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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.

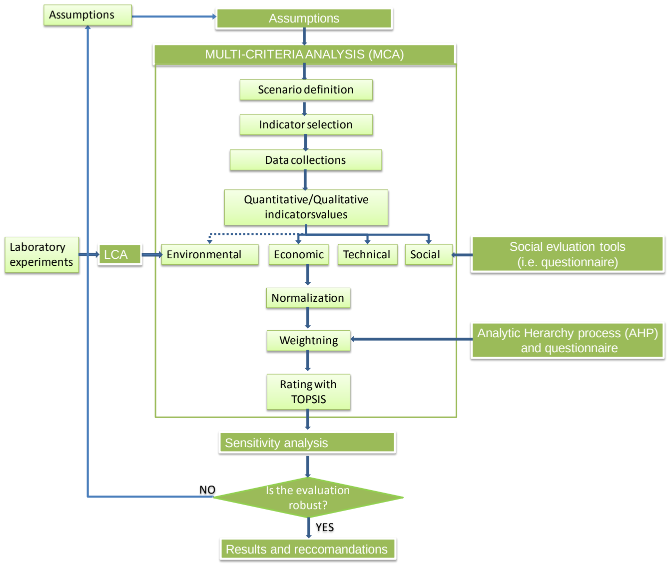

Fig. 1. Methodology concept for the sustainability analysis.

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),

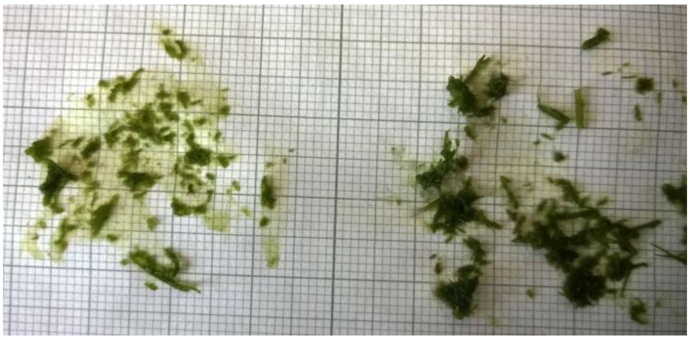

Fig. 2. Macrophyte *Ceratophyllumdemersum*, fraction sizes on mm paper (on left side smaller fractions, on right bigger fractions).

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.

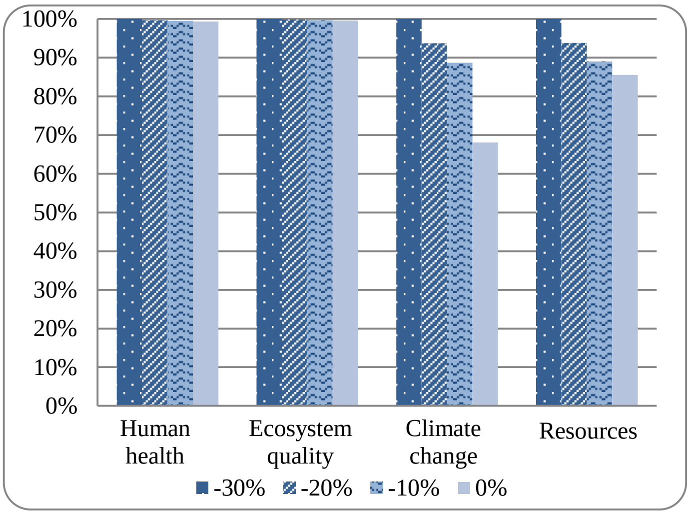

Fig. 3. Sensitivity analysis of alternative ON-F by changing biogas yield.

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.).

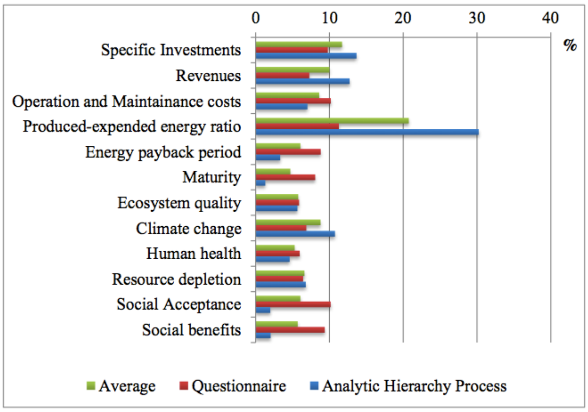

Fig. 4. Criteria weight values from Analytic Hierarchy Process methodology, expert questionnaires and the final weights.

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”).

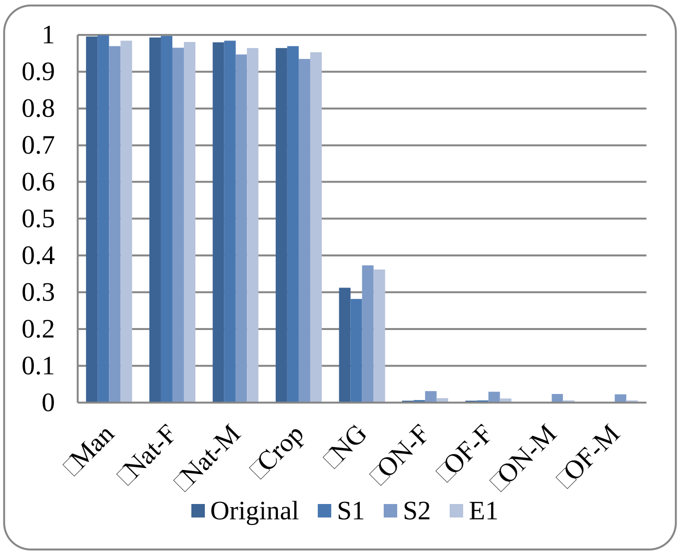

Fig. 5. Sensitivity analysis of weights within TOPSIS, where S1 – society point of view, S2 – stakeholders point of view, E1 – entrepreneurs point of view.

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

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