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Environmental life cycle assessment (LCA) of seaweed production at Queen's University Belfast

Report WP2A11.06

Energetic Algae ('EnAlgae')

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WP2A11.06 − Environmental life cycle assessment (LCA) of seaweed production at QUB

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1 Introduction

1.1 Background

The work presented in this report was undertaken within the context of the EnAlgae project, which is a 4-year Strategic Initiative of the INTERREG IVB North West Europe (NWE) Programme. The aim is to develop sustainable pathways for algal bioenergy, integrated with greenhouse gases (GHG) mitigation and bioremediation. A network of 9 pilot sites is distributed across NWE:

Macroalgae pilot
1. National University of Ireland, Galway (Ireland)
2. Queen's University Belfast (United Kingdom)
3. Centre d'Etude et de Valorisation des Algues (France)

Microalgae pilot
4. Swansea University (United Kingdom)
5. Hochschule für Technik und Wirtschaft des Saarlandes (Germany)
6. Ghent University, Campus Kortrijk (Belgium)
7. Wageningen UR / ACRRES (Netherlands)
8. Plymouth Marine Laboratory (United Kingdom)
9. InCrops Enterprise Hub (United Kingdom)

Although algae are claimed to be a sustainable resource, there has been an increasing awareness of the possible impact of algae production on the natural environment. Life cycle assessment (LCA) can be used as a tool to quantify all relevant emissions and resources consumed, as well as the related environmental impacts and resource depletion associated with a product's life cycle. LCA takes into account the entire lifecycle: from the extraction of resources, through production, use, recycling, to disposal of the remaining waste (Rebitzer et al., 2004). LCA along a product`s production chain allows for identifying opportunities to improve the environmental footprint of products at different phases of their life cycle. It can be used for decision makers in industry and (non-) governmental organizations.

1.2 Aim of the study

At Queen`s University Belfast (QUB) seaweed (macroalgae) experiments are carried out to determine physiological qualities of different algae species under different growth conditions, e.g. different production settings. The approach of this pilot facility is to set up a custom designed hatchery for macroalgae, which will then be transferred to longlines in Strangford Lough for onward growth. The long term aim is to see if it is possible to grow sufficient biomass of good enough quality to be used for the production of biofuels.

The pilot site of Queen's University of Belfast for the production of macroalgae, specifically the kelp species *Laminaria digitata, Saccharina latissima* and *Alaria esculenta* is located on the Ards Peninsula, with the hatchery at Queen's Marine Laboratory in Portaferry, and the at-sea ongrowing site in Strangford Lough.

Within the project context, different settings were tested and compared according to different process parameters. Scientists at QUB focused on exploring ways to grow, harvest and process the seaweed biomass. The data was obtained for the cultivation period of 2012/2013 for one trial. According to the project scope, final biomass application was defined as bioenergy production.

As there was no downstream processing data available, we decided to model the environmental impact of the combustion of algae-based biogas based on literature data. In this study we investigated the environmental burdens of algae-based biogas compared to the fossil reference of natural gas by conducting a LCA in a cradle-to-gate approach.

2 LCA methodology

In this study, the International Organization for Standardization (ISO) frameworks 14040 and 14044 were followed to assess the environmental sustainability of the nine algae production systems mentioned previously (International Organization for Standardization, 2006). The first phase of an LCA study consists of defining the goal and scope of the study, followed by a thorough inventory analysis, a life cycle impact assessment (LCIA) step and an interpretation phase (see Figure ***1***).

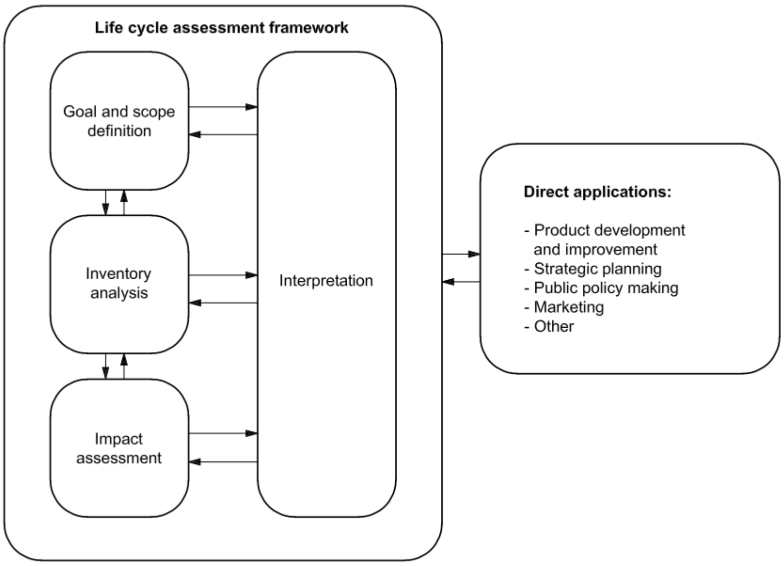

Figure 1: *LCA as a 4-phase process according to the ISO standards 14040: goal and scope definition, inventory analysis, impact assessment and interpretation (International Organization for Standardization, 2006).*

To evaluate the environmental burdens associated with algae production, two LCIA methods have been selected: the ReCiPe 1.10 hierarchical midpoint method (Goedkoop et al., 2013) and the Cumulative Exergy Extraction from the Natural Environment (CEENE) method (Dewulf et al., 2007).

The ReCiPe 2010 method is the result of a consensus of LCA experts willing to harmonize the CML (Centrum voor Milieukunde) midpoint and the Eco-Indicator 99 end-point methodologies. The work conducted to reach this goal led to the ReCiPe midpoint and endpoint methods, both widely recognized by LCA experts. The ReCiPe 2010 midpoint method comprises characterisation factors for 18 impact categories: climate change (CC), ozone depletion (OD), terrestrial acidification (TA), freshwater eutrophication (FE), marine eutrophication (ME), human toxicity (HT), photochemical oxidant formation (POF), particulate matter formation (PMF), terrestrial ecotoxicity (TET), freshwater ecotoxicity (FET), marine ecotoxicity (MET), ionising radiation (IR), agricultural land occupation (ALO), urban land occupation (ULO), natural land transformation (NLT), water depletion (WD), mineral resource depletion (MRD), and fossil fuel depletion (FD). Within the ReCiPe method uncertainties are incorporated in the form of different cultural perspectives: individualist (I), hierarchist (H) and egalitarian (E).

In this report, the hierarchist perspective was chosen, which is a consensus model between short-term (individualist) and long-term (egalitarian) perspectives and is considered as the default model of the ReCiPe method.

On endpoint level, the midpoints are aggregated and summarized to three categories: damage to ecosystem diversity, damage to human health and damage of resource availability (see *Table S 3*).

Additionally, the CEENE method was selected to account for the consumption of natural resources. It is based on thermodynamics through quantification of resources by their exergy content. Exergy is the maximal amount of work a system can deliver in equilibrium with its environment via a reversible process and provides an indication of the quality and quantity of the resource (Wall, 1977). In this way, all resources can be expressed in the same unit; this in turn facilitates interpretation and comparison of results (Dewulf et al., 2008). The resources are divided into eight categories: renewable resources, fossil fuels, nuclear energy, metal ores, minerals, water resources, land occupation and atmospheric resources (Dewulf et al., 2007). Therefore, the CEENE method is consistent by accounting for both non-energetic resources as well as land use (Dewulf et al., 2007). An extended version of the CEENE method is applied in this study which provides an improved site-specific approach to assess land resources (Alvarenga et al., 2013) and enables accounting for marine resources for different biogeographic ecoregions (Taelman et al., 2014).

For this LCA study the commercial software Umberto NXT LCA has been applied to model the production chain and get a complete inventory dataset. The impact assessment was conducted using MS Excel.

3 Scope of the study

The seaweed ongrowing pilot facilities of Queen`s University Belfast (QUB) are located in northern Ireland, in Strangford Lough, west of Jackdaw Island. The site is north/south oriented, with 4 x 100m longlines running parallel to each other, and along the flow of the water. The area is tidal, with about 4m in tidal range, a low current of about 40 cm/s, and in the considered year quite exposed to wind. The water depth varies between 3-7 m at mid tide. The hatchery is located close to the shore in a lab building. Here the growth cabinet and nursery tanks are situated. In the growth cabinet, non-reproductive gametophyte cultures from good quality adult fertile material are stored to guarantee stock cultures and allow flexibility of seeding time. The building is equipped with air conditioning and artificial lighting (for the whole year in the cabinet, and only during tank cultivation times for the room). Consequently high energy inputs were assumed, which are not reasonable to apply in larger scale but only for experimental purposes.

Saccharina latissima and *Laminaria digitata* were cultivated in the cultivation period 2012/13 on two longlines each. As *Laminaria* did not grow very well, average yield data obtained from the two longlines for *Saccharina* were used in the LCA model. The site was deployed in December and harvested seven months later in July. Plant samples were taken regularly for biological analysis. Main materials and their production were considered in the system, transport and manufacturing processes were not taken into account. Storage processes resulting from production lacks were not considered, downstream processes were modelled on a one year baseline.

Four main production steps built up the production chain (see Figure 2):

- hatchery
- cultivation
- harvesting/macerating and
- biogas production/combustion.

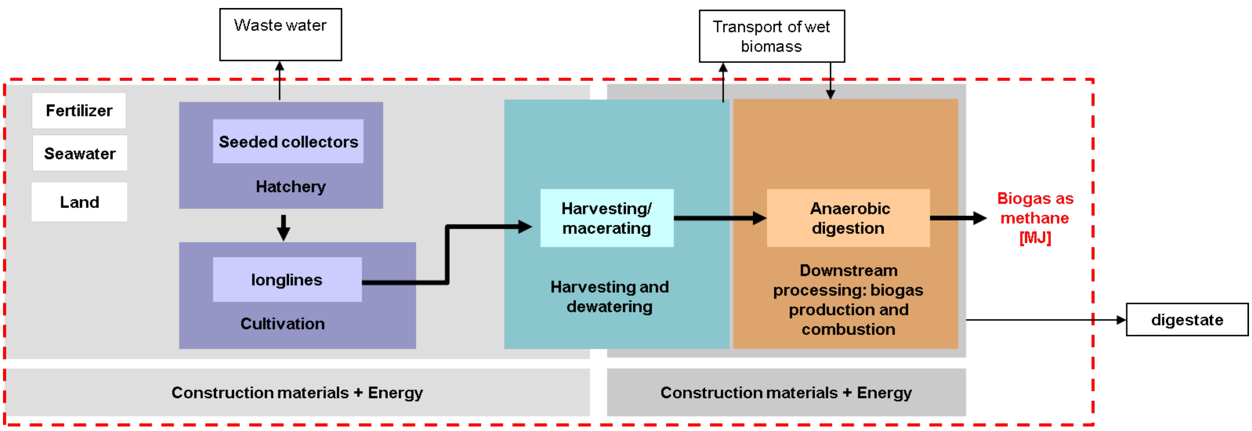

Figure 2: *System boundary and process flows included in the LCA: Processes supplied by experimental (lab) data and numbers are highlighted in light grey; processes supplied by database data and literature are highlighted in dark grey. The system boundary is displayed as red-dotted line.*

Table 1 summarizes the main cultivation parameters. First, the seeded collectors were prepared. The gametophyte cultures are induced to become reproductive and develop into sporophyte cultures in a growth cabinet under cool temperature and regulated light conditions. Twelve weeks before deployment, the plantlets were prepared. Plastic collectors were wrapped with cultivation string and sprayed with the sporophyte cultures. These collectors were transferred in 500 L HDPE tanks, being mixed by air gassing. The hatchery system is equipped with air conditioning and artificial lighting to maintain optimal growth conditions.

The culture medium was exchanged twice a week and fresh nutrients were provided. Twelve seeded collectors were obtained (three per longline) and transferred to the open sea system by boat. Four x 100m long longlines were installed. After deployment, the longlines were checked every two weeks and monthly biomass samples were taken. A small boat was used for the ca. 5 km cruise to the cultivation site. In total a yearly production of 5,316 kg wet biomass was estimated resulting from about 13 kg/m longline. Depending on density deployed lines, in this setting an areal yield of 8.95 t/ha/a was achieved.
Just small amounts of biomas were needed to be analyzed; therefore the vast majority was harvested in the end.

For the LCA total biomass was assumed to be chopped by a macerator unit. Afterwards the wet biomass was modelled to be digested and processed to biogas and burned in a cogeneration unit.
Main materials for construction process e.g. the hatchery, as well as energy inputs, e.g. for lighting the culture, representing real experimental values, were included in the system.

Table 1: *Main parameters for cultivation.*

Paramter	Description
Cultivation system	Single header longlines
Nutrient source (hatchery)	Chemical fertilizer
Number of seeders	12 à 40 m seeded string
Total biomass yield	5,316 kg (4 x 100 m longlines)
Areal yield	8.95 t/ha/a

In this LCA study the environmental burdens of the production of biogas were analyzed. The functional unit was chosen as "*1 MJ of burned algae-based biogas*". Impact results were presented in comparison to those related to the fossil reference, *1 MJ of burned natural gas*.

Biogas production and combustion were modelled to allow for a direct comparison to the other pilot case studies.

4 Life cycle inventory

Main data for the life-cycle inventory was collated, using a standardized questionnaire based on MS Excel. In close contact to the pilot operator, the spreadsheet was adapted to the system. To get an impression of the reactor built up and to ensure the same understanding of processes a guided facility and site visit was organized. Additionally, personal interviews as well as skype calls were useful to gather missing data. The considered system was small scale and focused on seaweed production. Data could be provided for the materials of the hatchery equipment and the cultivation as well as process energy used, only. Additionally, amounts and specifications for fertilizer and cleaning substances could be provided according to the experimental setup translated to a one-year baseline. Downstream processes were simply modelled on literature review and personal communication.

For the model, the main materials could be recalled from the ecoinvent 2.2 database. Processes were modelled using the following assumptions:

- **Hatchery**
  - The seeded collectors were produced, using about 1,120 kWh for lighting plus 242 kWh air pumping and 2,400 kWh for air conditioning
  - Material specification/amount used for equipment were obtained from the pilot operator and validated by literature
  - f/2 medium concentrations (22.5 g N, 1.5 g/L PO_4^-).
- **open sea cultivation**
  - During cultivation energy consumption is related to the vessel use and accounts for 1 L diesel; boat shares ¼ (according to ecoinvent v. 2.2: consumption of vessel $9.39x10^{-3}$ kg/tkm were assumed)
  - Material specification/amount used for the ropes, anchorage as well as buoys were obtained from the pilot operator and supplemented by literature data, and assumptions of the “economic model” by van Dijk and van der Schoot (2015)
  - For maintenance and sampling a smaller boat was used consuming about 35 L diesel (according to Aitken et al., 2014; a consumption of observation boat 0.75 L/km → distance to site 5 km one way, observation twice per month, cruise on-site 1 km was assumed).
- **Biomass harvesting/macerating**
  - For biomass harvesting the same vessel (¾) was used as for deployment
  - A RotaCut Grinder RXC 58 was modelled with a weight of 610 kg. Material shares were assumed to be 70% chromium steel, 20% steel converter, 10% HDPE with typical lifetimes. One unit was modelled independent of the produced biomass amount; 6 hours of grinding were assumed. The device was scaled to fulfill 3,600 operating hours per year
  - Electricity consumption was assumed to be 45 kWh (7.5 KW capacity).
- **Biogas production/combustion**
  - Materials as well as operation electricity demands for the biogas plant (100 kW baseline) were obtained from Weiß (2009) and scaled according to the electric plant capacity of 0.34 kW/kW output (data baseline: Rösch et al., 2009) and 8,500 operating hours/a
  - The biomethane recovery of *Saccharina latissima* was experimentally derived to be 0.02 m^3/kg (calculated according to personal communication by Peter Schiener and Karen Mooney-McAuley), the LHV of biomethane was assumed to be 35.78 MJ/m^3 obtained from experimental data corresponding to Collet et al. (2011)
  - Biogas was modelled as single output of the system without any losses; utilization of digestate was not considered
  - The combustion process was modelled equivalent to the fossil reference.

5 Results and Discussion

In the following paragraphs the results of the LCA are presented and discussed. The results are referring to the cultivation period of 2012/13.

Production stopped at the achieved biomass, downstream processes were modelled on literature baseline and common sense. Biogas production and combustion was modelled to allow for a direct comparison to the other pilot case studies.

5.1 ReCiPe

In the following paragraph the results of selected ReCiPe midpoints are presented. Most relevant impact categories have been graphically displayed; a table of the results for all 18 impact categories can be found in the Appendix (see *Table S 1*). A pre-selection of midpoint categories was carried out by calculating the endpoint results referring to the life cycle phases as well as the contribution by midpoint category.

Separated in the four process phases the endpoint results indicated that mainly the first two phases of the hatchery and the open sea cultivation phase made up the overall impact on the three dimensions damage to ecosystem diversity, damage to human health and damage of resource availability (see *Figure S 1*-S 3).

Climate change and fossil depletion are highly interconnected and represent the highest shares in the three endpoint categories. Therefore, those two midpoint categories were examined in detail according to their process contribution. Also, mineral resource depletion represented a huge share in the resource availability endpoint and was specifically investigated. Moreover, particulate matter formation was considered to be important for further detailed examination since it represented the second main contributor in damage to human health. Also natural land transformation contributed to a large extent in the category of ecosystem damage and was therefore separately displayed.

5.1.1 Climate change

The impact category climate change is well-known as it affects the environment on different levels (Goedkoop et al., 2013). Not only human health but also the ecosystem is concerned; therefore a detailed investigation was carried out according to the contribution per life cycle phase.

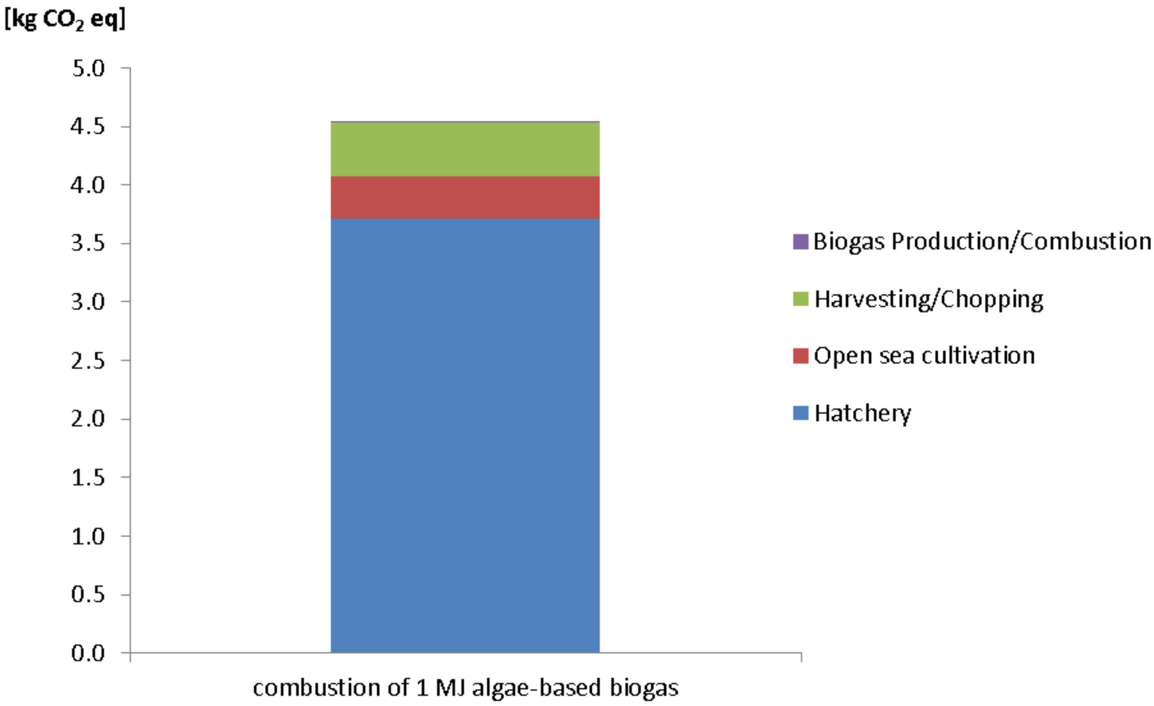

Figure 3: *Contribution of life-cycle phases to climate change for 1 MJ of burned algae-based biogas.*

Figure 3 shows the overall results for climate change expressed in CO_2 equivalents (eq). In the considered setting the hatchery phase represented the highest share (81.6 %) in total CO_2 eq. In total 4.54 CO_2 eq resulted per MJ algae-based biogas burned. The open sea cultivation made up 0.37 kg CO_2 eq (8.1 %). The emissions referring to the harvesting process and the mechanical pretreatment of macerating the wet biomass accounted for 0.46 kg CO_2 eq (10.1 %). The CO_2 eq associated with the anaerobic digestion process were negligible (0.2 %). As the CO_2 eq are related to the consumption (combustion) of fossil fuels for power generation, it could be proved that in this setting the hatchery phase is the most energy intense production step, although improvements might be expected if the equipment use is optimized and e.g. more batches per year could be achieved. In comparison, the CO_2 eq related to the combustion of 1 MJ natural gas totals up to 0.06 kg.

Aggregated process contribution to climate change

In the following the aggregated contribution was investigated and two main process types were distinguished. Processes contributing less than one percent were not displayed (e.g. operating supplies, biogas combustion).

- Electricity, e.g. for pumping and lighting, diesel consumption
- Construction materials, like steel and plastics for the boat and tanks but also the materials for the seeders and ropes

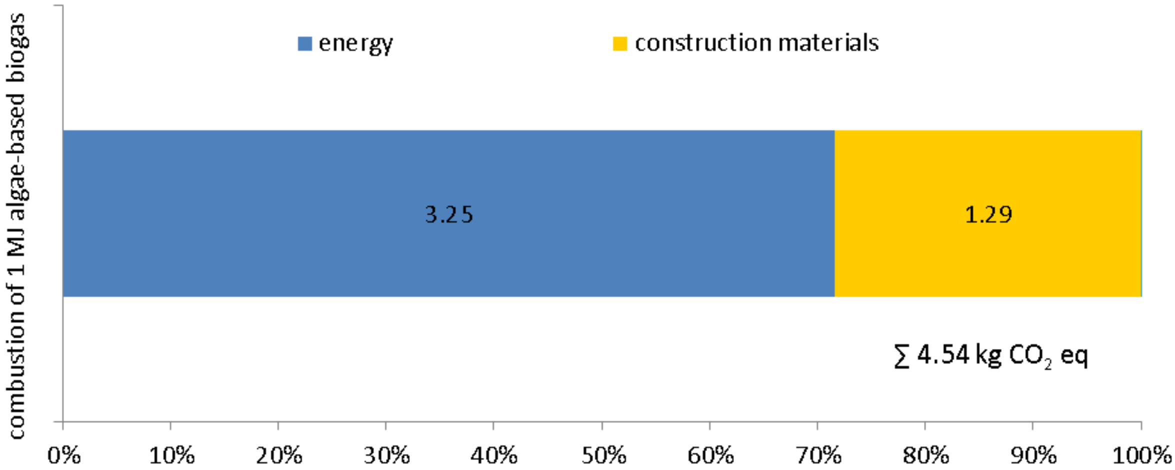

Figure 4: *Aggregated contribution of processes to climate change for 1 MJ of burned algae-based biogas.*

As can be seen from Figure 4, the main contribution to CO_2 eq is related to the consumption of energy. More than 99 % of this is related to direct electricity inputs. A British standard electricity mix was applied, which is predominantly composed of fossils like hard coal and natural gas (75 %) but also nuclear power generation (19.6 %) resulting in a carbon footprint of 0.68 kg CO_2 eq per kWh (Frischknecht et al., 2007). Direct energy inputs account for 72 % of the total CO_2 eq, through the use of the construction materials a share of 28 % of the total CO_2 eq was calculated.

Impact contribution to climate change resulting from single material use

As material usage contributed to a noticeable amount of CO_2 eq the materials were separately highlighted according to their shares.

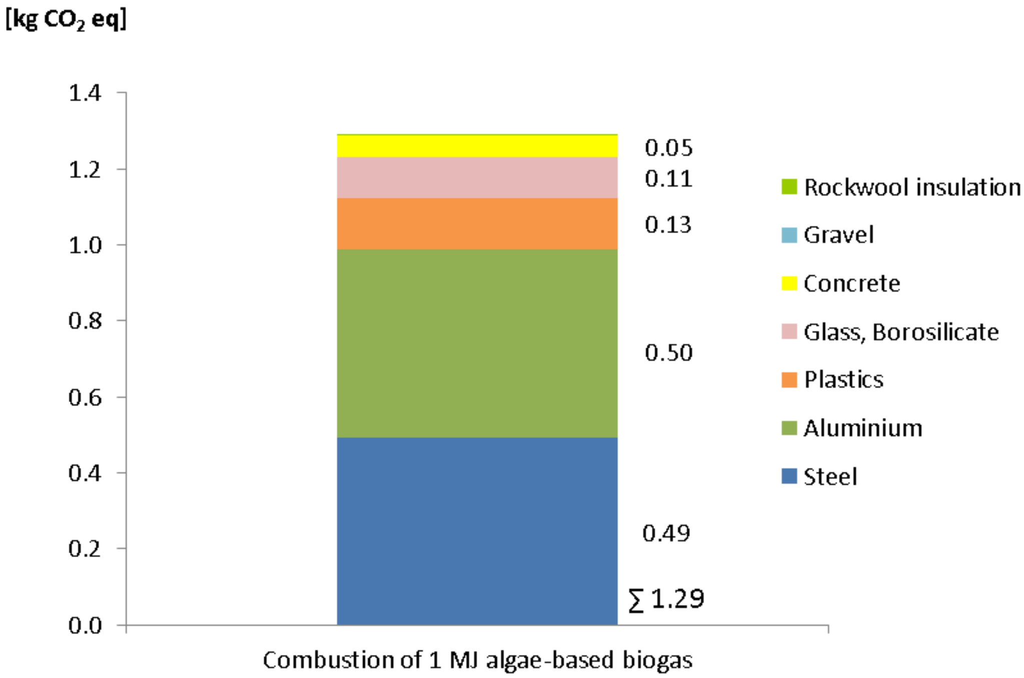

Figure 5: *Contribution to climate change for the process group construction materials, displayed in detail.*

If electricity was not considered, the construction materials made up a significant contribution to climate change. Within this process group, it could be noticed that aluminium made up the highest share with 39 %, followed by steel with 38 %. Relatively low impact could be calculated for plastics (e.g. the nursery tanks and the collectors) with 10 % and for glass (e.g. the fluorescent tubing and bulbs) with 9 %. The impact resulting from the anaerobic digestion facility (concrete, gravel and rockwool insulation) represented just a marginal fraction.

5.1.2 Fossil fuel depletion

The following section is dedicated to the presentation of the results for the impact category fossil fuel depletion (FD). Since fossil depletion is mainly related to the consumption of fossil energy (carriers) like coal, which is substantially included in the British electricity mix, it could be proved that the results strictly follow the ones of climate change.

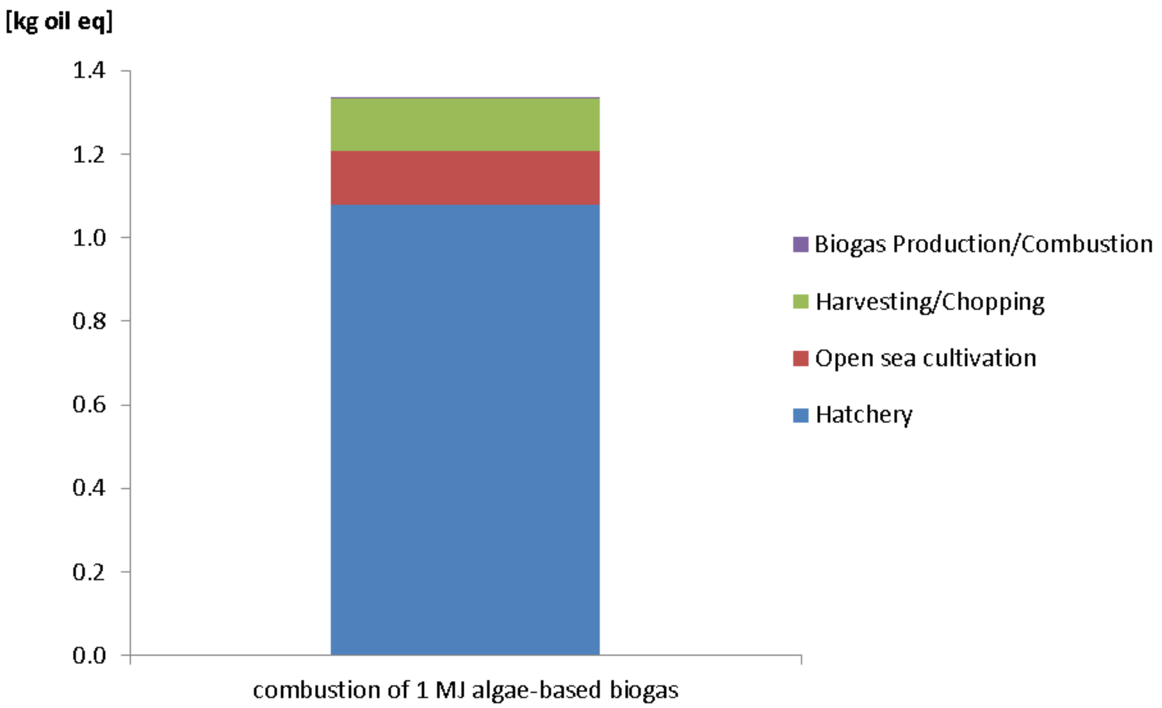

Figure 6: *Contribution of life-cycle phases to fossil fuel depletion for 1 MJ of burned algae-based biogas.*

Figure 6 shows the overall result for fossil fuel depletion expressed in kg of oil equivalents (eq). The ratio of the absolute values highly corresponds to that of the results for climate change. It was shown that most oil eq are consumed during hatchery phase. In this phase, the oil eq comprise 80.7 % of the total consumption per MJ burned algae-based biogas. In accordance to the results of climate change, the two phases of open sea cultivation and harvesting/chopping represent about 10 % each of portion of the total oil eq. During the life cycle of the fossil reference system (production and combustion of 1 MJ natural gas) only 0.02 kg oil eq are used.

Aggregated process contribution to fossil fuel depletion

The results show that the fossil fuel depletion shows the same pattern as the impacts on climate change also regarding the contribution of the different inputs to the impacts. In total we could derive that electricity contributes to about 70 % of overall fossil fuel depletion in the base scenario (see *Figure 7*). The remaining 30 % are almost completely covered by the construction materials impact. In a next step we further detailed their share.

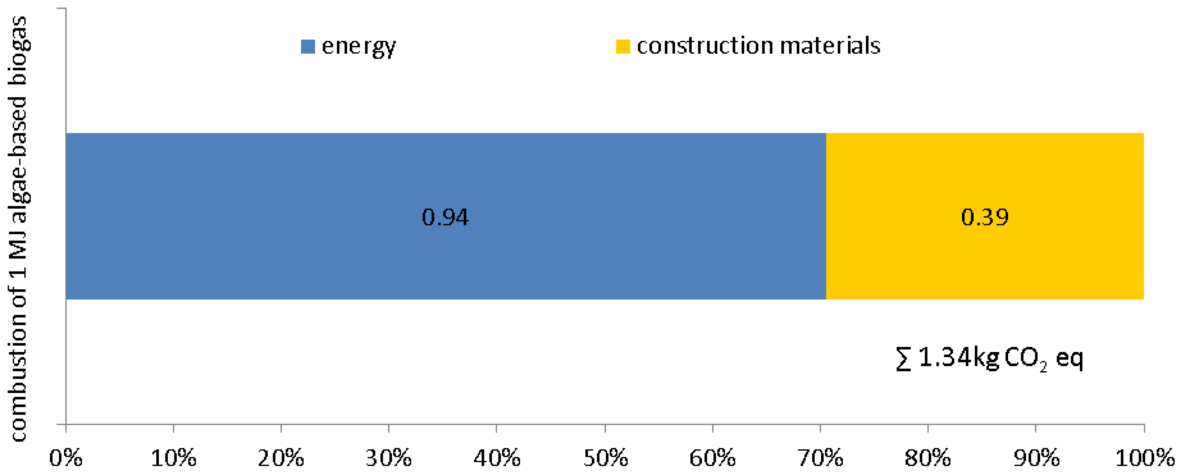

Figure 7: *Aggregated contribution of processes to fossil fuel depletion for 1 MJ of burned algae-based biogas.*

Impact contribution to fossil fuel depletion resulting from single material use

Single material processes were analyzed according to their contribution to this impact category if energy inputs are not taken into account. As already mentioned 30 % of the fossil depletion impact is related to the construction materials (see Figure 7). All these materials were separately expressed.

It could be demonstrated that plastics contributed 20 % for fossil fuel depletion, which is double the contribution to climate change. Plastics which were used for the nursery tanks and the collectors totaled 0.08 kg oil eq. For these materials fossil fuels are used, either directly as carbon source or for production processes e.g. melting. Therefore, the contribution of plastics using oil eg is significant among the materials process group. However, again aluminium and steel represented the highest shares. For those two materials an overall contribution to fossil depletion of 0.28 kg oil eq could be derived, giving a total share of almost 72 %.

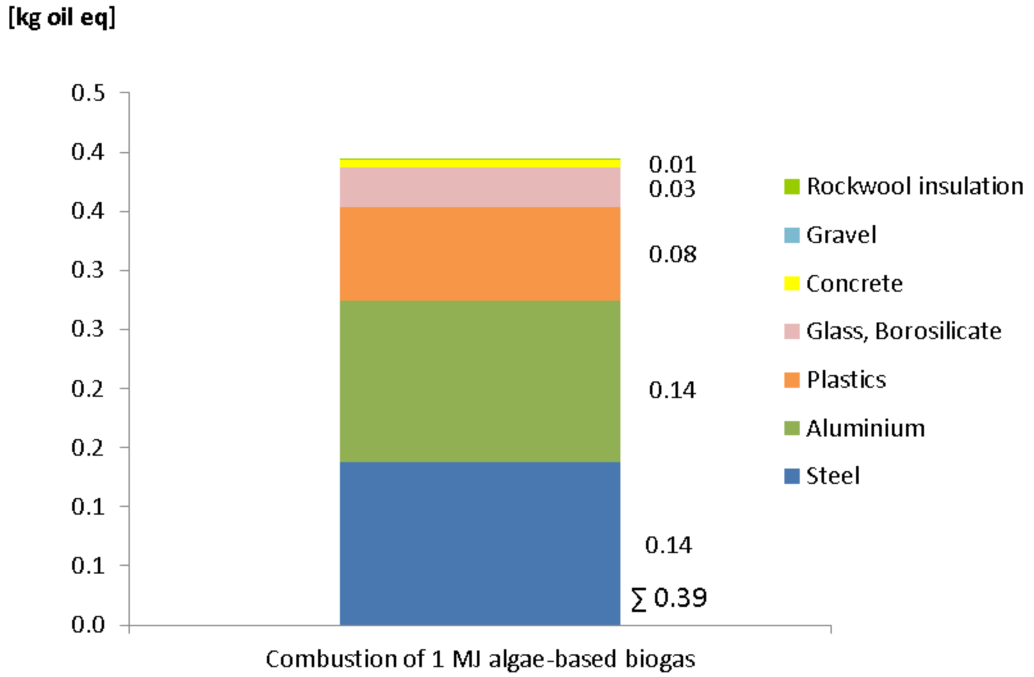

Figure 8: *Contribution to fossil fuel depletion for the process group construction materials, displayed in detail.*

5.1.3 Mineral resource depletion

Mineral resources are extracted from deposits via mining processes as they are feedstock for industrial life with steel as one of the most important materials used. All of the machinery used is at least partially composed of any metal product.

Every environmental LCA of a new technology, like algae production, should consider this impact category as it is highly dependent on equipment and machinery used.

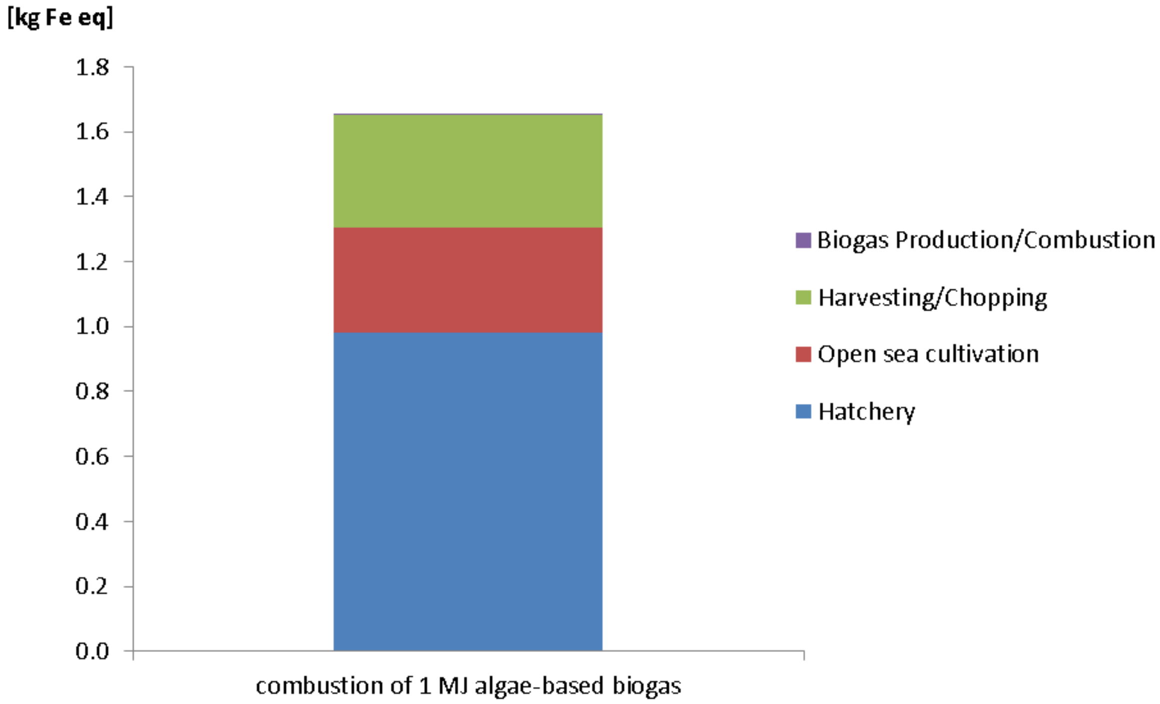

Figure 9: *Contribution of life-cycle phases to mineral resource depletion for 1 MJ of burned algae-based biogas.*

Figure 9 shows the overall result for mineral resource depletion (MRD) expressed in kg of Fe equivalents (eq). As the hatchery phase is the most intense phase concerning machinery and equipment use across the whole production chain, it was proved that most Fe eq were related to this production step (59 %). The following two phases showed similar contribution to the mineral resource depletion impact: 20 %: open sea cultivation; 21 % harvesting/chopping. The phase of biogas production/combustion was negligible.

The combustion of 1 MJ of natural gas comes along with 0.06 g Fe eq depleted.

Aggregated process contribution to mineral resource depletion

The results show that the impact category mineral resource depletion is driven by the construction materials used over the life cycle (see Figure 10). Ninety-two percent of the total Ge eq depleted are related to the direct material input. Energy consumption could be identified to have a contribution of 8 %, due to upstream processes and the infrastructure use; the footprint of energy concerning the Fe eq depleted is visible here.

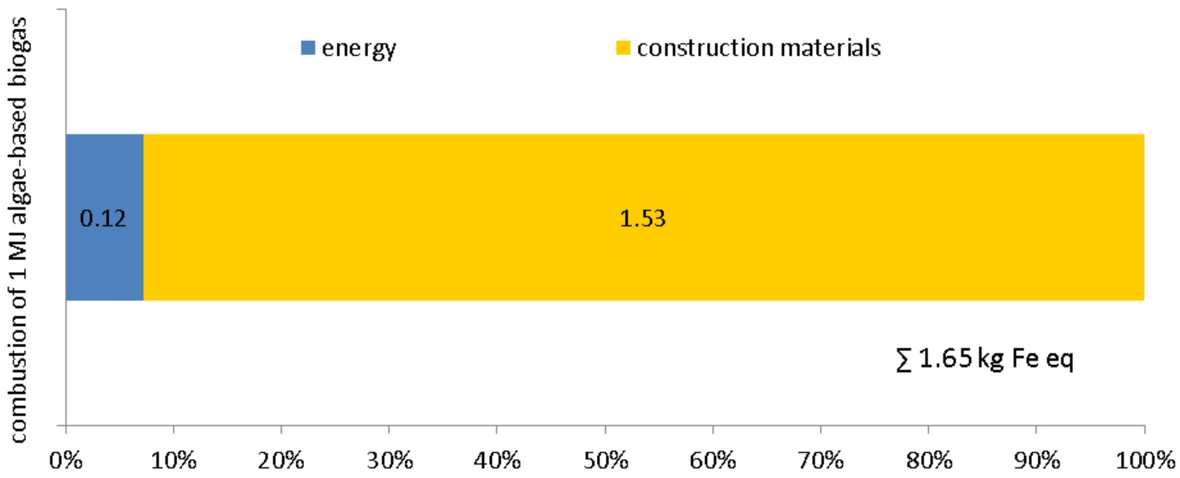

Figure 10: *Aggregated contribution of processes to mineral resource depletion for 1 MJ of burned algae-based biogas.*

Impact contribution to mineral resource depletion resulting from single material use

Single relevant materials were identified and depicted, electricity was cut off. The results can be seen in

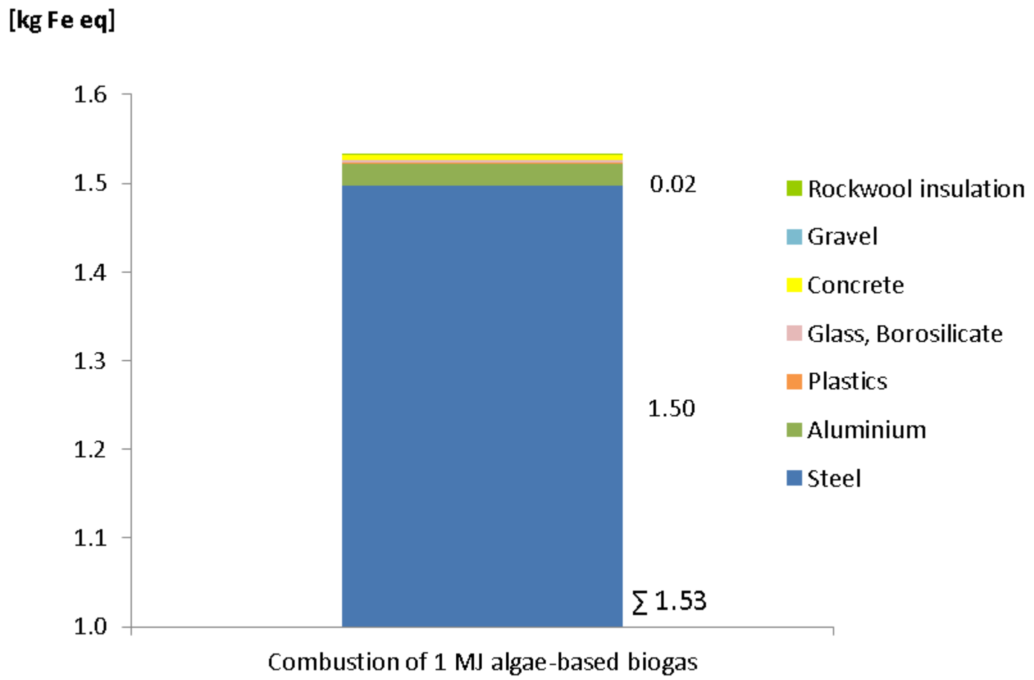

Figure *11*. Chromium steel is the most important input with a share of 98% of total value of 1.53 kg Fe eq mineral resource depletion category. Other contributors like plastics or glass were negligible. Processes that consume a lot of iron, like steel production, amplify the impact of this category. Aluminium i.e used for the small observation boat contributed with only 1.6 % and 0.02 kg Fe eq.

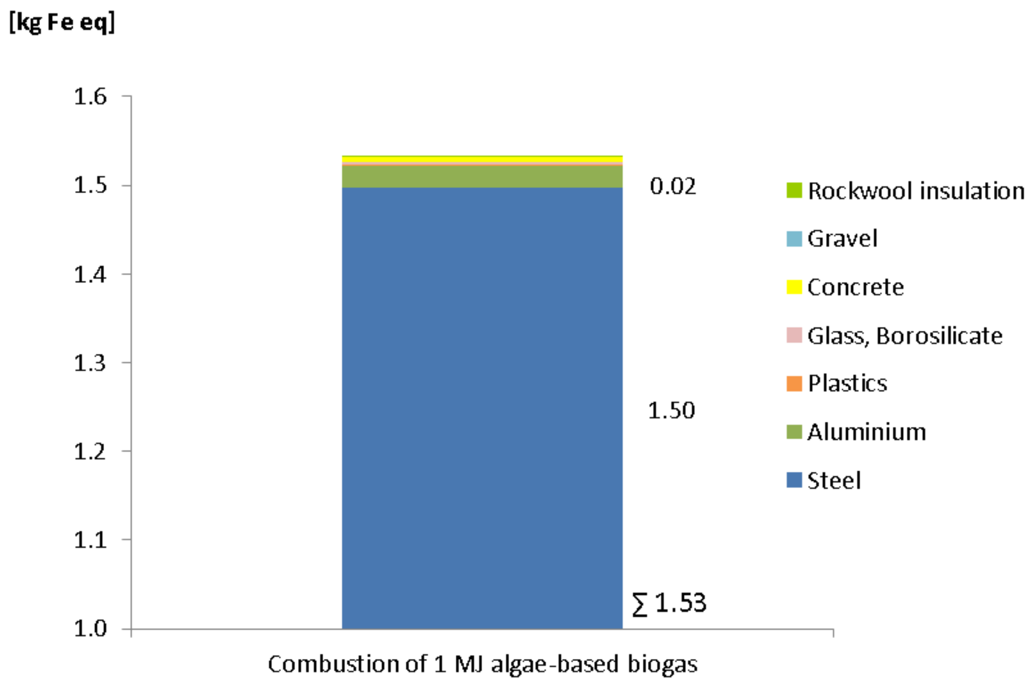

Figure 11: *Contribution to mineral resource depletion for the process group construction materials, displayed in detail.*

5.1.4 Particulate matter formation

Particulate matter formation was investigated in detail as it has a significant contribution (20 %), on the human health endpoint level. It describes the potential of harming particles released into the environment. It is expressed in kg PM10 equivalents (eq). The contribution of life-cycle phases is displayed in Figure 12.

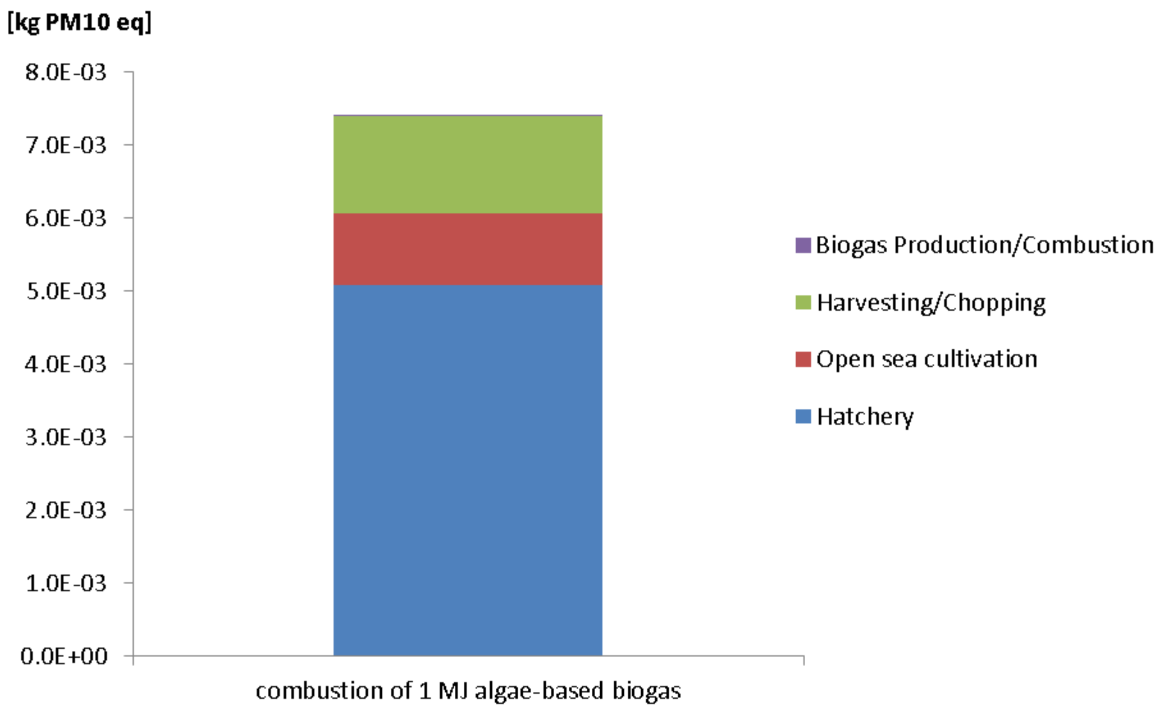

***Figure 12:** Contribution of life-cycle phases to particulate matter formation for 1 MJ of burned algae-based biogas.*

The hatchery phase could be determined to be the main contributor to particulate matter formation. The PM10 eq are mainly related to the burning of fossil. As hatchery phase including the incubation and seeded string production was the most energy intense phase, in total 69 % of the PM10 eq of 7.4E-03 are related to this seaweed production step.

The second main contribution is related to the harvesting/chopping step. This production step led to 1.3E-03 meaning 18 %. Open sea cultivation contributed to 13 % (9.81E-04 kg PM10 eq). Biogas production and combustion had a share of less than 1 % (1.3E-05 kg PM10 eq). In comparison to the fossil reference, which shows a value of 5.2E-06 kg PM10 eq for 1 MJ of burned natural gas, the algae based biogas performs worse.

Aggregated process contribution to particulate matter formation

Similar to the above described impact categories, the particulate matter formation impact was displayed according to the shares of clustered process contributions of energy inputs and construction materials over the life cycle, see *Figure 13*.

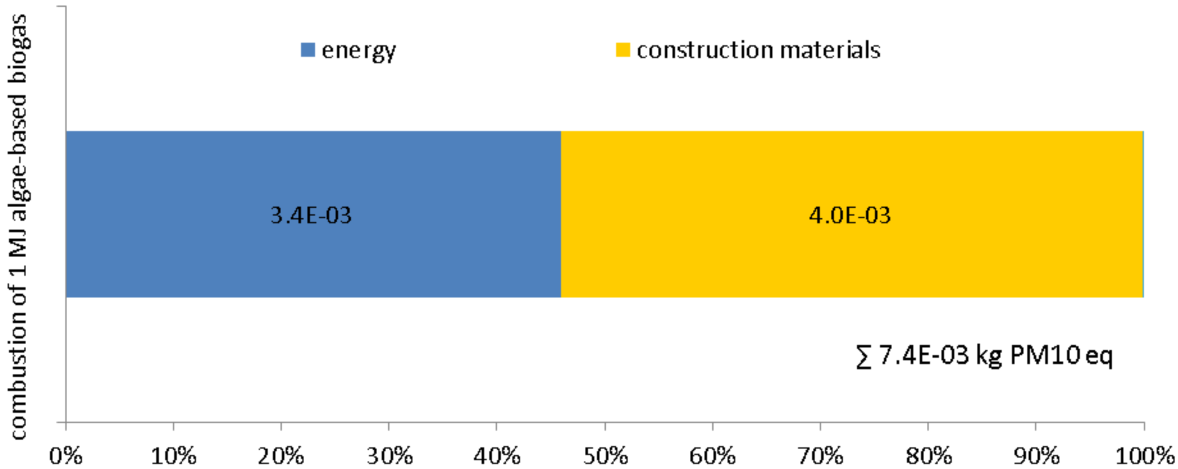

Figure 13: *Aggregated contribution of processes to particulate matter formation for 1 MJ of burned algae-based. Biogas.*

Across the life cycle, both construction materials and energy inputs had similar contributions to this impact category. A slightly higher value was calculated for the construction materials (4.0E-3) representing a share of 54 % of the total value of 7.4E-3 kg PM10 eq.

<u>Impact contribution to particulate matter formation resulting from single material use</u>

Apart from the impact of electricity, it was investigated in detail which materials contribute to the overall particulate matter formation impact and electricity was cut off (see Figure 14).

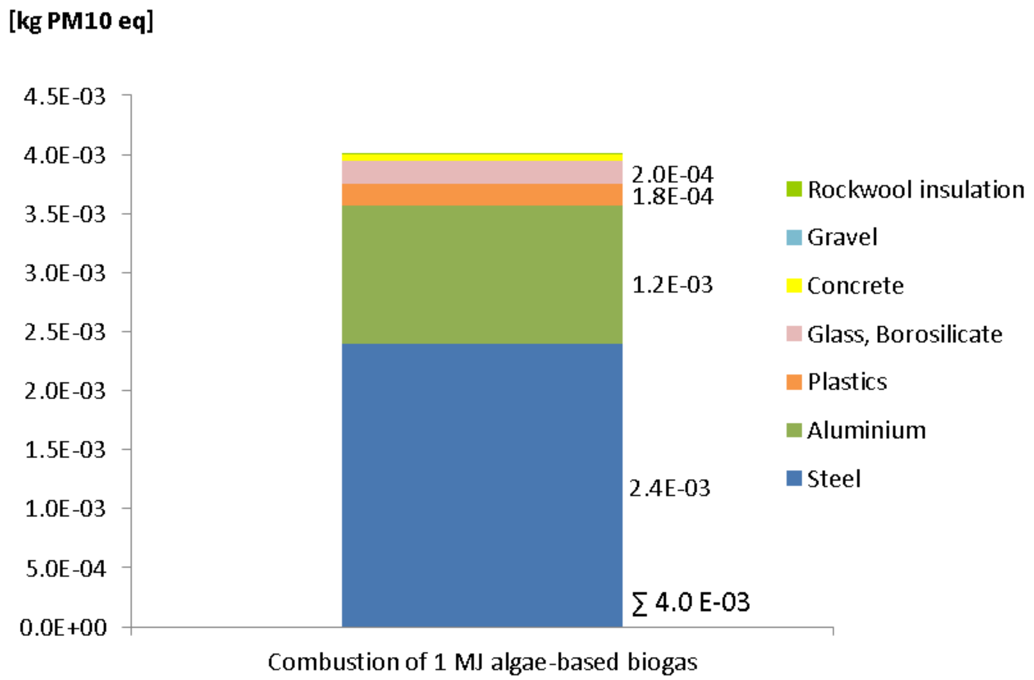

Figure 14: *Contribution to particulate matter formation for the process group construction materials, displayed in detail.*

In Figure 14 the single material contributions are displayed, as the construction had an overall impact of 54 % of the particulate matter formation impact. Therefore we investigated the detailed material contributions and cut off energy inputs. Steel, which is abundant on mining processes and consequently indirectly on electricity, represented the highest share in materials, 2.4E-3 kg PM10 eq (almost 60 % of the construction materials impact) per MJ of algae-based biogas burned. Another main contributor was aluminium with 1.2E-3 kg PM10 eq (29 %). Plastics are ranked as third main material contributor as they accounted for 1.8E-4 (5 %) The remaining single materials glass, concrete, gravel and rockwool had just marginal impact in the process group of construction materials (together they sum up to 2.5E-04 kg PM10 eq equivalent to 6 % of the total impact of construction materials).

5.1.5 Natural land transformation

Natural land transformation was detected to have a significant contribution to ecosystem damage on endpoint level (47 %; see Supplement: Figure S 2). The transformation of natural land affects biodiversity, soil conditions or ecosystem services and is therefore very important (Koellner and Scholz, 2007).

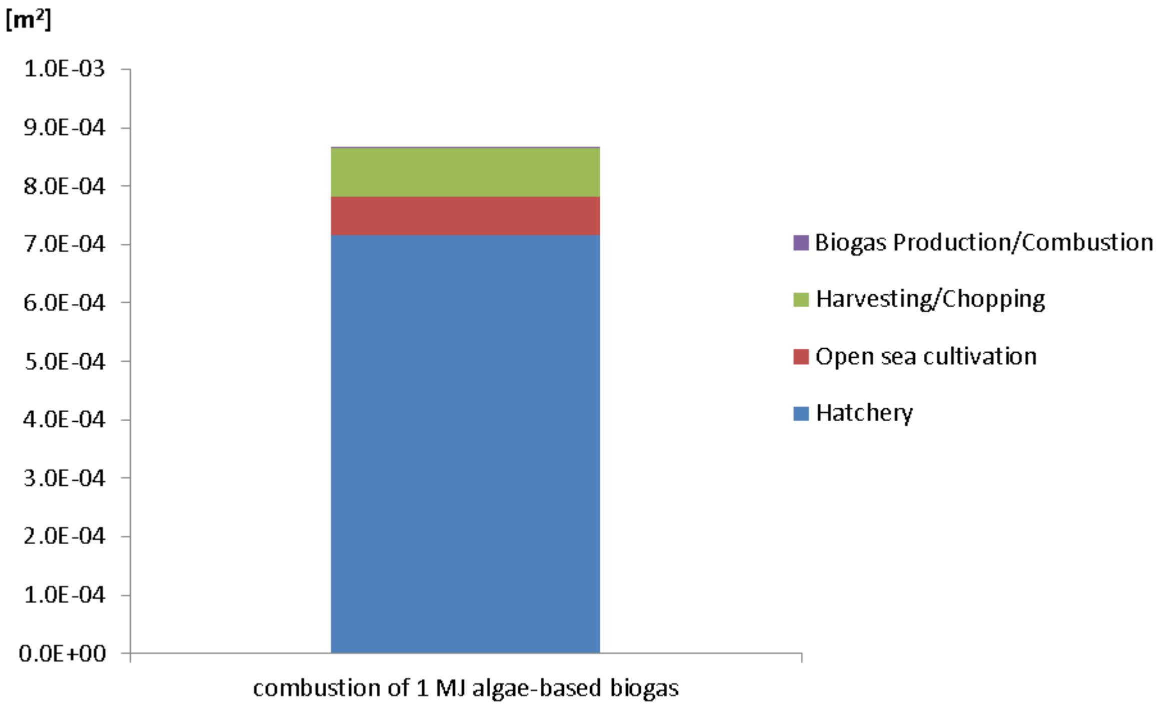

Figure 15: *Contribution of life-cycle phases natural land transformation for 1 MJ of burned algae-based biogas.*

Figure 15 shows the results for the impact category natural land transformation. The main contribution within the base scenario (82 %) was related to the hatchery phase accounting for 7.2E-04 m^2. Almost all the rest (18 %) was related to the open sea cultivation (6.6E-05 m^2; 8 %) and the harvesting/chopping phase (8.4E-05 m^2; 10 %). Compared to the life-cycle impact of natural gas, the absolute value (2.55E-05 m^2 per MJ burned algal biogas) is higher.

<u>Aggregated process contribution to natural land transformation</u>

Figure 16 shows the result of the natural land transformation impact. Referring to the clustered process contributions, it was observed that the natural land transformation was mainly driven by electricity; 6.6E-4 m^2 (76 %). The other main process group was the production and use of construction materials, 2.1E-4 m^2 (24 %).

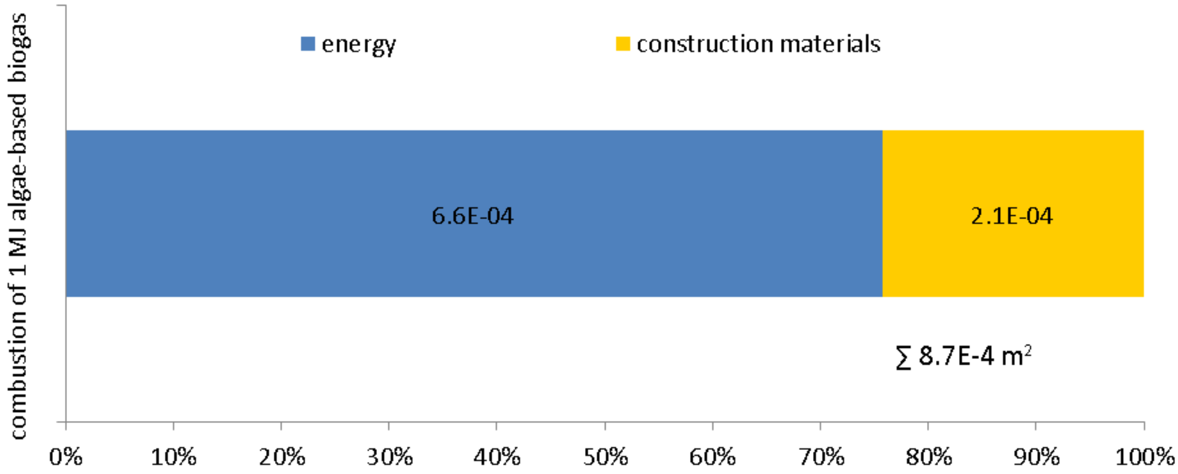

Figure 16: *Aggregated contribution of processes to water depletion for 1 MJ of burned algae-based biogas in different scenarios.*

Impact contribution to natural land transformation resulting from single material use

In the following the single material contributions are displayed within the process group of the production materials. The highest share in the natural land transformation impact was calculated as aluminium (50 %) (see *Figure 17*). The second important contributors in this impact category are glass and steel having equal shares of 23 %.

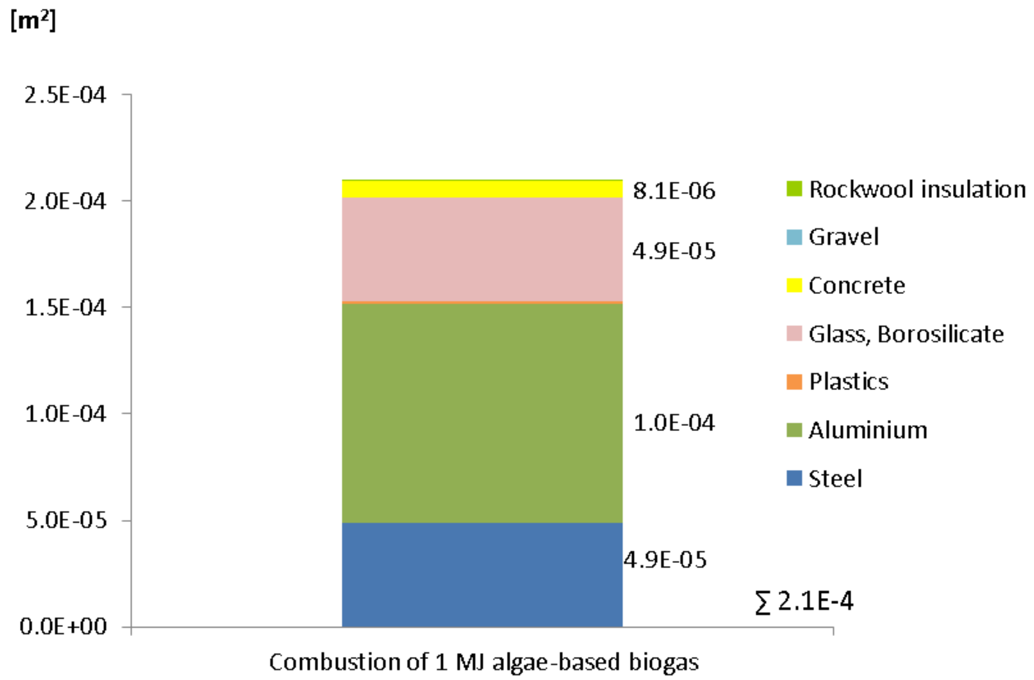

Figure 17: *Contribution to natural land transformation for the process group construction materials, displayed in detail.*

5.2 CEENE

The following section addresses results for the CEENE method. This method quantifies the impact on the environment through the extraction and/or consumption of natural resources. Generally, the CEENE method shows similar results and trends to those observed in the ReCiPe categories.

Impact contribution to CEENE per life-cycle phase

As can be seen in Figure 18, the first two production phases (hatchery and open sea cultivation) contribute the most to the aggregated CEENE impact. A total value of 100.5 MJ_{ex} was calculated. The fossil reference, the production and combustion of 1 MJ natural gas, shows a CEENE value of 0.99 MJ_{ex}. Consequently, the CEENE impact value for the algae biogas combustion exceeded the CEENE value for natural gas.

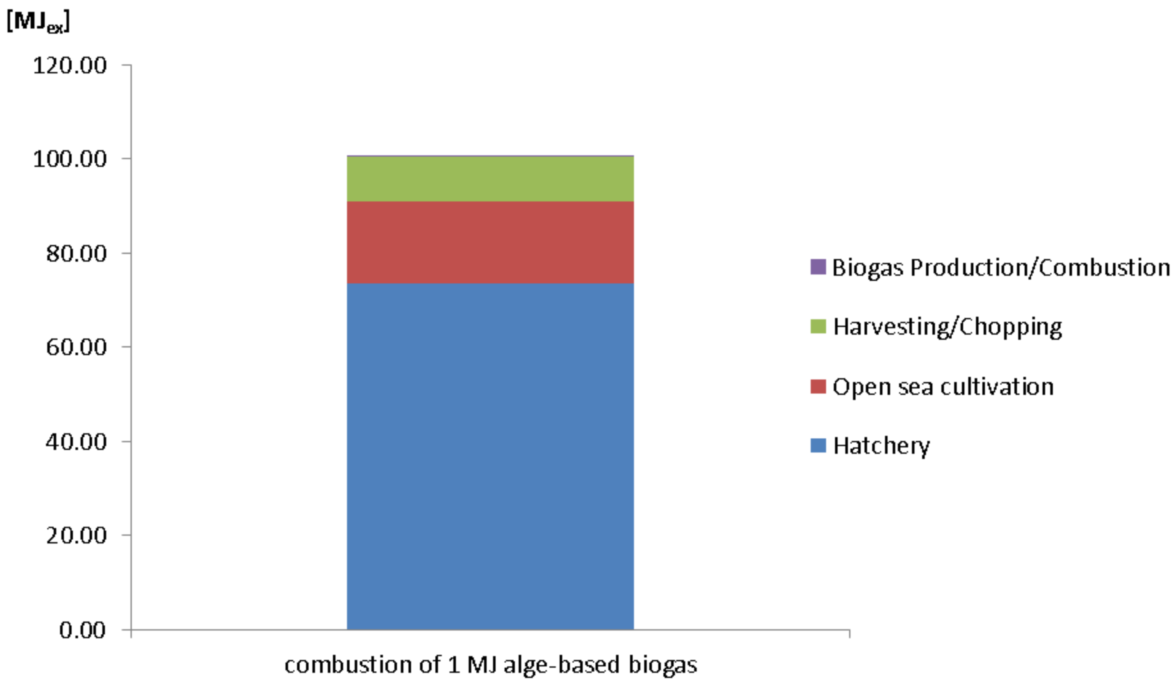

Figure 18: *Contribution of life-cycle phases to the CEENE footprint for 1 MJ of burned algae-based biogas.*

Impact contribution of the resource categories to CEENE per scenario

The results according to resource categories are presented in *Figure 19*. The highest share of the total CEENE impact is related to fossil fuel consumption, 60 %. Fossil fuels were followed by nuclear energy (15 %) representing the main shares of the British electricity mix. Also the marine resources were considered according to Taelman et al. (2015) and represented a share of 9 %.

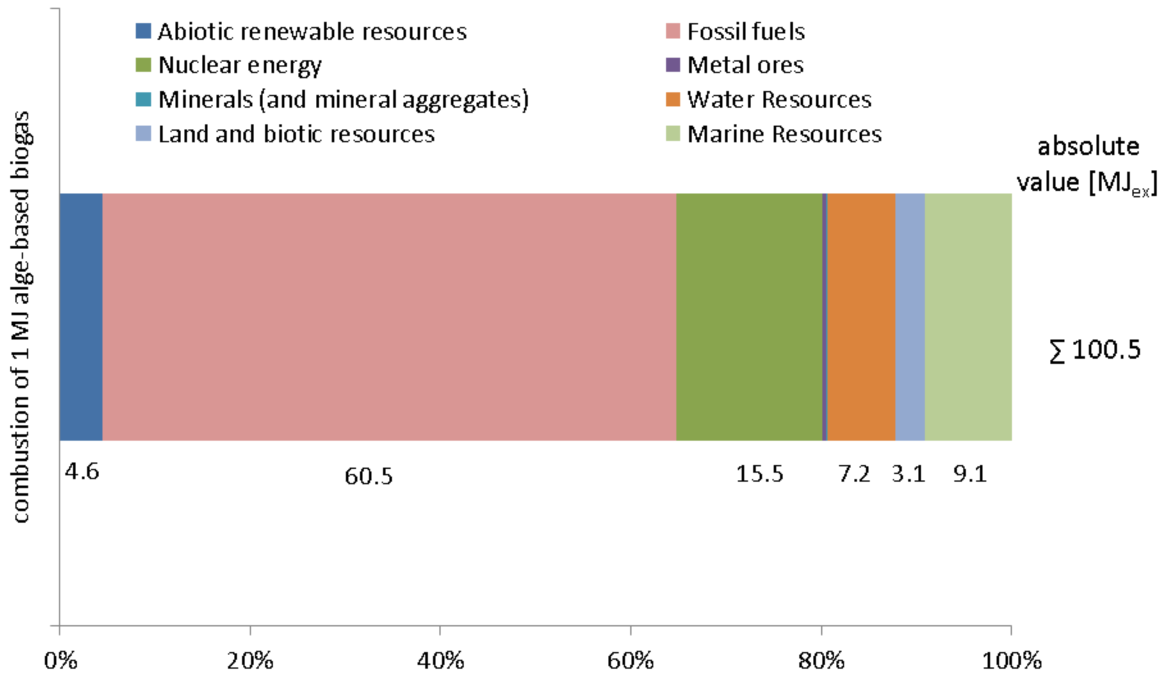

Figure 19: *Impact contribution to CEENE for different resource categories for 1 MJ of burned algae-based biogas.*

6 Summary and Interpretation

All environmental impacts were driven by fossil fuel consumption and the materials used for infrastructure. Upstream energy inputs incorporated in the materials used are further amplifying the impacts. The share of energy consumption in the overall results was high and had slightly higher impact than that resulting from materials used. To be able to detect impacts, apart from those related to energy, the impacts for the process group of construction materials was further investigated. Single material shares were displayed. If direct electricity contributions were not considered, steel and aluminum were drivers in the selected impact categories.

Generally, lower material inputs should be achieved. To reduce the environmental impacts, construction materials with lower footprints could be used in order to substitute materials with higher ones and reduced electricity inputs for lighting and cooling might improve the results.

Improvements need to be made to the hatchery system – these include using LED lights which have already been included in the final season, and running the hatchery at full capacity. The numbers given are for 4 x 100m lines which requires 12 seeders, but the cultivation cabinet could produce enough seed for over 4 times this much material, and there is currently material in the hatchery for 24 x 100m longlines (Karen Mooney-McAuley, pers.comm.). For the future, better hatchery insulation is planned to improve the energy efficiency. Additionally, solar panels on the roof would provide a renewable electricity source. For the offshore work, more efficient boats specifically designed to be energy efficient and more optimal deployment design are being discussed.

Finally, one could think about combined use of the infrastructure given e.g. to additionally cultivate another seaweed species or shellfish which could be allocated to the seaweed produced as suggested by van Dijk and van der Schoot (2015b).

7 Conclusions

At QUB the seaweed production runs on small scale. Technical equipment and materials used are not optimized concerning efficient energy consumption and utilization. Consequently, improvements can be expected, if correctly scaled and balanced equipment was used.

The LCA results give hints on where the bottlenecks of algae production are located. Fundamental energy reductions and material savings are needed to achieve a sustainable algae production. Therefore, future research should focus on process optimization and consequently cost reduction, independent of the final product. Energy in terms of biomethane from algae produced in the described system does not fulfill environmental sustainability criteria. However, improvements can be expected in an upscaled setting that might lead to a more efficient use of materials and improve the overall LCA results.

References

Aitken, D., Bulboa, C., Godoy-Faundez, A., Turrion-Gomez, J.L., Antizar-Ladislao, B., 2014. Life cycle assessment of macroalgae cultivation and processing for biofuel production. J. Clean. Prod. 75, 45–56. doi:10.1016/j.jclepro.2014.03.080

Alvarenga, R.A.F., Dewulf, J., Van Langenhove, H., Huijbregts, M.A.J., 2013. Exergy-based accounting for land as a natural resource in life cycle assessment. Int. J. Life Cycle Assess. 18, 939–947. doi:10.1007/s11367-013-0555-7

Collet, P., Hélias, A., Lardon, L., Ras, M., Goy, R.-A., Steyer, J.-P., 2011. Life-cycle assessment of microalgae culture coupled to biogas production. Bioresour. Technol. 102, 207–14. doi:10.1016/j.biortech.2010.06.154

Dewulf, J., Bösch, M.E., De Meester, B., Van der Vorst, G., Van Langenhove, H., Hellweg, S., Huijbregts, M. a J., 2007. Cumulative exergy extraction from the natural environment (CEENE): a comprehensive life cycle impact assessment method for resource accounting. Environ. Sci. Technol. 41, 8477–83.

Dewulf, J., Van Langenhove, H., Muys, B., Bruers, S., Bakshi, B.R., Grubb, G.F., Paulus, D.M., Sciubba, E., 2008. Exergy: its potential and limitations in environmental science and technology. Environ. Sci. Technol. 42, 2221–2232. doi:10.1021/es071719a

Frischknecht, R., Faist Emmenegger, M., Tuchschmid, M., Bauer, C., Dones, R., 2007. Strommix und Stromnetz. ecoinvent Rep. No. 6 143.

Goedkoop, M., Heijungs, R., De Schryver, A., Struijs, J., van Zelm, R., 2013. ReCiPe 2008. A LCIA method which comprises harmonised category indicators at the midpoint and the endpoint level. Characterisation. doi:http://www.lcia-recipe.net

International Organization for Standardization, 2006. ISO 14040: environmental management – life cycle assessment – principles and framework; 2006.

Koellner, T., Scholz, R.W., 2007. Assessment of land use impacts on the natural environment. Part 1: an analytical framework for pure land occupation and land use change. Int. J. Life Cycle Assess. 12, 16–23. doi:10.1065/lca2006.12.292.1

Rebitzer, G., Ekvall, T., Frischknecht, R., Hunkeler, D., Norris, G., Rydberg, T., Schmidt, W., Suh, S., Weidema, B., Pennington, D.W., 2004. Life Cycle Assessment: Framework, goal and scope definition, inventory analysis, and applications. Environ. Int. 30, 701–720.

Rösch, C., Skarka, J., Raab, K., Stelzer, V., 2009. Energy production from grassland - Assessing the sustainability of different process chains under German conditions. Biomass and Bioenergy 33, 689–700. doi:10.1016/j.biombioe.2008.10.008

Taelman, S.E., Champenois, J., Edwards, M.D., De Meester, S., Dewulf, J., 2015. Comparative environmental life cycle assessment of two seaweed cultivation systems in North West Europe with a focus on quantifying sea surface occupation. Algal Research. 11, 173–183. doi:10.1016/j.algal.2015.06.018

Taelman, S.E., De Meester, S., Schaubroeck, T., Sakshaug, E., Alvarenga, R. a F., Dewulf, J., 2014. Accounting for the occupation of the marine environment as a natural resource in life cycle assessment: An exergy based approach. Resources, Conservation & Recycling. 91, 1–10. doi:10.1016/j.resconrec.2014.07.009

van Dijk, W., van der Schoot, J.R., 2015a. Economic model for offshore growing of macroalgae.Excel workbook. EnAlgae Project., WP2A7.06, Version 1.0, Date: February, 2015. www.enalgae.eu

van Dijk, W., van der Schoot, J.R., 2015b. *An economic model for offshore cultivation of macroalgae.* Public Output report of the EnAlgae project, Swansea, June 2015, 21 pp. www.enalgae.eu

Wall, G., 1977. Exergy - A useful concept. PhD Thesis, Chalmers Univ. Technol. Univ. Göteborg. www.exergy.se/ftp/ex77c.pdf

Weiß, J., 2009. Universität Karlsruhe (TH) Fakultät für Maschinenbau Studienarbeit zum Thema „Vereinfachte Energie- und CO_2 -Bilanzen ausgewählter Verfahren zur Energiegewinnung aus Mikroalgen“.

8 Supplement

All ReCiPe midpoints have been calculated in a first step. The list of midpoint categories and the contribution of life-cycle phases to each category is displayed in *Table S 1*. However, for detailed investigation, only five categories have been selected.

Table S 1: *ReCiPe midpoints, absolute values and shares according to life-cycle phases.*

ReCiPe Impact category (midpoints)		Hatchery	%	Open sea cultivation	%	Harvesting/Chopping	%	Biogas Production/combustion	%	Sum
Climate change (CC)	kg CO2 eq	3.71E+00	81.60	3.70E-01	8.13	4.59E-01	10.10	7.62E-03	0.17	4.54E+00
Ozone depletion (OD)	kg CFC-11 eq	1.08E-07	67.08	2.24E-08	13.87	3.04E-08	18.87	2.73E-10	0.17	1.61E-07
Terrestrial acidification (TA)	kg SO2 eq	1.25E-02	76.66	1.57E-03	9.62	2.20E-03	13.46	4.11E-05	0.25	1.63E-02
Freshwater eutrophication (FE)	kg P eq	1.27E-03	77.15	1.37E-04	8.33	2.31E-04	14.09	7.16E-06	0.44	1.64E-03
Marine eutrophication (ME)	kg N eq	5.77E-04	79.69	5.95E-05	8.22	8.52E-05	11.76	2.39E-06	0.33	7.24E-04
Human toxicity (HT)	kg 1,4-DB eq	1.27E+00	76.07	1.54E-01	9.23	2.40E-01	14.40	4.98E-03	0.30	1.67E+00
Photochemical oxidant formation (POF)	kg NMVOC	8.32E-03	76.07	1.20E-03	10.96	1.39E-03	12.70	2.98E-05	0.27	1.09E-02
Particulate matter formation (PMF)	kg PM10 eq	5.07E-03	68.47	9.81E-04	13.24	1.34E-03	18.11	1.32E-05	0.18	7.41E-03
Terrestrial ecotoxicity (TET)	kg 1,4-DB eq	3.03E-04	77.89	3.59E-05	9.22	4.98E-05	12.80	3.78E-07	0.10	3.90E-04
Freshwater ecotoxicity (FET)	kg 1,4-DB eq	1.27E-02	65.45	2.50E-03	12.90	4.16E-03	21.41	4.71E-05	0.24	1.94E-02
Marine ecotoxicity (MET)	kg 1,4-DB eq	1.56E-02	65.96	3.09E-03	13.09	4.90E-03	20.74	4.90E-05	0.21	2.36E-02
Ionising radiation (IR)	kg U235 eq	1.55E+00	88.11	7.57E-02	4.31	1.31E-01	7.44	2.63E-03	0.15	1.76E+00
Agricultural land occupation (ALO)	m2a	7.77E-02	84.43	7.28E-03	7.91	6.96E-03	7.56	1.02E-04	0.11	9.21E-02
Urban land occupation (ULO)	m2a	3.14E-02	82.74	2.97E-03	7.83	3.55E-03	9.35	2.92E-05	0.08	3.80E-02
Natural land transformation (NLT)	m2	7.16E-04	82.65	6.60E-05	7.63	8.37E-05	9.66	4.91E-07	0.06	8.66E-04
Water depletion (WD)	m3	1.22E+01	36.85	7.53E+00	22.67	1.34E+01	40.39	3.07E-02	0.09	3.32E+01
Mineral resource depletion (MRD)	kg Fe eq	9.83E-01	59.50	3.23E-01	19.56	3.45E-01	20.86	1.42E-03	0.09	1.65E+00
Fossil fuel depletion (FD)	kg oil eq	1.08E+00	80.72	1.29E-01	9.63	1.27E-01	9.53	1.59E-03	0.12	1.34E+00

Table S 2: *ReCiPe midpoints per MJ natural gas (GB).*

ReCiPe Impact category (midpoints)		Value
Climate change (CC)	kg CO2 eq	5.77E-02
Ozone depletion (OD)	kg CFC-11 eq	1.96E-10
Terrestrial acidification (TA)	kg SO2 eq	1.24E-05
Freshwater eutrophication (FE)	kg P eq	8.46E-08
Marine eutrophication (ME)	kg N eq	7.81E-07
Human toxicity (HT)	kg 1,4-DB eq	1.07E-04
Photochemical oxidant formation (POF)	kg NMVOC	2.37E-05
Particulate matter formation (PMF)	kg PM10 eq	5.15E-06
Terrestrial ecotoxicity (TET)	kg 1,4-DB eq	6.48E-08
Freshwater ecotoxicity (FET)	kg 1,4-DB eq	9.90E-07
Marine ecotoxicity (MET)	kg 1,4-DB eq	5.35E-05
Ionising radiation (IR)	kg U235 eq	3.99E-05
Agricultural land occupation (ALO)	m2a	3.12E-06
Urban land occupation (ULO)	m2a	2.79E-05
Natural land transformation (NLT)	m2	2.55E-05
Water depletion (WD)	m3	5.35E-04
Mineral resource depletion (MRD)	kg Fe eq	5.91E-05
Fossil fuel depletion (FD)	kg oil eq	2.12E-02

For detailed investigation, only five categories have been selected. The ReCiPe endpoints have been calculated to get an impression of the contribution on midpoint level to the overall environmental sustainability (baseline: base scenario). In *Table S 3* , the absolute values as well as the percentage share to the three endpoint categories, divided into life-cycle phases, are depicted. As can be gathered from*Table S 3*, the first two phases, the hatchery and open sea cultivation, account for almost 100 % of the individual impacts. Biomass harvesting/chopping and biogas production/use are negligible concerning their shares in environmental impacts.

Table S 3: *Contribution of midpoints, absolute values and shares, to the endpoint categories human health, ecosystems and resources, according to life-cycle phases.*

Human health [DALY]	per 1 MJ algal biogas combustion	Hatchery	%	Open sea cultivation	%	Harvesting/Chopping	%	Biogas Production/combustion	%	aggregated Endpoint
Photochemical oxidant formation	kg NMVOC	3.25E-10	76.07	4.68E-11	10.96	5.42E-11	12.70	1.16E-12	0.27	9.49E-06
Ozone depletion	kg CFC-11 eq	1.81E-09	57.36	5.80E-10	18.35	7.65E-10	24.19	3.39E-12	0.11	
Ionising radiation	kg U235 eq	2.54E-08	88.11	1.24E-09	4.31	2.14E-09	7.44	4.32E-11	0.15	
Particulate matter formation	kg PM10 eq	1.32E-06	68.47	0.000000	13.24	3.49E-07	18.11	3.42E-09	0.18	
Human toxicity	kg 1,4-DB eq	8.87E-07	76.07	1.08E-07	9.23	1.68E-07	14.40	3.49E-09	0.30	
Climate change	kg CO2 eq	5.19E-06	81.60	5.17E-07	8.13	6.42E-07	10.10	1.07E-08	0.17	
Ecosystems [species*yr]	**per 1 MJ algal biogas combustion**	**Hatchery**	**%**	**Open sea cultivation**	**%**	**Harvesting/Chopping**	**%**	**Biogas Production/combustion**	**%**	**aggregated Endpoint**
Marine ecotoxicity	kg 1,4-DB eq	2.94E-08	81.60	2.93E-09	8.13	3.64E-09	10.10	6.04E-11	0.17	7.26E-08
Freshwater ecotoxicity	kg 1,4-DB eq	7.25E-11	76.66	9.11E-12	9.62	1.27E-11	13.46	2.39E-13	0.25	
Terrestrial ecotoxicity	kg 1,4-DB eq	5.62E-11	77.15	6.07E-12	8.33	1.03E-11	14.09	3.18E-13	0.44	
Terrestrial acidification	kg SO2 eq	4.57E-11	77.89	5.41E-12	9.22	7.51E-12	12.80	5.69E-14	0.10	
Freshwater eutrophication	kg P eq	1.09E-11	65.45	2.16E-12	12.90	3.58E-12	21.41	4.06E-14	0.24	
Urban land occupation	m2a	2.74E-12	65.96	5.44E-13	13.09	8.63E-13	20.74	8.64E-15	0.21	
Agricultural land occupation	m2a	9.32E-10	84.39	8.75E-11	7.92	8.37E-11	7.58	1.22E-12	0.11	
Natural land transformation	m2	6.51E-10	82.74	6.16E-11	7.83	7.36E-11	9.35	6.06E-13	0.08	
Climate change	kg CO2 eq	2.54E-09	7.36	3.19E-08	92.59	1.17E-11	0.03	3.64E-12	0.01	
Resources [$]	**per 1 MJ algal biogas combustion**	**Hatchery**	**%**	**Open sea cultivation**	**%**	**Harvesting/Chopping**	**%**	**Biogas Production/combustion**	**%**	**aggregated Endpoint**
Metal depletion	kg Fe eq	1.78E-01	80.72	2.13E-02	9.63	2.11E-02	9.53	2.63E-04	0.12	3.39E-01
Fossil depletion	kg oil eq	7.03E-02	59.50	2.31E-02	19.56	2.46E-02	20.86	1.01E-04	0.09	

The total contribution to the different endpoint categories serves as decision support to select relevant midpoint categories for further examination. The following three graphs (*Figure S 1*- S 3) show the aggregated contribution of impact categories to the endpoint levels damage of human health, damage of ecosystem diversity and damage of resource availability.

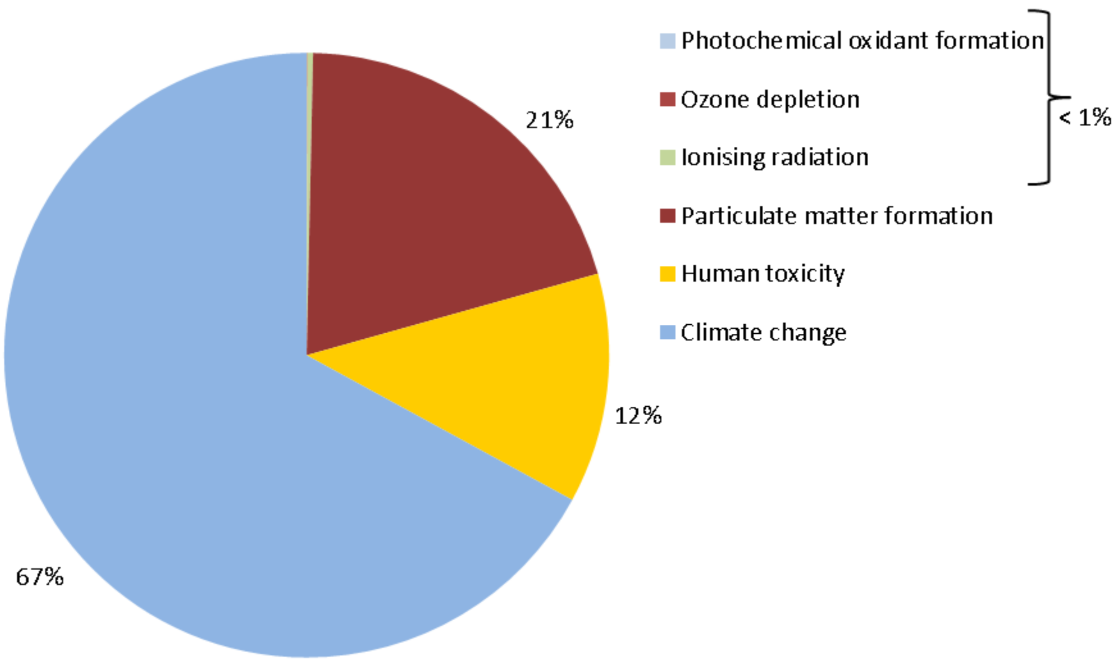

Figure S 1: *Weighted contribution of midpoint categories on the endpoint level "damage to human health".*

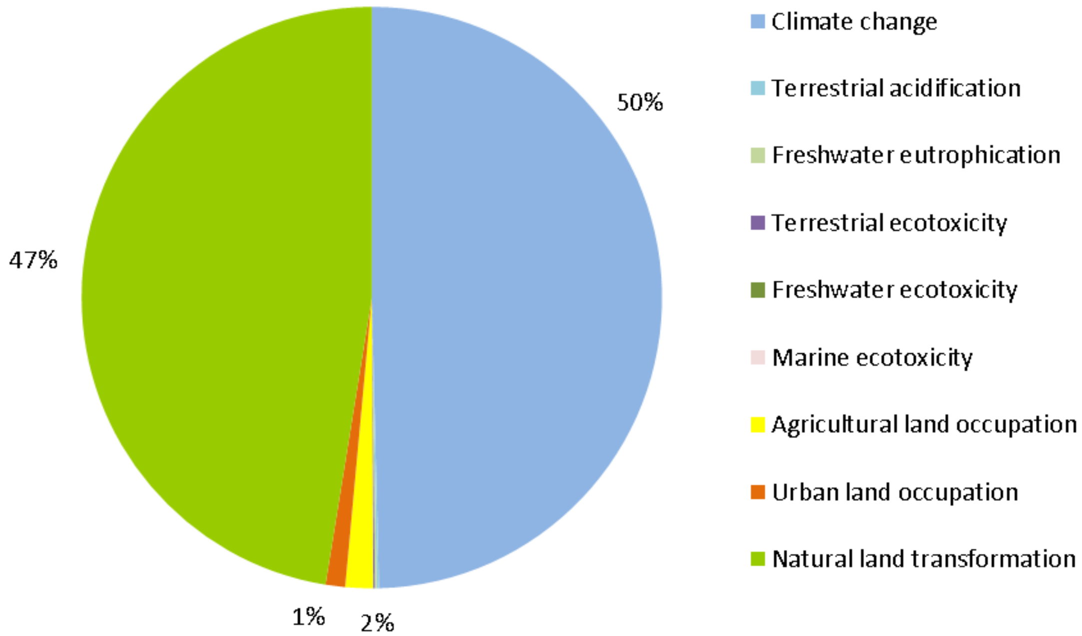

Figure S 2: *Weighted contribution of midpoint categories on the endpoint level "damage to ecosystem diversity".*

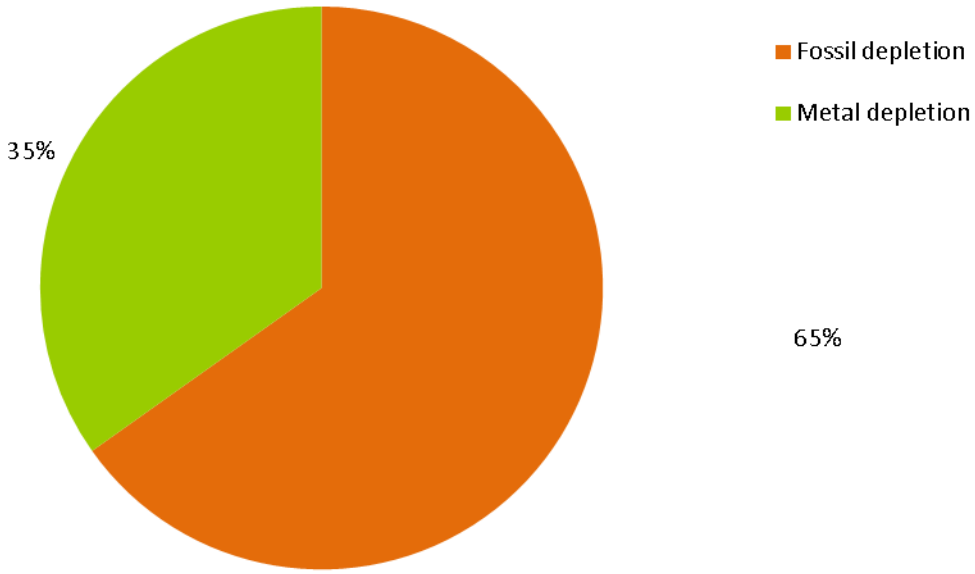

Figure S 3: *Weighted contribution of midpoint categories on the endpoint level "damage to resource availability".*

Investing in Opportunities

This project has received European Regional Development Funding through INTERREG IV B.

INTERREG IVB

EnAlgae is a four-year Strategic Initiative of the INTERREG IVB North West Europe programme. It brings together 19 partners and 14 observers across 7 EU Member States with the aim of developing sustainable technologies for algal biomass production.

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