestion appears to be the optimal solution for energy production. Many scientists agree that anaerobic digestion shows the most potential for successful production of bio-fuels as the conversion technology is existing, mature, available and highlights the pros of algae use in energy production. (Sustainable Energy Ireland, 2009) (Debowski *et al.* 2013)

As global warming is an on-going issue within European Union (EU) agenda, targets have been set for both energy sustainability and climate change. The EU targets for 2020 (know as 20-20-20) are stated to reduce greenhouse gas (GHG) emissions by 20 % compared to year 1990, to comprise 20 % of energy from renewables and 20 % increase in energy efficiency. As a part of EU Latvia has also set these targets and is working toward achieving them. Even though Latvia has a historically high use of renewable resources (36.3 % of primary energy consumption in 2012) most of it comprises from wood biomass and hydro energy. Nevertheless, Latvia has set a target to increase also other renewable energy technologies, including biogas production. Third generation biofuels from such raw materials as algae has shown great potential in scientific research and thus should be studied more carefully for application in Latvian conditions. (Europe 2020, 2010) (Environmental policy strategy, 2009) (Biogas in…2012)

The objective of the article is to evaluate economical, technical, social and environmental aspects of biogas production form macro-algae (also macrophytes) and to find the optimal solution (cultivation, harvesting, processing etc.) for producing sustainable algal biogas in Latvia.

Multi-criteria analysis

There are different methodological approaches to evaluate different aspects of energy production, but most of them focus only on one of them. The evaluation of the sustainability of algal biogas production is carried out through multi-criteria analysis (MCA) that includes 4 major dimensions – economical, technical, environmental and social. MCA uses groups of indicators with their corresponding weights to determine the overall score for each scenario. (Munier 2004)

The criteria within the different categories of MCA are chosen so that they can be adopted not only for algal scenarios but also for benchmarking scenarios. Also the criteria are chosen so that its value could be easily determined. A set of 12 criteria has been identified. The environmental criteria are chosen as end-point categories from life cycle assessment (LCA) program (see Table 1).

Table 1. The indicators in multi-criteria analysis

INDICATOR	
ECONOMIC CRITERIA	
A	Specific Investments
B	Revenues
C	Operation and maintenance costs
TECHNICAL CRITERIA	
D	Produced – expended energy ratio
E	Energy payback period
F	Maturity
ENVIRONMENTAL CRITERIA	
G	Ecosystem Quality
H	Climate Change
I	Human health
J	Resource depletion
SOCIAL CRITERIA	
K	Social Acceptance
L	Social benefits

The evaluation carried out with MCA is taking into account several scenarios. The scenarios have been chosen based on extended literature review. The most promising scenarios of being economically viable and sustainable have been selected. There are a total of 9 scenarios from which 6 describe algal conversion and 3 are benchmarking scenarios. 3 different growing, harvesting and treating scenarios are chosen for both marine and freshwater macro-algae (thus comprising 6 scenarios). The first pair of scenarios is collecting macro-algae from natural water bodies. In case of marine algae the water bodies are either the Gulf of Riga of the Baltic Sea itself; in case of freshwater algae the water bodies are not excluded to lakes, ponds, rivers as some of the freshwater species grow in the brackish water of gulf of Riga or near it. By choosing such scenario (of natural growth) the growth phase is limited from evaluation thus lowering the impact. The next pair of scenarios is algae cultivation in open ponds offshore. By choosing to operate the ponds directly next to natural water bodies the need for extra nutrients is diminished. In case of marine species the

Table 2. Criterion weight assessment asymmetric matrix within AHP method, where A – Specific investments, B – Revenues, C – Operation and maintenance costs, D – Energy return, E – Energy payback period, F – Maturity, G – Ecosystem quality, H – Climate change, I – Human health, J – Resource depletion, K – Social acceptance, L – Social benefits.

INDICATORS	A	B	C	D	E	F	G	H	I	J	K	L
A	1	3	5	0.125	5	5	3	1	3	1	5	7
B	0.33	1	1	0.2	6	9	3	2	3	3	7	5
C	0.2	1	1	0.2	3	5	3	0.2	3	3	3	1
D	8	5	5	1	5	7	5	3	5	5	7	5
E	0.2	0.167	0.33	0.2	1	3	0.5	0.33	0.5	0.5	3	3
F	0.2	0.11	0.2	0.14	0.33	1	0.2	0.14	0.2	0.2	0.33	1
G	0.33	0.33	0.33	0.2	2	5	1	0.5	2	1	4	3
H	1	0.5	5	0.33	3	7	2	1	2	1	5	3
I	0.33	0.33	0.33	0.2	2	5	0.5	0.5	1	0.5	5	2
J	1	0.33	0.33	0.2	2	5	1	1	2	1	5	3
K	0.2	0.14	0.33	0.14	0.33	3	0.25	0.2	0.2	0.2	1	3
L	0.14	0.2	1	0.2	0.33	1	0.33	0.33	0.5	0.33	0.33	1

maintaining of needed water conditions is easier. The third pair of scenarios is traditional alga cultivation in open ponds on-shore. The harvesting from open pond scenarios is carried out manually. The benchmarking scenarios include biogas production form other locally available sources – manure and energetic crop. The last scenario is for a natural gas use. Like all previous scenarios it includes all processes from its extraction to its use for energy generation. The functional unit (FU) for MCA is chosen to be 1 MWh of power produced in combined heat and power (CHP) unit.

Analytical Hierarchy Process

The next step in MCA is the weight assigning for chosen criteria. Most of the methods used for weight assigning use expert opinion thus introducing subjectivity in the analysis. A mathematical method for determining criteria weights has been created by American mathematician Thomas Saaty. The Analytical Hierarchy Process (AHP) method is based on a pair-wise comparison of criteria. Values of the comparison are assigned and later a mathematical procedure of these comparison values is applied. Eigenvalues and eigenvectors are used to determine the weight of each criterion. Values obtained from the pair-wise comparison are then affected by the calculated criteria weight. A Preference scale of 1 to 9 is used. Where 1 describes a relation of both criteria where both are equally important or preferred, 3 describes a moderate importance of one criterion over another (weak preference), 5 refers to a strong preference of one criteria over another, 7 describes a strong importance of one criteria over another and 9 describes absolute preference of one over another, a definitely more important criterion. Values 2-4-6-8 are intermediate values. If the criteria A over criteria B has a weak preference the value is 3, but the value of criteria B over criteria A is reversed, as in $^1/_3 = 0.33$. (Munier 2004)

A table of criterion assessment (see Table 2) is created as an asymmetric matrix from which the criteria weights are calculated. For each row calculations are carried out (Munier 2004):

$$\prod_{i=1}^{n} C_i \qquad (1)$$

Where Π is the multiplication of all elements in a row, C is criteria, n – number of criteria (12).

The root of 12 is then calculated for each criterion (Munier 2004):

$$\sqrt[12]{\prod\nolimits_{1}^{12} C_1} \qquad (2)$$

The final weight is then calculated from these gained square roots for each criterion. In order to gain weights that comprises a total of 1 or 100 % a sum of all last calculations is needed (Munier 2004):

$$\sum_{i}^{n} \sqrt[n]{\prod_{i=1}^{n} C_i} \qquad (3)$$

Then the final weights of each criterion is calculated as a part of total weight sum, as follows (Munier 2004):

$$W_N = \frac{\sqrt[12]{\prod_1^{12} C_1}}{\sum_i^n \sqrt[n]{\prod_{i=1}^{n} C_i}} \qquad (4)$$

where W_N is weights of criteria. (Munier 2004)
The assigned weight values for each criteria category are gathered (see Fig. 1.).

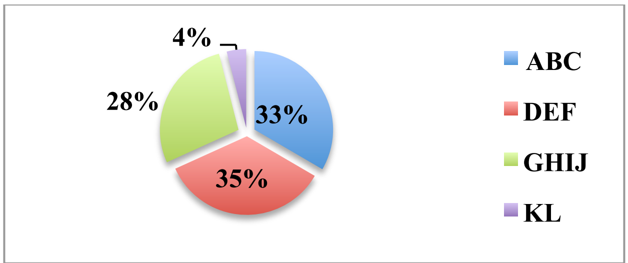

Fig. 1. Total weights of each criteria category, where ABC – economic criteria, DEF – technical criteria, GHIJ – environmental criteria and KL – social criteria.

The highest weight is assigned for criterion D – Energy return. As the evaluation is for energy production from alternative resources it is important to make sure that you actually get more energy out of the process than you spend on the process itself. The next few criteria with similarly high weights are Specific investments, Revenues and Climate change. The smallest weights assigned are for social criteria. For 3 out of 4 criteria categories the assigned weights are similar, around one third of total weights, but the social criteria are considerably less important in this case.

Sensitivity analysis was also carried out for the AHP method. As this isn't a typical calculation of few variable the sensitivity analysis was adjusted for this case. The proposed steps for carrying out sensitivity analysis for AHP methodology gained weights are described further. In order to observe sensitivity of some criteria or calculations carried out, some parts of calculation must be changed. In this case the relation values between criteria were changed (both lowered and increased). The rule of thumb is to alter the values (assigned within each pairwise comparison) in a range of – 30 % to + 30 %, in this case the relation values were altered by -3 and +3 (and the values in-between) points were possible. Where the relation value for two criteria after alteration would be 0 or lower, the relation was expressed as "1" meaning that importance of one factor over another was lowered to the point of becoming equal. Also the value of criteria relations was increased only till the value of 9 that is the highest importance of one factor over another. For the relations between criteria that were already equal (value of "1") the relation value wasn't changed, as there is no possible way of determining in favour of which factor to change it. Of course if the relation of factor A over B was increased or decreased the relation of factor B over A changed accordingly (meaning that only those values higher than 1 were changed, the smaller one changed automatically).

Even though the AHP method is mathematical it still has subjectivity of the relation value assigning. In order to diminish the subjectivity of weight assigning an expert questionnaire was carried out. The respondents are asked to assign weights for the 12 criteria chosen previously as well as for the categories themself. The average assigned weight values then are no longer impacted by the individual and are used to compare with the values gained from AHP methodology.

Experimental part

The aim of the experiments carried out is to determine the characteristics and biogas yield of locally available algae species. The experiments where carried out in several stages – experimental planning, algae parameter examination, initial biogas yield experiments, final biogas yield experiments and data analysis. (Auziņš and Januševskis, 2007)

Based on a literature review and the availability of algae species in wintertime a species of freshwater macrophyte were chosen (the experiments were carried out in February till April 2014). A preference was given to a fresh water species over a marine species, because they are easier to grow in laboratory conditions and are sooner available for collection from natural water in springtime. A species called Coontail or Hornwort (*Ceratophyllum demersum*) were chosen. It is a cosmopolite species so it's widely available in nature, as it is widely used as a plant for aquariums it's also available during wintertime when most water bodies are covered with ice. *C.demersum* grows in lakes, ponds and other water bodies with fresh water and very slow-moving water. The Coontail has no roots and is submerged, free-flowing macrophyte. (Keskinkan *et al.* 2004)

Fig. 2. Macrophyte Ceratophyllum demersum, where A – newly grown sample, B – an older sample

The initial experiment was carried out in order to understand the behaviour of samples in anaerobic digestion and to understand the impact of changeable parameters. The final experiment was carried out to understand the impact of different pre-treatment methods on biogas yield. (Auziņš and Januševskis, 2007)

The determination of total solids (TS) and volatile solids (VS) of the used algae was carried out by the US Environmental Protection Agency (EPA) issued methodology. The determination of total solids is carried out by drying the samples at 105 °C for at least 13 hours till the change of dried sample weight doesn't change more that 4 %. The determination of volatile solids is carried out by igniting the samples in a muffle furnace at 550 °C for at least 2.5 hours till the change of weight of the sample is less than 4 %. The results for TS and VS tests are presented in table 4. The biomass was shredded before using it in batch tests. (Environmental Protection...2001)

Like most of the aquatic plants the total solids content is low. The inoculum for batch experiments was sludge from waste water treatment plant in Latvia, with the TS content of 3 %. The inoculum was degased for a week to improve the batch tests.

Table 3. TS and VS values of *C. demersum* with standard deviation

	TS	σ	VS	σ
New	5.11%	0.3%	78.30%	0.9%
Old	3.70%	0.1%	82.01%	0.1%

Two different particle sizes in samples were obtained by using a hand blender. The bigger size particles were in range of about 5 to 2 mm, but the smaller size particles were smaller than 2 mm.

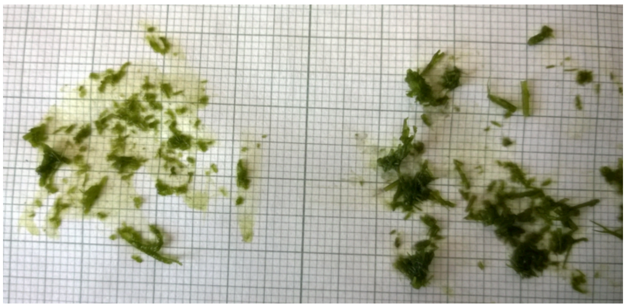

Fig. 3. Macrophyte Ceratophyllum demersum, fraction sizes on mm paper (on left side smaller fractions, on right bigger fractions)

The tests were carried out in 100 ml glass bottles. Biomass was prepared and inserted into bottles (1.2 to 2.4 g depending on the TS_{algae} : $TS_{inoculum}$; the ratio chosen was 1:10 and 1:5), distilled water (30 ml) and buffer $NaHCO_3$ (3 g per litre) was added. 20 ml of inoculum was added to each bottle. After that the bottles were flushed with CO_2, rubber caps were secured with crimping tool. After the bottle were shaken and put into incubator in 35 °C. Biogas yield from the bottles are measured with syringes filled with 5 ml of NaOH solution. Every while (at first every day, later every second day) a syringe is added to the bottle through the rubber cap and it fills up with the produced biogas. Due to different pressures in both mediums, the syringe plunger moves accordingly to the amount of gas flowing into it. As the biogas bubbles through the alkali solution the CO_2 dissolves and the amount left is almost pure CH_4. The measures are taken daily and recorded till the point that no samples are producing biogas.

The gained methane yield results from initial experiments of *C. demersum* after two weeks depending on the chosen parameters varies between 200 – 500 l CH_4 per kg VS. As the samples have not yet stopped producing biogas the results are not yet conclusive, but general conclusions can be drawn. As there is no available data of experimental or theoretical biogas or methane yields of this particular species a comparison of whether the yield from these samples was higher or lower can't be drawn. Comparing with other species is also limited due to the different chemical compositions. But overall macro-algae biogas yields are in range of 90 to 450 l CH_4 per kg VS, in which part of the samples yielded within. For the samples outside of this range (as in higher) the biogas yield can be considered as high and thus the species can potentially be considered as appropriate for biogas production in larger scale. More tests of pre-treatment methods and algae behaviour in larges scale models are needed to understand their impact on biogas yield and to understand the options with the highest possible yield. (Zamalloa *et al*. 2011)

Life Cycle Assessment

Within the overall study a life cycle assessment (LCA) modelling has been carried out with data gained from experiments. While carrying out the LCA more clarity upon the processes of chosen scenarios can be gained as well as data for the MCA itself. The end-point categories of LCA modelling done in program SimaPro are used as indicators in MCA. (Jolliet et al. 2003)

The goal of modelling in SimaPro is to compare different scenarios of algal biogas production (the same scenarios as in MCA). The comparison also including 3 benchmarking scenarios to understand whether the overall impact of such energy production means are viable (i.e., not more energy spent that gained etc.). The results should show the main differences and weak points of all scenarios. Scope – 6 algal scenarios, two other input biogas scenarios and a natural gas scenario. Algal scenarios include 3 different production phases of algae for freshwater and marine algae. The main things to take into account regarding system boundaries:

- Growth phase of scenarios of collecting biomass from natural waters is not included in the study;
- Digestate use as fertilizer included (with digestate treatment and transportation);
- The construction phase of needed plants not included;

The functional unit used in the LCA is the same as defined in MCA – 1 MWh of power produced with a CHP unit. Limitations and assumptions regarding the LCA of algal biogas production are:

- Transportation of workers not included;
- Feedstock quality assumed homogenous;
- No emissions arise from storage;
- Constant biogas yield and methane content for each type of input;
- Constant calorific value of produced biogas;
- Nutrient demand of same species algae are the same;

Used impact category is IMPACT 2002+, which is a methodology with a feasible implementation of a combined midpoint/ damage-oriented approach. The IMPACT 2002+ links all types of LCI results via 14 midpoint categories (human toxicity, respiratory effects, ionizing radiation, ozone layer depletion, photochemical oxidation, aquatic ecotoxicity, terrestrial ecotoxicity, terrestrial acidification/nutrification, aquatic acidification, aquatic eutrophication, land occupation, global warming, non-renewable energy, mineral extraction) to four damage categories (human health, ecosystem quality, climate change, resources). (Jolliet et al. 2003)

The data used in LCA comes from experiments, scientific publications and other literature, where actual data unknown assumptions are made based on the available information about said subject. Where available the data for Latvian specific conditions is used. The best-case scenarios are used, meaning the highest biogas yields, the lowest costs, the shortest distances etc.

Results and discussion

This paper proposes a methodological approach for the evaluation of the overall sustainability on the use of macro-algae as feedstock for biogas production in a Latvian context.

The aim of the study is thus focused on a holistic evaluation of the potential use of algae for biogas production using multi-criteria analysis (MCA) integrated with the main outcomes from a Life Cycle assessment (LCA). Within this holistic aspect and thanks to the proposed integrated methodology it is possible to assess an overall sustainability of the proposed algae-based scenarios.

Each analysed scenario is taking into account different algal growing, harvesting and processing phases. In specific 12 scenarios have been investigated on which 3 were devoted to a benchmarking comparison including the use of locally available biomass (i.e. manure) and the use of agricultural leftover (i.e. rapeseeds). The latest benchmarking scenario was foreseeing the use of natural gas use instead of biogas.

Authors found that the proposed methodology represent a good tool useful for carried a sustainable plan based on alternative biomass. The overall integrated methodology is implementing the benefits that each method if solely used would provide.

In fact the multi-criteria analysis is the main tool with which the results of comparison are gained. This method includes the possibility to assess the effect of a process on a set of identified criteria compared simultaneously. The result of each scenario is expressed as single number; consequently the results are presented in an aggregated way more understandable for a stake-holder-based audience.

The AHP method allows assessing the relative weight of multiple criteria. The weights are determined thanks to pairwise comparisons between the set of the criteria selected, this is expressed with a set of numbers representing the relative priority of each of the criteria based on the level of relation (weak to strong). The results from the questionnaire are included within the definition of the final weight thus decreasing the level of subjectivity. A specific questionnaire was carried out for the evaluation of the social acceptance of use of biogas from algae-based feedstock.

The LCA method implementation within the MCA analysis allows gaining a better insight in connection to the environmental criteria selected. As the analysis is carried out from cradle to grave the environmental aspects is gaining a deeper perspective than just taking into account the emissions and environmental impact in production phase. The results not only show the impact in different categories, but also show from which steps of the whole cycle they are coming from and accordingly which areas should be examined more carefully to improve their performance.

Within the overall study an LCA modelling using the SimaPro software has been implemented where an experimental part was also included. Biogas batch for the evaluation of biogas yield have been conducted in order to have a higher level of contextualization of the parameters used in the modelling part. Moreover within the same rounds of experiments have been tested the effects of different pre-treatments on the algae biomass (i.e. different size of the algae biomass within the mix with the inoculum, autoclaving, use of enzymes) in order to be further used in potential optimal scenario aiming at maximizing the biogas yield with the minimal request of external inflows within the considered scenario (i.e. energy and material inflows).

When combining the described methodologies a holistic evaluation tool is gained matching the criteria on being comprehensive, decreasing the level of subjectivity, an including experimental data. Within this perspective it is possible to understand - and consequently acting on – the weak points that are decreasing the level of sustainability for each scenarios.

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EIROPAS SOCIĀLAIS FONDS

EIROPAS SAVIENĪBA

IEGULDĪJUMS TAVĀ NĀKOTNĒ

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References

Auziņš J., Januševskis A. 2007. Eksperimentu plānošana un analīze (Eksperimental planning and analysis). Riga Technical univeristy press. Riga. 255 p.

Biogas in Latvia [online]. 2012 [cited 23 January 2014] Available from internet:< http://www.lvportals.lv/likumi-prakse.php?id=251397 >.

Debowski M., Zielinski M., Grala A., Dudek M. 2013. Algae biomass as an alternative substrate in biogas production technologies – Review. Renewable and Sustainable Energy Reviews. 27. 596-604. p

Europe 2020. 2010. A strategy for smart, sustainable and inclusive growth. European Commission. 24 p.

Environmental policy strategy 2009-2015. 2009. Cabinet order 517. Latvijas Vēstnesis 122 (4108). 53 pages

Environmental Protection Agency, Office of Water, Office of Science and Technology, Engineering and Analysis Division. 2001. METHOD 1684: Total, Fixed, and Volatile Solids in Water, Solids, and Biosolids. US EPA, 13 p.

Jolliet O., Margni M., Charles R., Humbert S., Payet J., Rebitzer G., Rosenbaum R. 2003. IMPACT 2002+: A New Life Cycle Impact Assessment Methodology. Ecomed publishers. 324-330.

Keskinkan O., Goksu M. Z. L., Basibuyuk M., Forster C.F. 2004. Heavy metal adsorbtion properties of a submerged aquatic plant (Ceratophyllum demersum). Bioresource Technology 92 (2), 197 – 200 p.

Munier N. 2004. Multicriteria Environmental assessment: A practical guide. Kluwer Academic Publishers, USA. 322 p.

Sustainable Energy Ireland. 2009. A review of the potential of marine algae as a source of biofuel in Ireland. Dublin, Ireland. 88 p.

Zamalloa C., Vulsteke E., Albrecht J., Verstraete. 2011. The techno-economic potential of renewable energy through the anaerobic digestion of microalgae. Bioresource Technology. 102. 1149-1158.

NO MAKROAĻĢĒM IEGŪTAS BIOGĀZES NOVĒRTĒŠANA AR MULTI-KRITĒRIJU ANALĪZI. METODOLOĢIJA

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Darba mērķis ir apakstīt biogāzes iegūšanas scenāriju novērtējumā izmantoto metadoloģiju. Biogāzes iegūšanas scenāriji apraksta dažādus paņēmienus tās iegūšanai no makroaļģēm Latvijas apstākļos. Scenāriju novērtējuma analīze tiek veikta ar Multi-kritēriju analīzi, kuras veiksmīgai īstenošanai tiek izmantotas arī citas metodes – Analītiskā hierarhijas procesa metode kritēriju svaru noteikšanai, ekspertu un sabiedrības aptaujas, ekperimentu veikšana, dzīves cikla analīze un citas. Šo metožu kombinācija ir tēmēta uz to, lai samazinātu jebkādu subjektivitāti, kas rodas eksperta pieņēmumu rezultātā, kā arī lai iegūtu skaidru gala rezultātu, kurš no scenārijiem ir vislabākais un piemērotākais tieši Latvijas apstākļiem. Analīzes veikšanai ir nepieciešami daudz izejas dati, no kuriem lielākā daļa ir balstīta uz reāliem mērījumiem vai objektiem nevis teorētiskiem aprēķiniem.

Atslēgas vārdi: Makroaļģes, biogāze, dzīves cikla analīze, multi-kritēriju analīze, Analītiskais hierarijas process.