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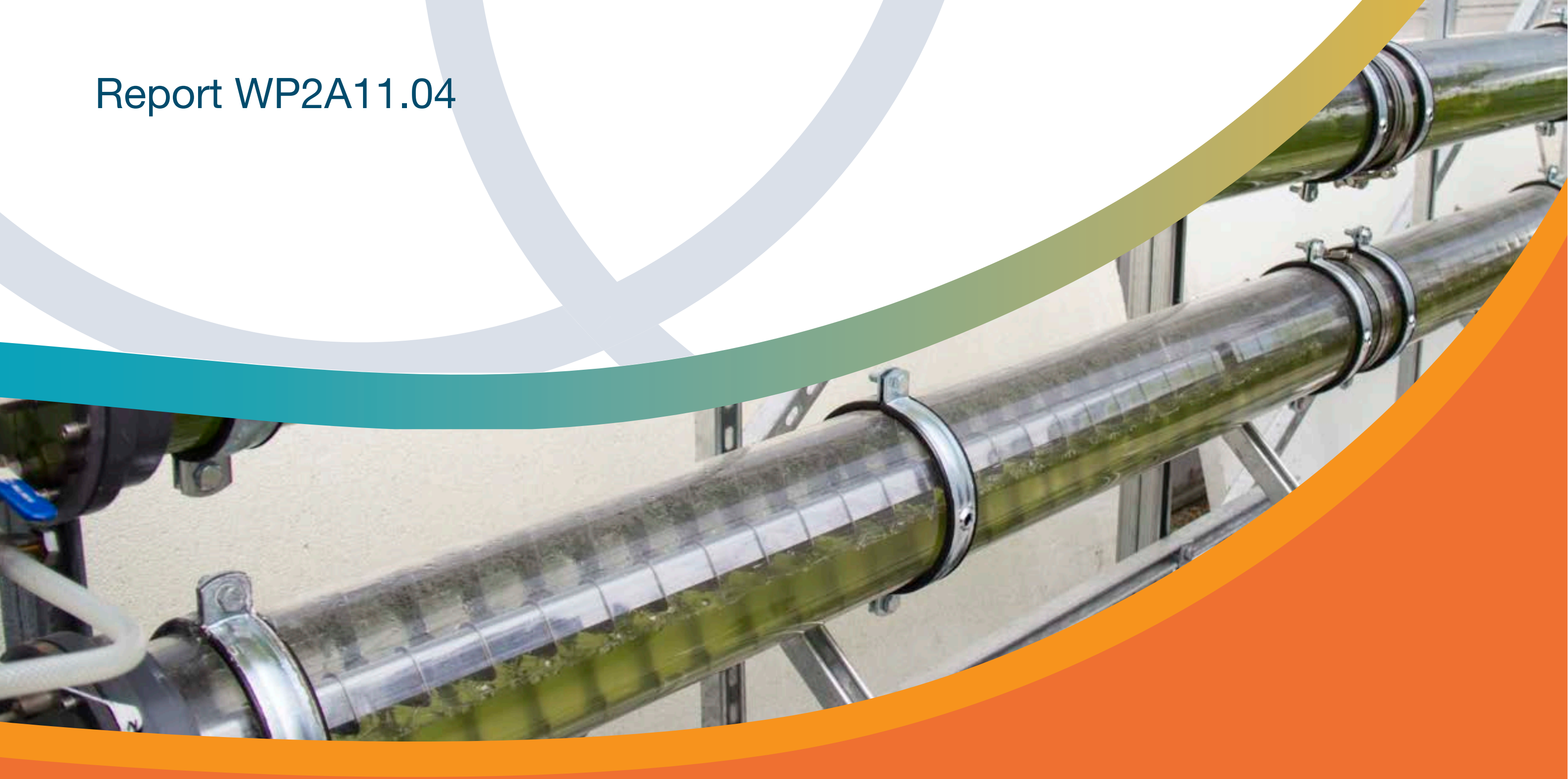
Environmental life cycle assessment (LCA) of microalgae production at InCrops Enterprise Hub

Report WP2A11.04



Energetic Algae ('EnAlgae')

Project no. 215G

Public Output

WP2A11.04 − Environmental life cycle assessment (LCA) of microalgae production at InCrops Enterprise Hub

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This project has received European Regional Development Funding through INTERREG IV B.
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Environmental life cycle assessment (LCA) of microalgae production at InCrops Enterprise Hub

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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 the InCrops pilot in microalgae experiments are carried out to determine physiological qualities of different algal species under different growth conditions, specifically using industrial clean wastewater as nutrient source.

Within the project context, the horizontal tubular reactor system was built and different process parameters were investigated. Scientists at InCrops focused on exploring ways to grow, harvest and process microalgal biomass. The marine species *Phaeodactylum tricornutum* was cultivated as the wastewater contained high concentrations of NaCl salt as well as nitrates for growth. Data was provided based on extrapolations from short term experiments (1-3 week experiments), for a one year microalgae biomass production. As there was no downstream processing data available, the final biomass application was defined as bioenergy production according to the project scope. Therefore, we decided to model the environmental impact of the combustion of algae-based biogas. 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 framework of the International Organization for Standardization (ISO) 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***).

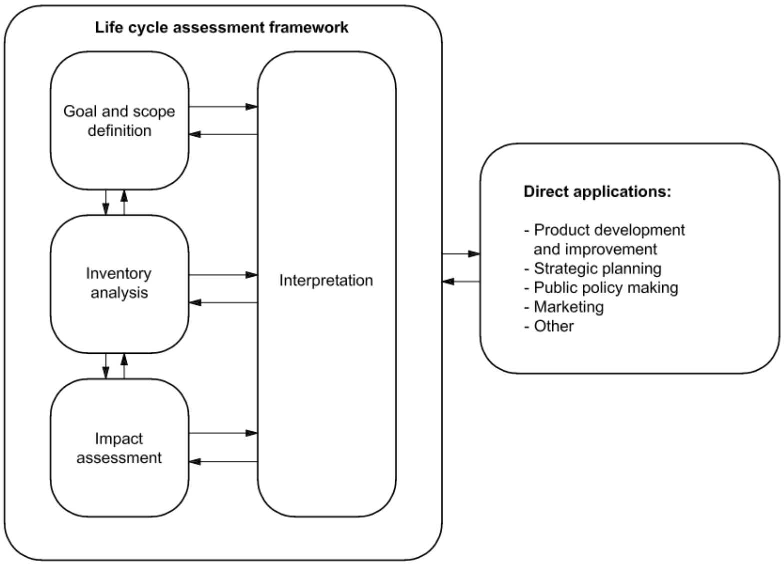

Figure 1: *LCA as a 4-phase process according to the ISO standards 14040: goal and scope definition, inventory analysis, impact assessment and interpretation (International Organization for Standardization, 2006)*

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 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 5*).

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 that 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 in 8 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 to account 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 microalgae pilot facilities of InCrops are located at the University of Cambridge, Botanic Garden, UK. Cambridge is characterized with maritime climate, with weather that is often cloudy, wet and windy but mild and moderate variations between temperatures. Main materials and their production were considered in the system, transport and manufacturing processes were not taken into account. Waste water from cleaning processes was simply diluted and drained untreated and is therefore not considered in the LCA system, however a cleaning credit was applied for the service provided by the algae culture. Storage processes resulting from production lacks were not considered, downstream processes were modelled on a one year baseline. Due to maintenance and cleaning processes a net cultivation period of 300 days was assumed. The system was operated in batch mode. Twelve consecutive full harvests per year could be achieved including maintenance and cleaning processes. Four main production steps built up the production chain (see Figure 2) inoculation and cultivation, harvesting/dewatering and finally downstream processing in this case biogas production/combustion.

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

- Inoculation
- Cultivation
- Harvesting/dewatering and
- Biogas production/combustion

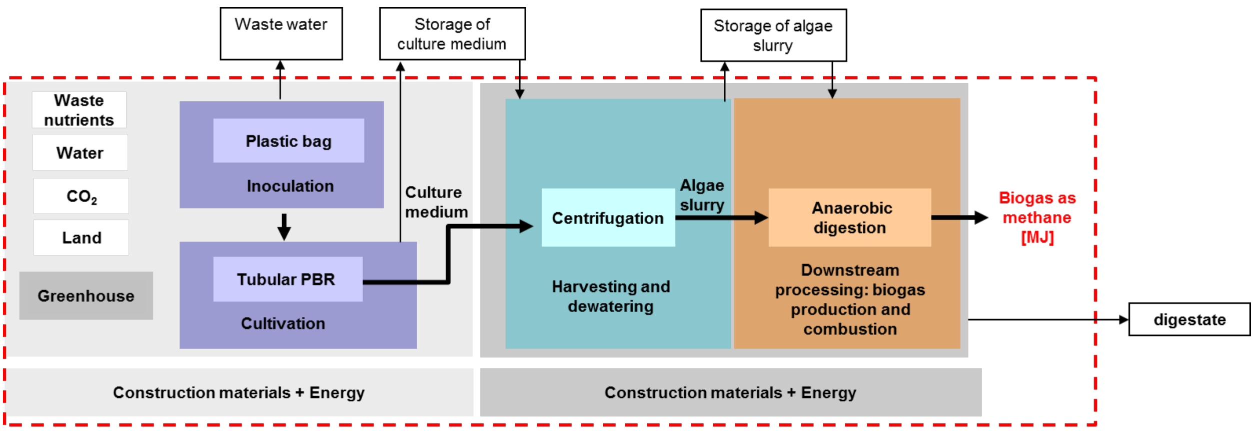

Figure 2: *System boundary and process flows included in the LCA: Processes supplied by experimental (laboratory) data and numbers are highlighted in light grey; processes supplied by database data and literature are highlighted in dark grey. The system boundary is displayed as red-dotted line.*

Table 1 summarizes the main cultivation parameters. First, the inoculation culture has been prepared in 5 L plastic bags, being mixed by air gassing. The inoculation system was operated parallel in a batch mode and a fresh culture was fixed every three weeks. Twelve inoculum batches were realized with a biomass concentration being transferred to the cultivation reactor assumed to be 1.0 g/L. With only 10 % of the final reactor volume the inoculation volume was assumed to be 10 L. The inoculation culture was transferred and diluted in the horizontal tubular closed PBR with a total volume of 100 L. After three weeks of cultivation, the biomass was harvested. Twelve runs per year could be realized with buffer time in between for cleaning and maintenance purposes.

The 100 L reactor was located in a greenhouse consisting of one polycarbonate tube supported by a steel frame. The system was equipped with probes to measure pH, temperature, and optical density. It contained a level - and a pressure control system for automatic operation. In total, a yearly production of 1.2 kg of dry algal biomass was estimated, resulting in an areal yield of 1.6 t/ha/a (on baseline of only one reactor unit per occupied area).

Just small amounts of biomass were needed to be analyzed; therefore the vast majority was drained.
For the LCA total biomass was assumed to be concentrated by a centrifuge after a one-week settling process which achieved a concentration to 50 % of initial culture volume. Afterwards the dry biomass was modelled to be digested and processed to biogas and burned in a cogeneration unit.

Main materials for construction process e.g. the greenhouse, as well as energy inputs, e.g. for pumping the culture, representing real experimental values, were included in the system.

***Table 1**: Main parameters for cultivation.*

Paramter	**Description**
Reactor Type	Horizontal tubular PBR (internal rotor)
Nutrient source	Waste water Cambridge Water PLC.
Culture volume	100 L
Average algae conc.	1.0 g/L
Total biomass yield	1.2 kg
Areal yield	1.6 t/ha/a (1 unit)

The marine diatom *Phaeodactylum tricornutum* was cultivated as it was shown from small scale laboratory experiments at Cambridge that *Phaeodactylum tricornutum* has potential to treat wastewater. *Phaeodactylum tricornutum* might potentially increase in biomass with increasing waste- water additions until a mixture of about 40 % wastewater, 60 % sea water was reached as it was shown by Goldman (1976). Consequently, the avoided process of water cleaning was modelled as a credit. In the experiments, however, a 1-2% wastewater to water mix was applied, as the nitrate was very concentrated in the waste water.

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 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 microalgae production. Data could be provided for the materials of the reactors for inoculation and cultivation as well as their 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:

- **Inoculation**
  - The inoculum was produced, using about 500 kWh/a (gassing)
  - Material specification/amount used for the 5 L plastic bags were obtained from the pilot operator
  - Estimations of waste nutrients following f/2 medium concentrations (12.4 mg/L N, 3.4 mg/L $PO4^-$)
- **Cultivation**
  - During cultivation about 860 kWh/a were assumed for pumping (horizontally) and mixing (vertically)
  - Material specification/amount used for the 100 L cultivation reactor unit as well as the supporting frame were obtained from the pilot operator
  - A standard greenhouse (materials/size) was modelled with 15 m^2 floor space
  - Estimations of waste nutrients following f/2 medium concentrations (12.4 mg/L N, 3.4 mg/L $PO4^-$)
- **Biomass concentration**
  - The centrifuge (Beckmann Coulter, specification Avanti 2kW) was modelled assuming 12 h of concentration per day meaning approximately 4,400 operating hours/a) to concentrate the biomass slurry for further fermentation. The 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 and scaled to the real running scheme according to the time needed to process 50 L of settled culture in 4 L samples (12.5 runs per biomass harvest and 10 min per run)
  - Electricity, used to concentrate the biomass depended on the time needed and was assumed to be 50 kWh/a
  - Biomass slurry was assumed to have a total solid content of 20 % (total biomass 1.2 kg), consequently a slurry volume of 6 L per harvest (6 L*12 batches = 72 L/a); no other pre-treatment for fermentation was included
- **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 *Phaeodactylum triconutum* was experimentally derived to be 0.48 m^3/kg (according to experimental data from Patel et al., 2015; 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 (compare results *Table S 4*)

5 Results and Discussion

In the following paragraphs the results of the LCA based on the data collected from the plant operator are presented and discussed. The following cases were elaborated and named as scenario. In this sense scenario describes options as analytical units. The following two scenarios were defined.

- **Original data scenario:** The flows and impacts were computed with the original data according to the pilot setup.
- **Improved productivity (prod.) scenario:** In this scenario a theoretical improvement of the productivity to 2g/L was assumed. Material and energy inputs remained at the original values of the real setting
- **Improved productivity/electricity (prod./elec.) scenario:** This scenario is developed having the improved prod. Scenario as baseline plus improvements in electricity consumption. For the inoculation phase as well as the cultivation, electricity inputs for mixing the culture were reduced to 55 %, as the power of the devices might be minimized at night. Material inputs remained at the original values of the real setting.

As production was not aiming for a specific product, except biomass, downstream processes were modelled on literature baseline and common sense. Fertilizer/waste nutrients were sufficiently supplied; cells were not forced to accumulate lipids to promote the biodiesel production. Besides, there is an ongoing debate about the usability of the oil fraction as biodiesel feedstock. Moreover, some studies show that lipid extraction is not economically feasible (Brennan and Owende, 2010; Chisti, 2007). Biogas can be processed without prior fractionation steps and the whole biomass is used. Therefore, 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 Supplement (see *Table S 1*- S 4). 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, on the baseline of the original dataset for the 100 L reactor (see Supplement).

Separated in the four process phases the endpoint results indicated that mainly the first two phases of inoculum production and even more the 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 Supplement).

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. Besides, 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 detail examination since it represented the second main contributor in damage to human health. Although, the water impacts hardly showed up in the endpoint results, eventually because two water categories (marine eutrophication and water depletion) are simply not considered within the endpoint methodology, especially water depletion was consulted on midpoint level.

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. The three scenarios as described above are separately depicted and explained.

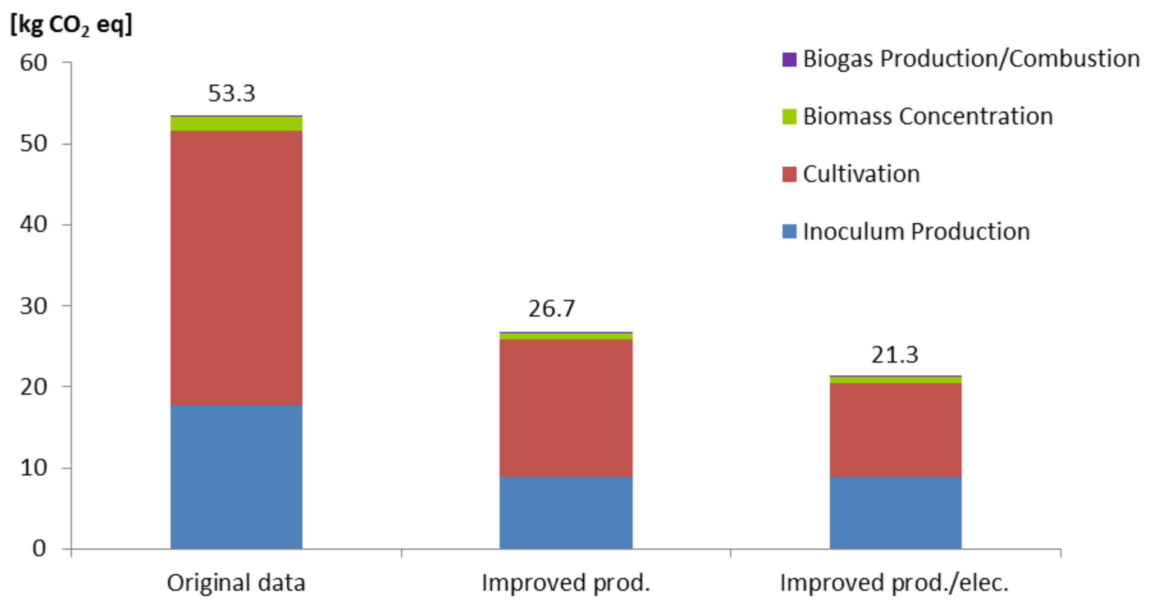

Figure 3: *Contribution of life-cycle phases to climate change for 1 MJ of burned algae-based biogas in different scenarios.*

Figure 3 shows the overall results for climate change expressed in CO_2 equivalents (eq). In all considered scenarios the cultivation phase represented the highest share in total CO_2 eq. In the original data scenario most CO_2 eq are resulting per MJ algae-based biogas burned. About 63 % (33.8 kg CO_2 eq) of the 53.3 kg CO_2 eq are related to the cultivation phase followed by 33.4% (17.8 kg CO_2 eq) related to the inoculation phase. As the model is built in a linear way, the doubling of biomass yield leads to a decrease in all impact categories by half as can be seen in the imporved prod. scenario.

Further improvements on electricity inputs to referring to the improved prod./elec. scenario. In this scenario 21.3 kg total CO_2 eq were calculated. The cultivation accounted for 54 % which means an absolute value of 11.6 kg. The inoculation phase made up a total value of 8.9 kg CO_2 eq. The combustion of 1 MJ natural gas, however results in 0.06 kg CO_2 eq.

<u>Aggregated process contribution to climate change per scenario</u>

In the following the aggregated contribution was investigated and four main process types were distinguished. Process types like biogas combustion, occupation as well as the wastewater cleaning credit were not displayed, as they had negligible impact:

- Electricity, e.g. for pumping, mixing
- Water as culture medium, for cleaning
- Operating supplies, like chemicals for cleaning

- Construction materials, like steel and plastics for the reactor but also the materials used for the greenhouse

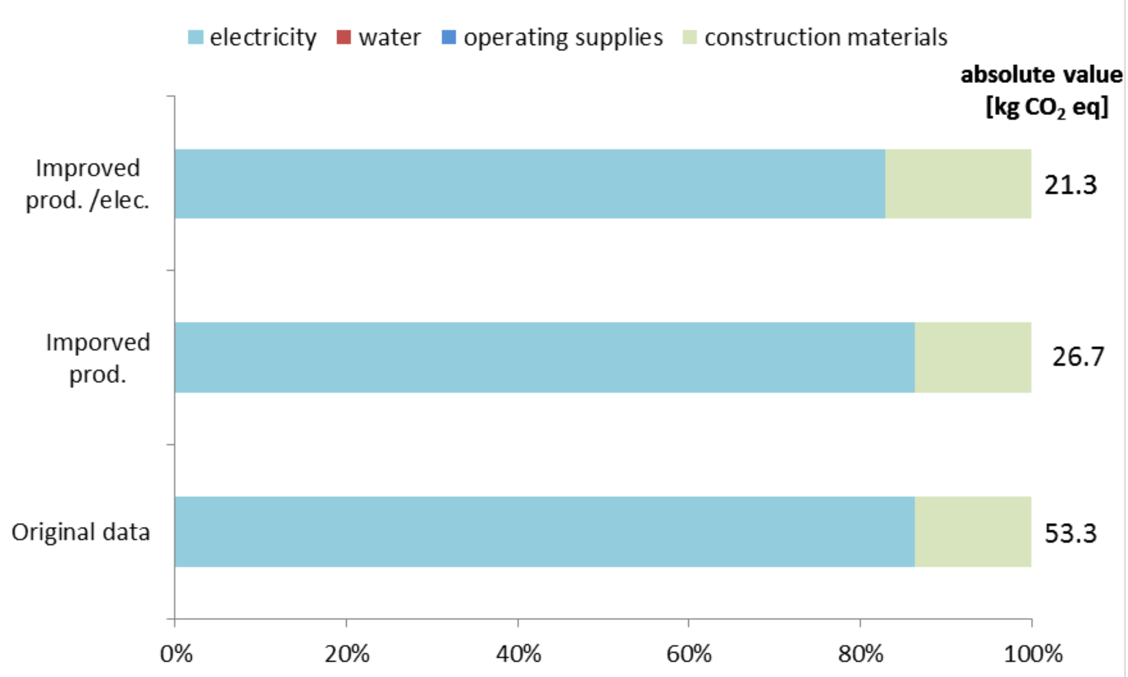

Figure 4: *Aggregated contribution of processes to climate change for 1 MJ of burned algae-based biogas in different scenarios.*

As can be extracted from Figure 4, in all life-cycle phases the main contribution to climate change was due to the consumption of electricity in all scenarios. 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).

Electricity is contributing to 83 % (improved prod./elec. Scenario) up to 86 % (original data scenario). Contributions from operating supplies and water inputs hardly show up in the climate change category.

Life-cycle related impact contribution to climate change for the improved prod./elec. scenario (electricity cut off)

We "zoomed in" and analysed the processes apart from electricity with the highest shares by cutting of the electricity input contributions across the whole process chain. Without electricity inputs, 99.6 % of the shares are related to construction materials, which are expressed in detail (see Figure 5).

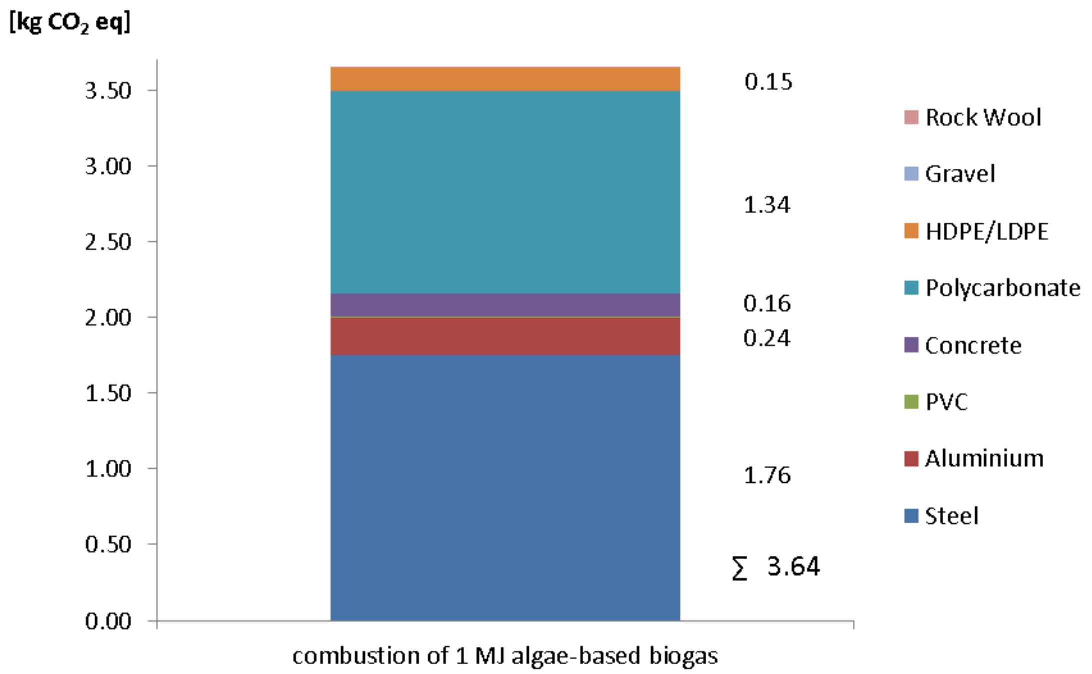

Figure 5: *Contribution to climate change for the improved prod./elec. scenario; the process group, construction materials, is displayed in detail.*

Steel represented highest contribution (48.4 %) in the climate change impact category, if electricity was cut-off. In the production system, steel is e.g. used for the internal rotor within the reactor as well as the supporting frame of the reactor tubes but also for the centrifuge. The second important share (36.8 %) is represented polycarbonate for the greenhouse and reactor tubes. The reactor set-up is still not efficient and material savings could be expected, especially in upscaled settings and when the supporting construction is holding more than one reactor unit.

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.

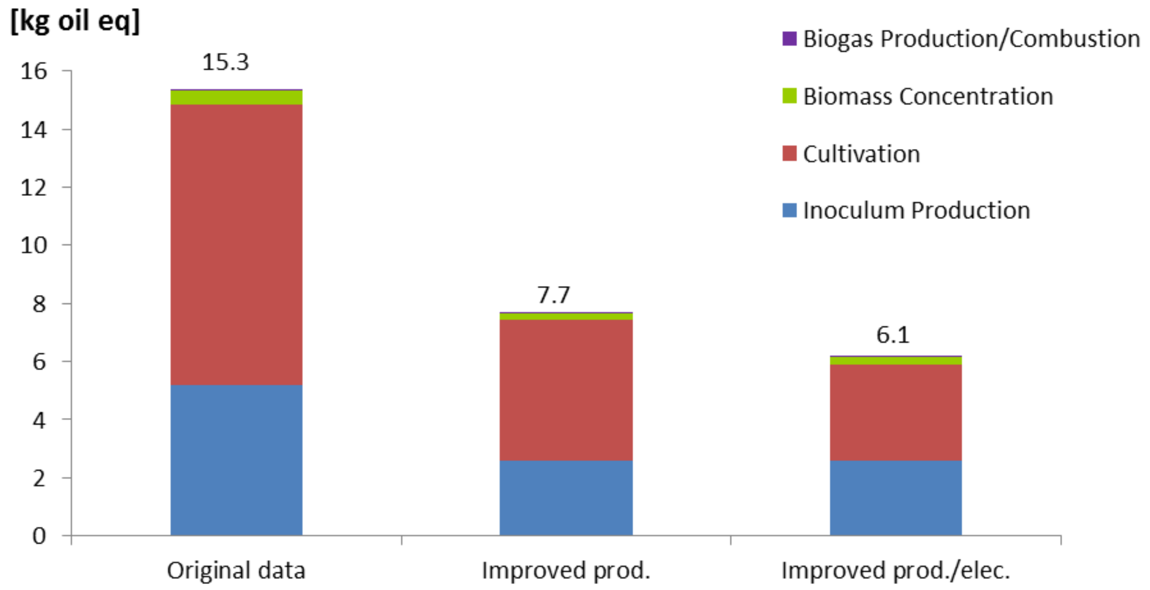

***Figure 6**: Contribution of life-cycle phases to fossil fuel depletion for 1 MJ of burned algae-based biogas in different* scenarios.

Figure 6 shows the total results for fossil fuel depletion expressed in kg of oil equivalents. The ratio of the absolute value shares of phases for the three scenarios highly corresponds to that of the results for climate change. It was shown that most oil eq are consumed during to the phase of cultivation. In this phase, the oil eq sum up to 63 % of the total consumption per MJ burned algae-based biogas in original data scenario. In accordance to the results of climate change, the first two phases represent the main 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 in contrast. In the improved prod. scenario, the value for fossil fuel depletion was reduced, by almost 50 %. Still, biomass concentration and biogas production were hardly visible in the phase contribution. In the improved prod./elec. scenario, the total fossil depletion decreased further by 21 % (1.6 kg oil eq), compared to the improved prod. scenario.

Aggregated process contribution to fossil fuel depletion per scenario

The results show that the fossil fuel depletion follows 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 86 % to overall fossil fuel depletion in the original data scenario (see *Figure 7*). In the improved prod./elec. scenario the contribution of electricity is about 82 %. Contributions for water, operating supplies were low.

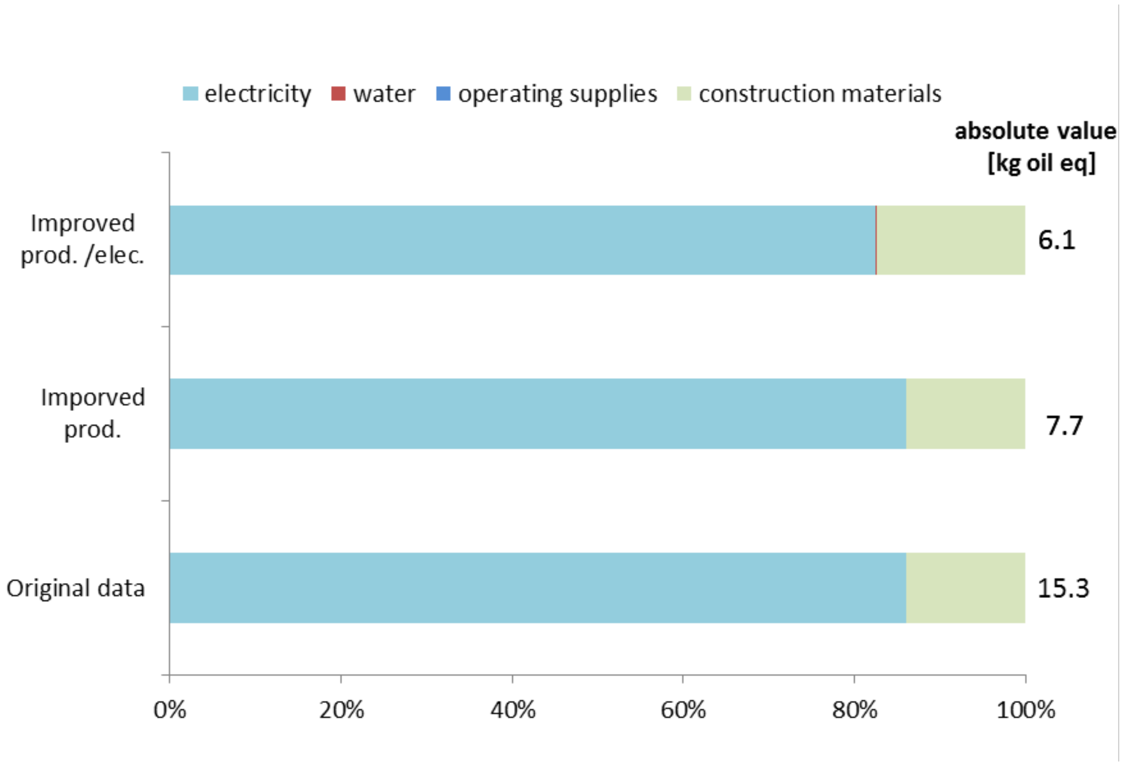

Figure 7: *Aggregated contribution of processes to fossil fuel depletion for 1 MJ of burned algae-based biogas in different scenarios.*

Life-cycle related impact contribution to fossil fuel depletion for the improved prod./elec. scenario (electricity cut off)

As was demonstrated, the cultivation phase made up the highest contribution to fossil fuel depletion (compare Figure 6). In a next step we tried to further display the share of construction materials more detailed, on the improved prod. scenario baseline. As electricity was cut off the impacts of the accounted for 99.7 % of the fossil fuel depletion (see Figure 8). All these materials were separately expressed.

It could be demonstrated that steel, contributed most, with 0.5 kg (45 %) oil eq/MJ burned algae-based biogas. Steel is followed by polycarbonate (0.4 kg oil eq, 36 %).) used for the tubes and the greenhouse. For these materials fossil fuels are used, either for production processes (melting) or directly as carbon source.

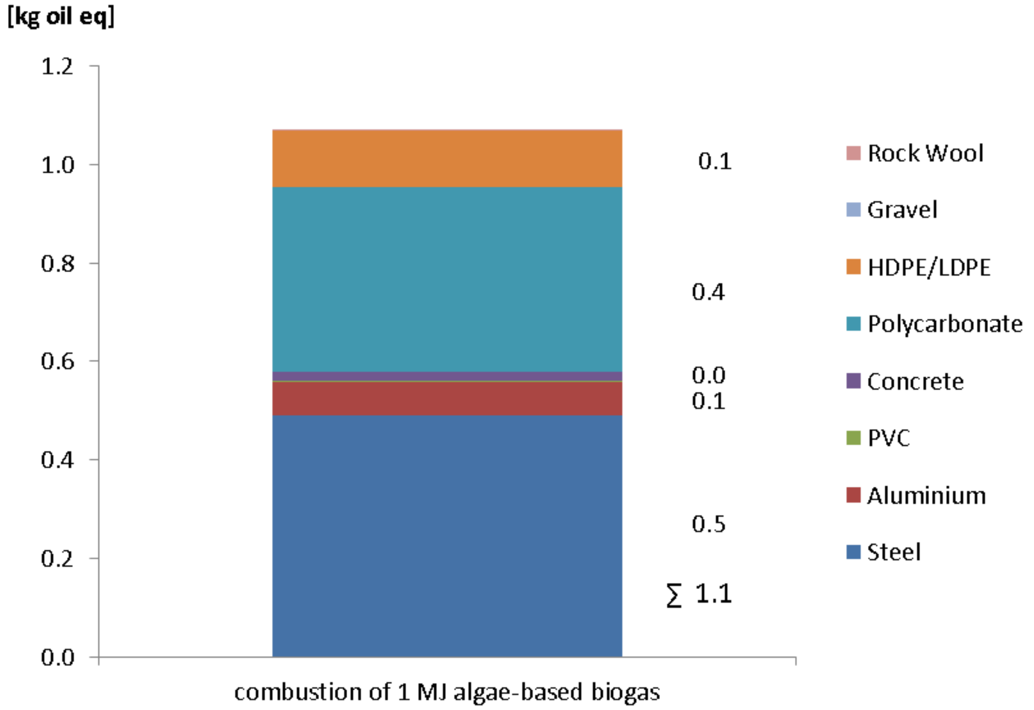

Figure 8: *Contribution to fossil fuel depletion for the improved prod./elec. scenario; the process group, construction materials, is displayed in detail.*

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 the high-tech equipment used.

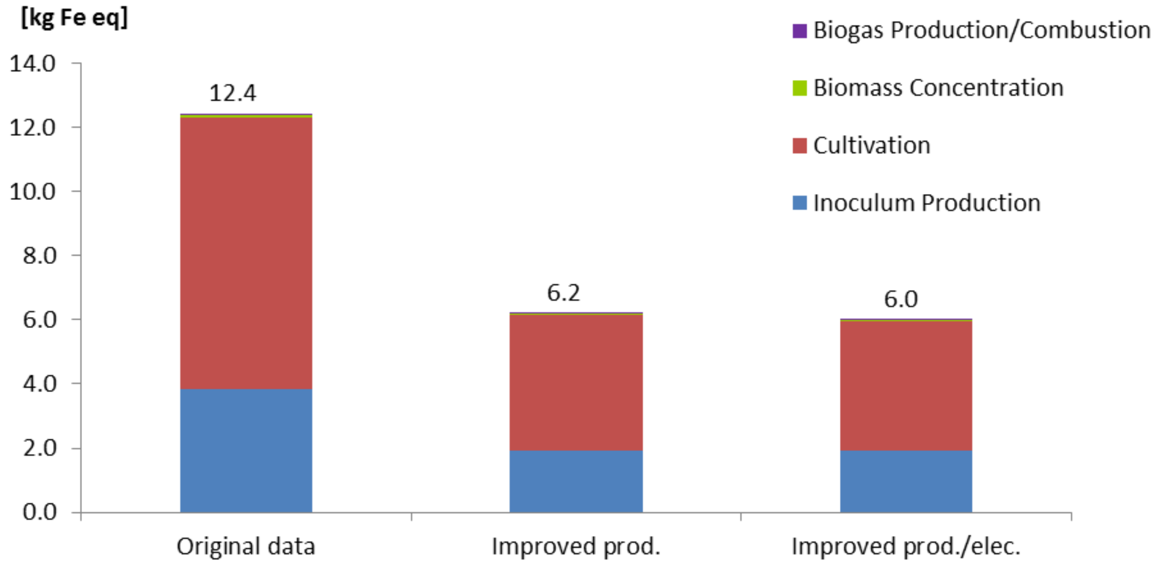

Figure 9: *Contribution of life-cycle phases to mineral resource depletion for 1 MJ of burned algae-based biogas in different scenarios.*

Figure 9 shows the overall result for mineral resource depletion (MRD) expressed in kg of Fe equivalents (eq) per scenario. As high-tech equipment was used during cultivation, this process step contributes 68 %, for the original data scenario, showing an absolute total value of 12.4 kg Fe eq. In contrast, the production and combustion of natural gas accounted for only 0.06 g Fe eq.

In the improved prod. scenario, results for higher biomass productivity are presented. As productivity was doubled, impacts decreased by 50%.

Compared to climate change and fossil depletion the improvements scenario by scenarios led to lower improvements of the total value from 12.4 kg oil eq to 6.0 kg oil eq in mineral resource depletion. The improved prod,/elec. scenario still represented 48 % of the original data impact.

<u>Aggregated process contribution to mineral resource depletion per scenario</u>

The results show that the impact category mineral resource depletion is driven by electricity used over the life cycle (see Figure 10). In the original data scenario construction materials made up a share of 86 %. Complemented by electricity with about 14 % almost the total Fe eq are depleted by these inputs. Comparing the original data scenario and the improved prod. scenario, the absolute values differ strongly whereas the shares of the aggregated process contributors remain constant. In the improved prod./elec. scenario relatively more Fe eq were related to the direct input of construction materials (89 %).

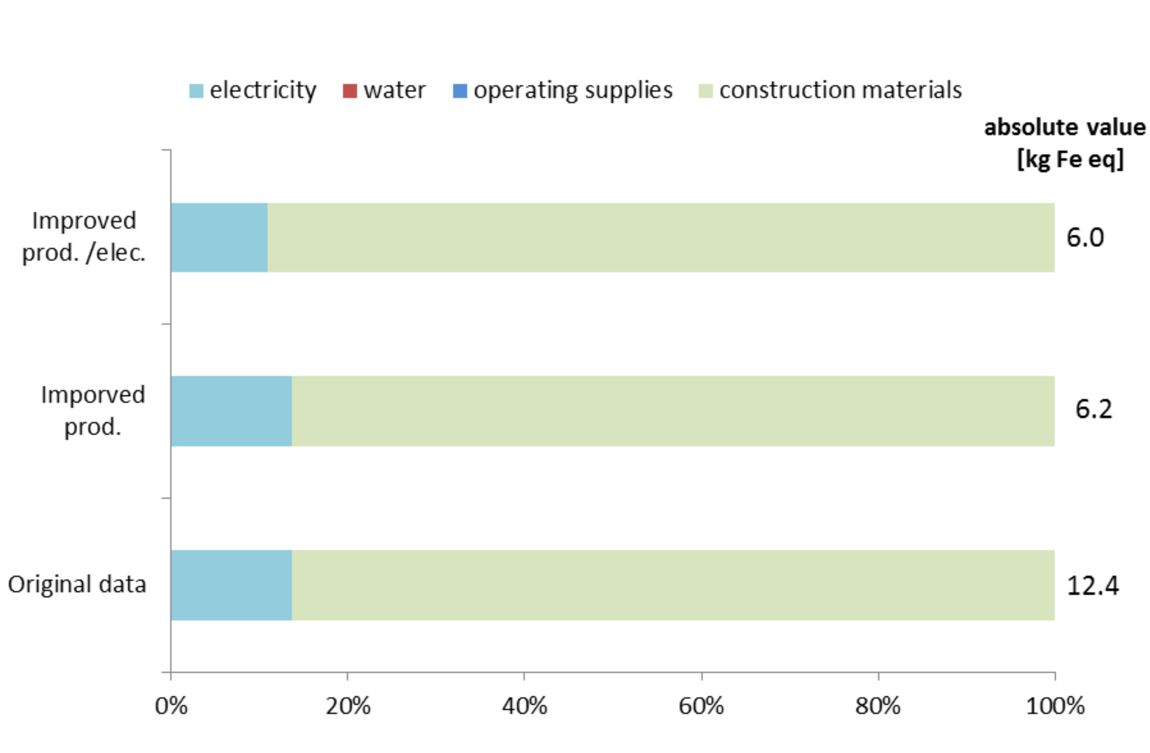

Figure 10: *Aggregated contribution of processes to mineral resource depletion for 1 MJ of burned algae-based biogas in different scenarios.*

Life-cycle related impact contribution to mineral resource depletion for for the improved prod./elec. scenario (electricity cut off)

In the following chart, electricity shares to mineral resource depletion are cut off and the single relevant input was identified and depicted. The results can be seen in Figure 11. Chromium steel is the most important input in this impact category with a share more than 99% of total mineral resource depletion. Other contributors like water, operating supplies as well as other materials were negligible. Consequently, processes that consume a lot of iron, like steel production, amplify the impact of this category.

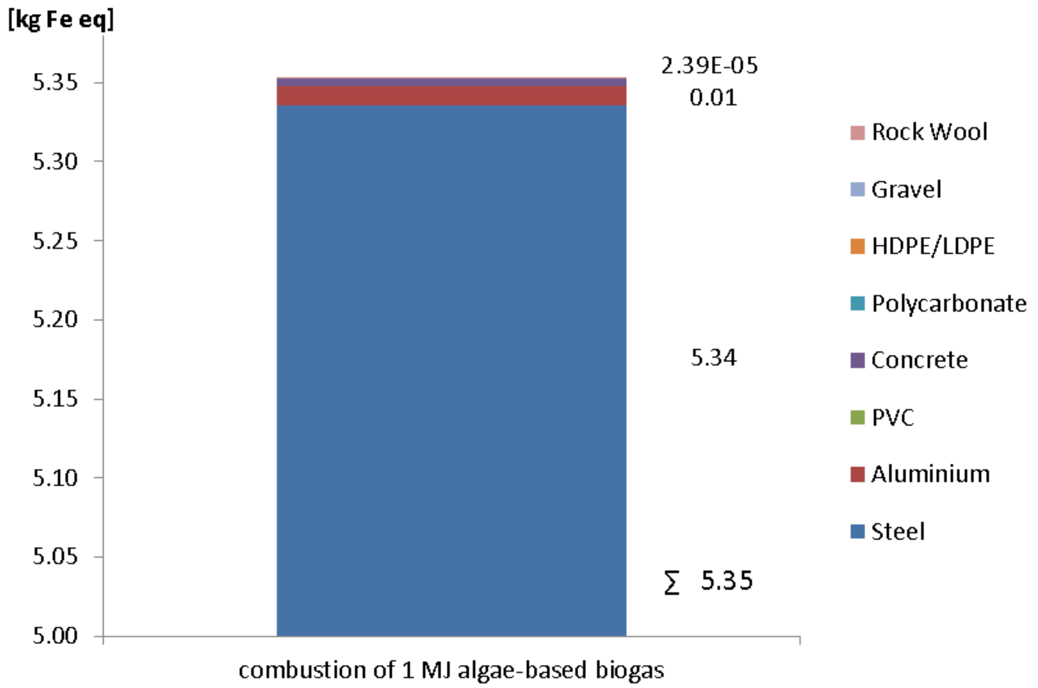

Figure 11: *Contribution to mineral resource depletion for the improved prod./elec. scenario; the process group construction materials is displayed in detail.*

5.1.4 Particulate matter formation

Particulate matter formation was investigated in detail as it had significant contribution, 17 %, 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 release of particles does not take place on-site but it is highly dependent on the use of electricity. The contribution of life-cycle phases is displayed in Figure 12.

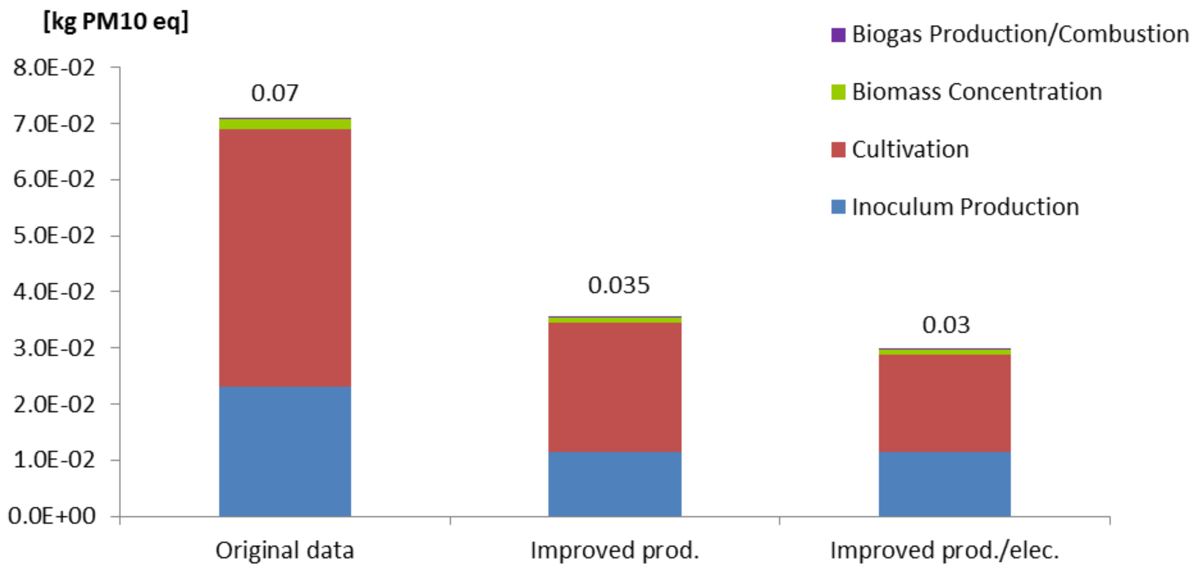

Figure 12: *Contribution of life-cycle phases to particulate matter formation for 1 MJ of burned algae-based biogas for different scenarios.*

The cultivation phase could be determined to be main contributor in all scenarios. In the original data scenario 65 % the PM10 eq are related to the phase of cultivation as it is the most energy intense production step, representing an absolute value of 0.05 kg PM10 eq per MJ algae-based biogas burned. The absolute value decreased step by step as productivity increased and energy inputs were reduced respectively. In the improved prod./elec. scenario the share of the cultivation phase accounted for 67 % equivalent to 0.02 kg PM10 eq. The release of particles is highly related to the electricity used. Therefore the both phases inoculation and cultivation are driving the PM 10 eq formation.

Aggregated process contribution to particulate matter formation per scenario

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

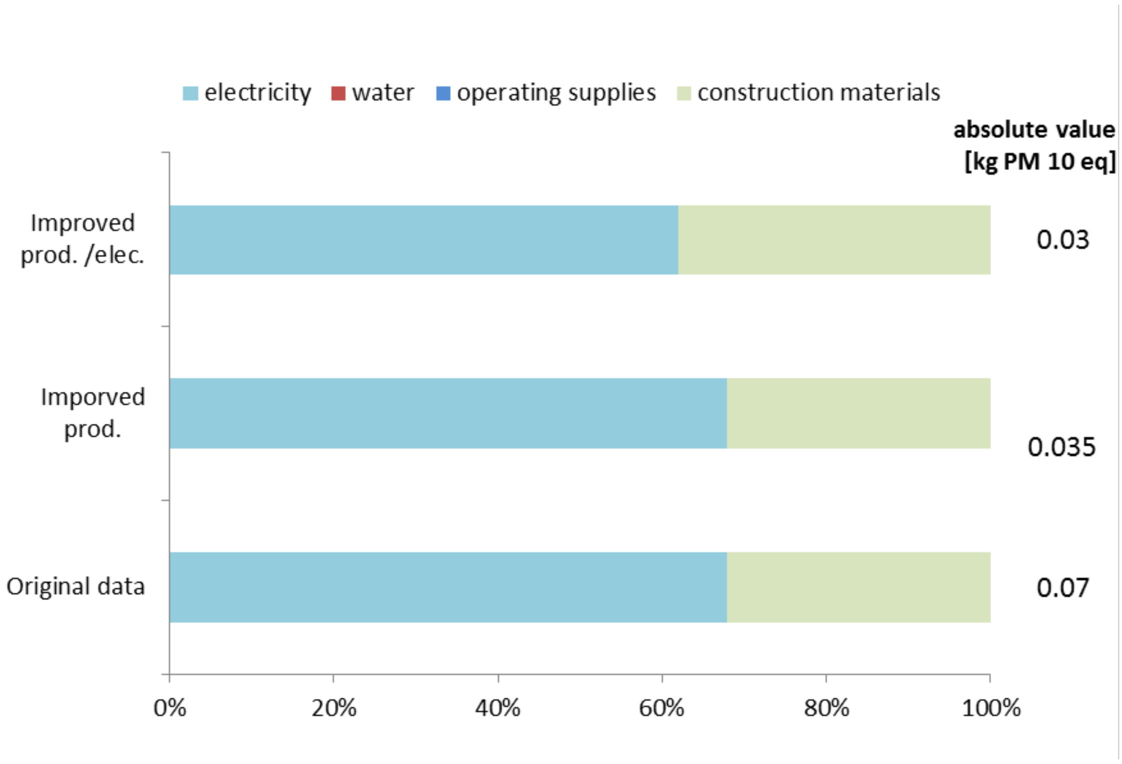

Figure 13: *Aggregated contribution of processes to particulate matter formation for 1 MJ of burned algae-based biogas in different scenarios.*

Among the whole life cycle electricity was identified as the driver of particulate matter formation in all three scenarios varying between 62 % (improved prod./elec. scenario) and 68 % (original data scenario). Among the scenario series the contribution to the PM10 eq formation of water consumption and the use of operating supplies are too low to be visible.

Life-cycle related impact contribution to particulate matter formation for the improved prod./elec. scenario (electricity cut off)

Apart from the direct impact of electricity, it was investigated in detail which materials contributed to the overall particulate matter formation impact. Therefore Figure 14 shows only the contribution of construction materials to PM10 eq formation; still their production is including energy inputs.

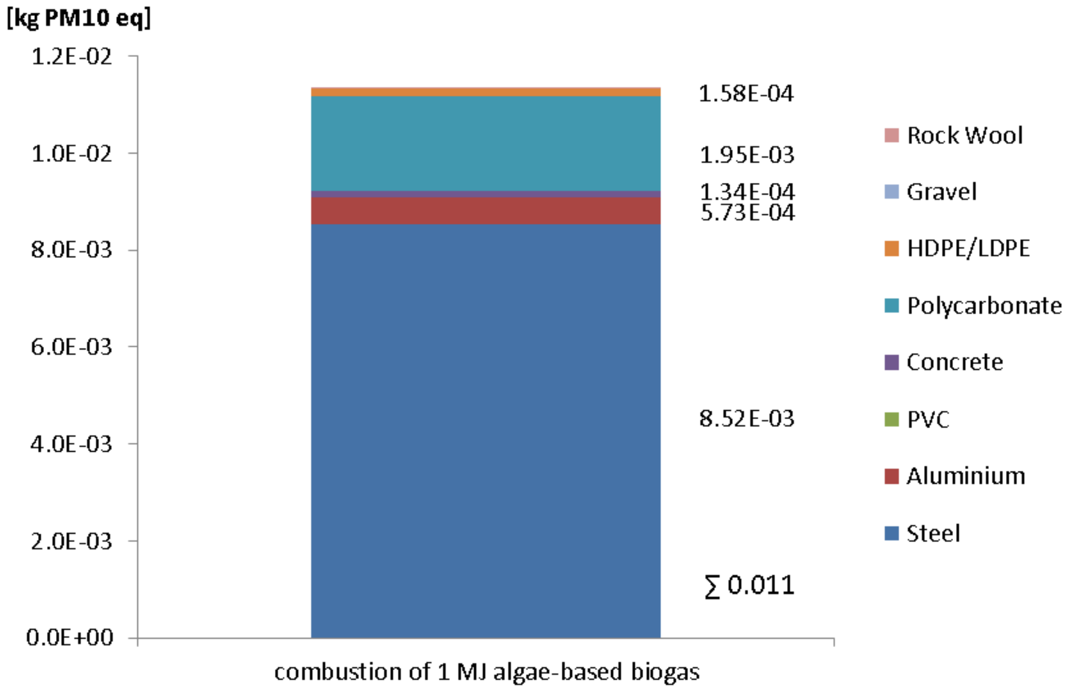

Figure 14: *Contribution to particulate matter formation for the improved prod./elec. scenario; the process group construction materials is displayed in detail.*

In **Error! Reference source not found.** the single material contributions are displayed, as the construction had an overall impact of 99.8 % if direct electricity inputs were cut off. Chromium steel, which is abundant on mining processes and consequently indirectly on electricity, represented the highest share in materials, 8.52E-3 kg PM10 eq (77 %) per MJ of algae-based biogas burned. Another main contributor was polycarbonate with 1.959E-3 kg PM10 eq (18 %).

5.1.5 Water depletion

Water depletion (WD) was assumed to be crucial for algae production systems. The scarcity of water will increase in future (Olesen and Bindi, 2002; Schröter et al., 2005). Consequently, this impact category will gain additional importance even in Europe.

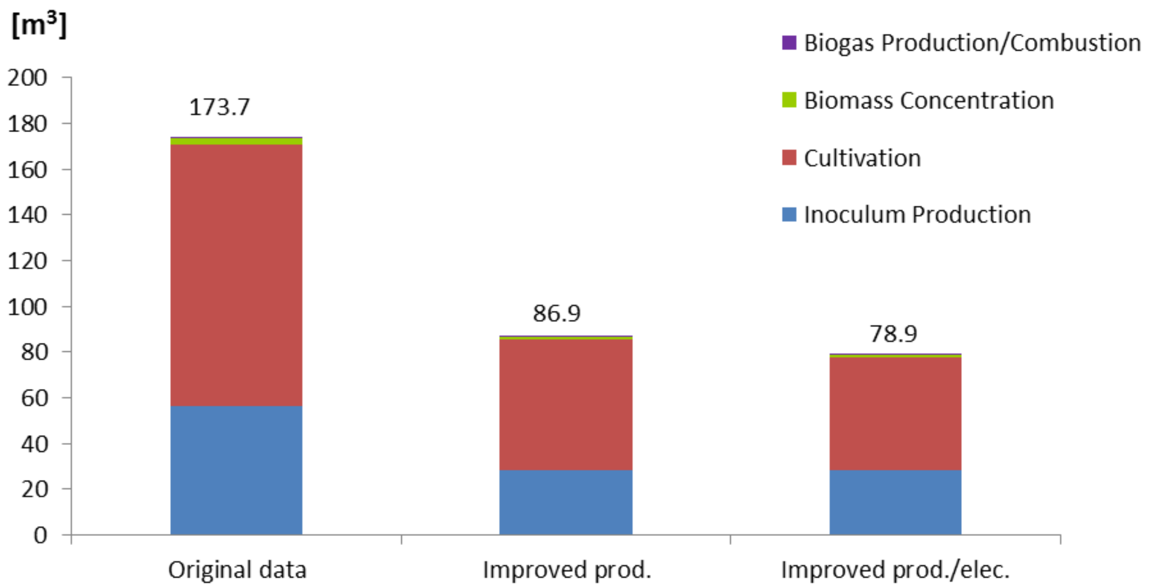

Figure 15: *Contribution of life-cycle phases to water depletion for 1 MJ of burned algae-based biogas for different scenarios.*

Figure 15 shows the results for the impact category water depletion in different scenarios. Main contribution within the original data scenario (66 %) was related to the phase of cultivation. Almost all the rest (32 %) was related to the inoculum production phase. Compared to the life-cycle impact of natural gas, the absolute value (79.3 m^3 per MJ burned algal biogas) is higher.

The theoretical scenario improvements also show up in the results. In the improved prod./elec. scenario the cultivation phase represents a share of 62% with a total value of 78.9 m^3 of water depleted.

<u>Aggregated process contribution to water depletion per scenario</u>

Figure 16 shows the result of the water depletion impact per scenario. Referring to the clustered process contributions, it was observed that the water depletion in all scenarios was mainly driven by construction materials. As the production of steel is quite water intense almost 144 m^3 of water is directly related to the footprint of 1 kg steel.

The depleted water is related to water used in turbines an consequently to the production processes depending on electricity. Like this also direct electricity inputs were determined as important, specifically hydropower generation, which is part of the GB electricity mix.

Both process contributions resulting from materials as well as electricity are referring to water used in turbines. In the latest version of the used impact assessment method (ReCiPe) this water flow was characterized with a factor of one, leading to this huge impact. However, previous versions of the ReCiPe (up to version 1.07) impact assessment method did not include that flow in this impact category.

In the original data scenario for example 99 % of the absolute water depletion is related to the water used in turbines (for hydropower generation). If this flow was cut off, the absolute value would have been 4.3 m^3 instead of 173.7 m^3. In improved prod./elec. scenario we could derive an absolute water depletion value of 0.7 m^3, if turbine water was not considered. Direct water inputs as well as operating supplies were too low to be visible. In the improved prod./elec. scenario 67 % (52.7 m^3) of the depleted water was related to the materials used for the construction of the production system.

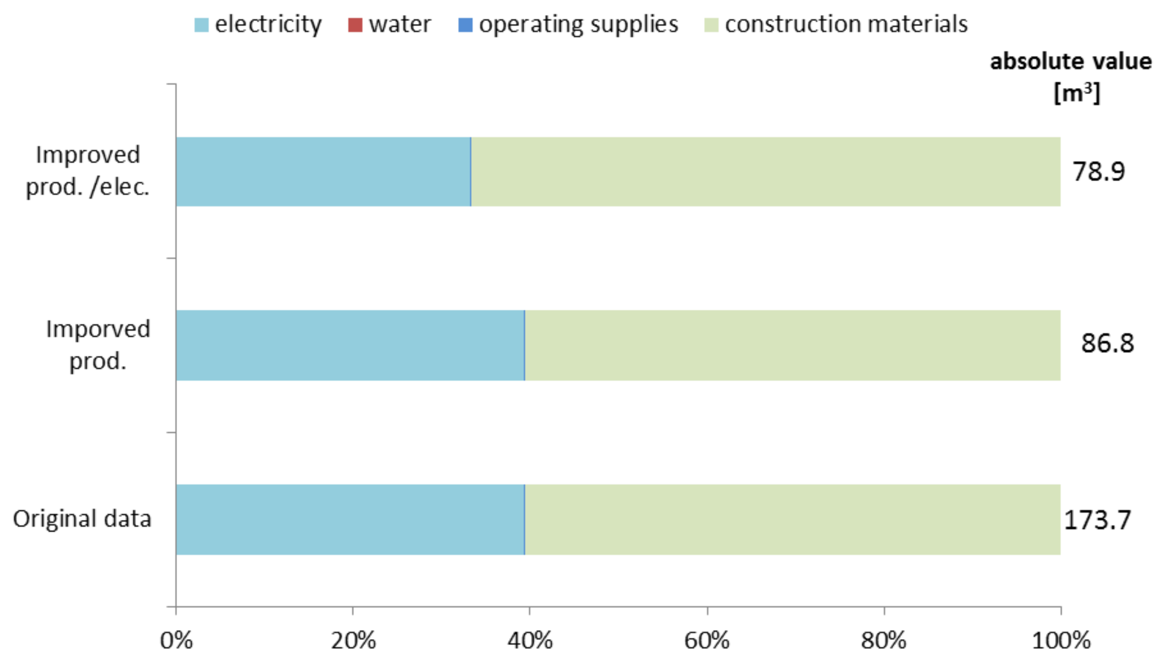

Figure 16: *Aggregated contribution of processes to water depletion for 1 MJ of burned algae-based biogas in different scenarios.*

Life-cycle related impact contribution to water depletion for the improved prod./elec. scenario (electricity cut off)

As it could be demonstrated that direct water inputs do not represent the highest share in water depletion, materials contributions were investigated more detailed (see ***Figure 17***). Upstream electricity inputs among other things like production processes for materials cover the direct water contributions. Water as cultivation medium and for cleaning purposes accounted for only 0.09 m^3. In this scenario the highest wastewater cleaning credit was applied with 0.09 m^3 per MJ algal biogas burned which counterbalances the direct water used.

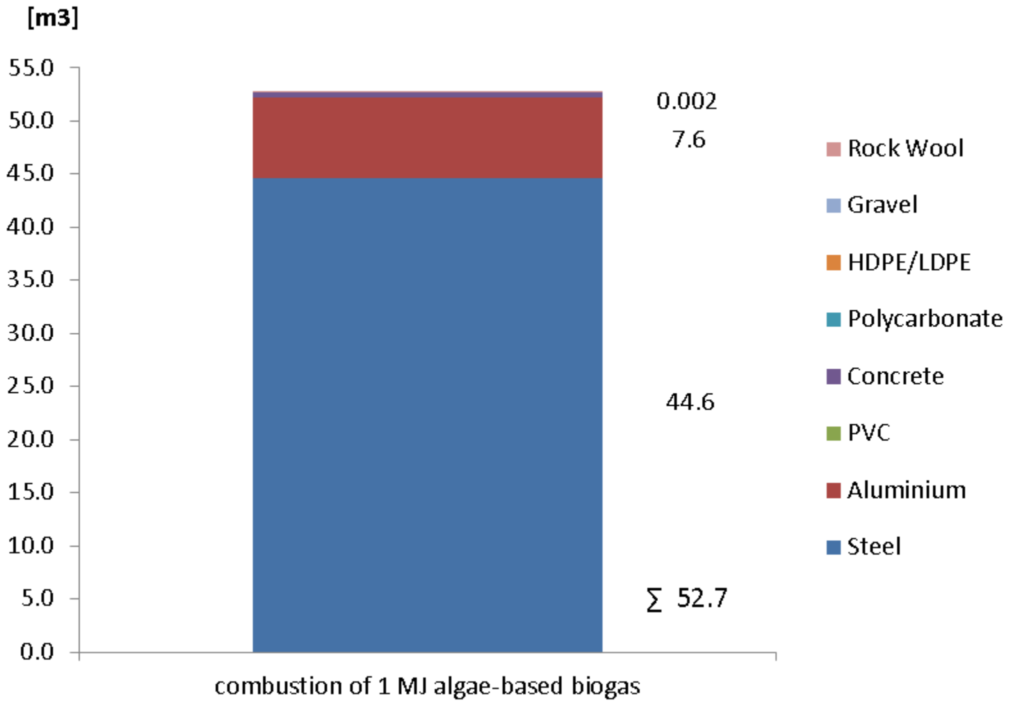

Figure 17: *Contribution to water depletion for the improved prod./elec. scenario; the process group construction materials is displayed in detail.*

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 show similar results and trends to those observed in the ReCiPe categories.

<u>Impact contribution to CEENE per life-cycle phase</u>

As can be seen in Figure 18 the first two production phases (inoculation and cultivation) contribute the most to the aggregated CEENE impact in all three scenarios. In the original data scenario an absolute value of 1050 MJ_{ex} per MJ algal biogas burned was calculated. Similar to the emission base impact assessment of ReCiPe, the resource based CEENE reacts with a reduction of MJ_{ex} by half, when doubling the productivity. From the original data scenario up to the improved prod./elec. scenario improvements by 59 %. 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 referring to all scenarios exceeded the CEENE value for natural gas.

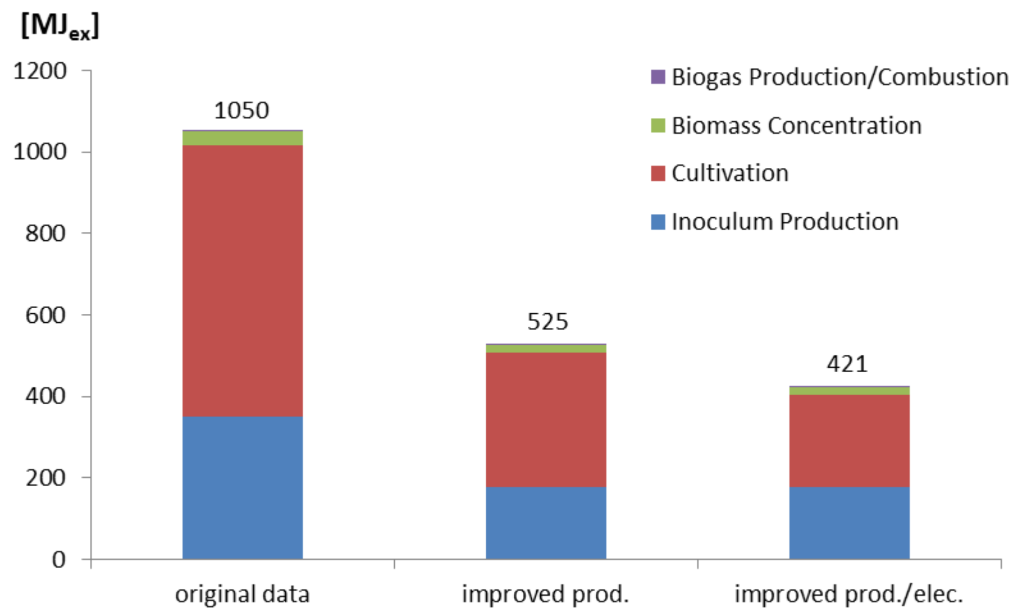

Figure 18: *Contribution of life-cycle phases to the CEENE footprint for 1 MJ of burned algae-based biogas for different scenarios.*

Impact contribution of the resource categories to CEENE per scenario

The results according to resource categories of the three scenarios are presented in ***Figure 19***. The highest share of the total CEENE impact for all scenarios is related to fossil fuel consumption ca. 66 %. Fossil fuels were followed by nuclear energy (ca.18 %), both representing the main shares of the British electricity mix. Water resources were also remarkable with a contribution of about 5 % resulting from indirect water for energy production but also for the material processing. In this respect, the CEENE results differ substantially from the ReCiPe results for water depletion since turbine water for hydropower generation was characterized with a factor of zero in this methodology.

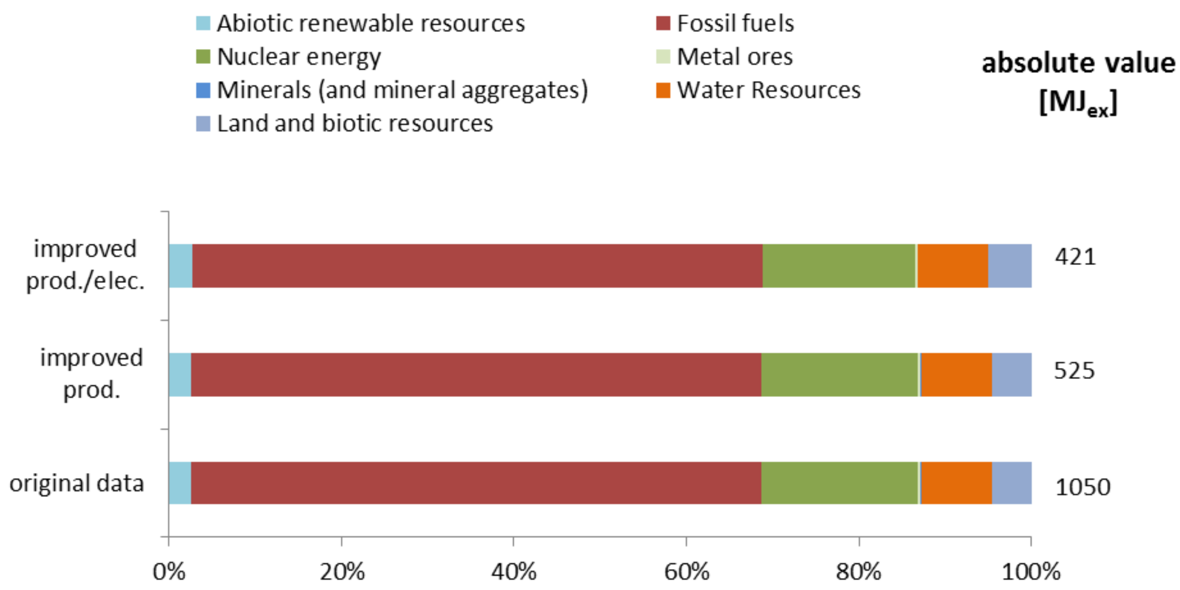

Figure 19: *Impact contribution to CEENE for different resource categories for 1 MJ of burned algae-based biogas.*

6 Summary and Interpretation

In accordance to the economic models developed in the EnAlgae context by Spruijt et al. (2015) who concluded that “electricity costs make up a greater part of the cost price as upscaling continues, showing that the electricity requirement of algae production needs to decrease considerably in order to make bulk markets accessible for micro-algae”, the environmental perspective also highlights, that electricity represents a huge contributor within the algae production of the considered system.

All environmental impacts were driven by the electricity consumption. The share of electricity in the overall results was tremendous and even covered the contribution of other flows like construction materials. To be able to detect impacts, apart from those related to electricity, all electricity inputs were cut off and impacts other than resulting from energy inputs were displayed.

The construction materials used were the second important driver in the considered impact categories, especially chromium steel, and polycarbonate.

To reduce the environmental impacts, construction/reactor materials material saving should be achieved but also materials with lower footprints could be used in order to substitute materials with higher ones.

Optimizing the cultivation for prolonged production cycles allows purchasing an inoculum on demand instead of maintaining the algae in an “inoculation culture” as described here. In tubular systems, the entire water volume has to be lifted to the highest point of the glass modules. A reduction in the pumping energy demand might be achieved if the system is run regularly with slower flow velocity on an equal production level.

Moreover, a single output system was presented, consisting of production, dewatering and energetic use for biogas production. This study showed that a pure energetic use of algae biomass produced in a closed system in stand-alone operation is not feasible. The credit, that was applied for wastewater treatment was negligible, as the amount of water processed was marginal.

7 Conclusions

At InCrops (University of Cambridge Algal Innovation Centre) the microalgae production units assessed in this study are at a laboratory scale. Technical equipment and materials used are not optimized concerning efficient energy use. Consequently, improvements can be expected, if correctly scaled and balanced equipment was used. The small scale prevented theoretical upscaling approaches, as the data baseline was not suitable to be abstracted.

The LCA results specify where the bottlenecks of algae production are located. Fundamental energy reductions are needed to achieve a sustainable algae production. Under current technology restrictions (process set up and scale) it seems hardly possible to overcome the unfavorable energy inputs. 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 sustainability criteria.

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Investing in Opportunities
This project has received European Regional Development Funding through INTERREG IV B.
INTERREG IVB

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 according to the four scenarios in *Table S 1*- S 4. However, for detailed investigation, only five categories have been selected.

Table S 1: *ReCiPe midpoints, absolute values and shares according to life-cycle phases (Original data scenario).*

ReCiPe Impact category (midpoints)		Inoculum Production	%	Cultivation	%	Biomass Concentration	%	Biogas Production/combustion	%	Sum
Climate change (CC)	kg CO2 eq	1.78E+01	33.38	3.38E+01	63.47	1.67E+00	3.14	7.35E-03	0.01	5.33E+01
Ozone depletion (OD)	kg CFC-11 eq	6.16E-07	27.14	1.61E-06	71.00	4.21E-08	1.86	1.73E-10	0.01	2.27E-06
Terrestrial acidification (TA)	kg SO2 eq	5.88E-02	33.44	1.12E-01	63.47	5.38E-03	3.06	5.01E-05	0.03	1.76E-01
Freshwater eutrophication (FE)	kg P eq	5.85E-03	34.01	1.08E-02	62.75	5.55E-04	3.23	2.00E-06	0.01	1.72E-02
Marine eutrophication (ME)	kg N eq	2.50E-03	40.04	3.51E-03	56.20	2.33E-04	3.74	1.48E-06	0.02	6.24E-03
Human toxicity (HT)	kg 1,4-DB eq	5.81E+00	33.32	1.11E+01	63.66	5.25E-01	3.01	2.01E-03	0.01	1.74E+01
Photochemical oxidant formation (POF)	kg NMVOC	3.85E-02	33.36	7.35E-02	63.64	3.43E-03	2.97	3.43E-05	0.03	1.15E-01
Particulate matter formation (PMF)	kg PM10 eq	2.31E-02	32.63	4.58E-02	64.80	1.80E-03	2.55	1.58E-05	0.02	7.07E-02
Terrestrial ecotoxicity (TET)	kg 1,4-DB eq	1.37E-03	33.39	2.61E-03	63.60	1.23E-04	3.00	4.76E-07	0.01	4.10E-03
Freshwater ecotoxicity (FET)	kg 1,4-DB eq	5.74E-02	33.16	1.11E-01	64.05	4.80E-03	2.78	1.98E-05	0.01	1.73E-01
Marine ecotoxicity (MET)	kg 1,4-DB eq	7.07E-02	33.38	1.35E-01	63.88	5.77E-03	2.72	2.48E-05	0.01	2.12E-01
Ionising radiation (IR)	kg U235 eq	7.45E+00	34.20	1.36E+01	62.33	7.54E-01	3.46	2.53E-03	0.01	2.18E+01
Agricultural land occupation (ALO)	m2a	3.42E-01	33.94	6.32E-01	62.76	3.31E-02	3.28	1.21E-04	0.01	1.01E+00
Urban land occupation (ULO)	m2a	2.45E-01	23.43	7.91E-01	75.83	7.69E-03	0.74	3.44E-05	0.00	1.04E+00
Natural land transformation (NLT)	m2	3.27E-03	34.15	5.98E-03	62.41	3.28E-04	3.43	1.16E-06	0.01	9.57E-03
Water depletion (WD)	m3	5.64E+01	32.47	1.15E+02	65.92	2.78E+00	1.60	2.10E-02	0.01	1.74E+02
Mineral resource depletion (MRD)	kg Fe eq	3.85E+00	31.03	8.45E+00	68.14	1.02E-01	0.82	1.41E-03	0.01	1.24E+01
Fossil fuel depletion (FD)	kg oil eq	5.18E+00	33.80	9.67E+00	63.05	4.81E-01	3.14	1.68E-03	0.01	1.53E+01

Table S 2: *ReCiPe midpoints, absolute values and shares according to life-cycle phases (Improved prod. scenario).*

ReCiPe Impact category (midpoints)		Inoculum Production	%	Cultivation	%	Biomass Concentration	%	Biogas Production/combustion	%	Sum
Climate change (CC)	kg CO2 eq	8.89E+00	33.37	1.69E+01	63.46	8.37E-01	3.14	7.35E-03	0.03	2.66E+01
Ozone depletion (OD)	kg CFC-11 eq	3.08E-07	27.14	8.06E-07	70.99	2.11E-08	1.85	1.73E-10	0.02	1.14E-06
Terrestrial acidification (TA)	kg SO2 eq	2.94E-02	33.43	5.58E-02	63.46	2.69E-03	3.06	5.01E-05	0.06	8.79E-02
Freshwater eutrophication (FE)	kg P eq	2.93E-03	34.01	5.40E-03	62.74	2.78E-04	3.23	2.00E-06	0.02	8.60E-03
Marine eutrophication (ME)	kg N eq	1.25E-03	39.99	1.76E-03	56.23	1.17E-04	3.73	1.48E-06	0.05	3.12E-03
Human toxicity (HT)	kg 1,4-DB eq	2.90E+00	33.31	5.55E+00	63.65	2.63E-01	3.01	2.01E-03	0.02	8.72E+00
Photochemical oxidant formation (POF)	kg NMVOC	1.93E-02	33.35	3.68E-02	63.62	1.71E-03	2.97	3.43E-05	0.06	5.78E-02
Particulate matter formation (PMF)	kg PM10 eq	1.15E-02	32.62	2.29E-02	64.79	9.01E-04	2.55	1.58E-05	0.04	3.54E-02
Terrestrial ecotoxicity (TET)	kg 1,4-DB eq	6.85E-04	33.38	1.30E-03	63.60	6.15E-05	3.00	4.76E-07	0.02	2.05E-03
Freshwater ecotoxicity (FET)	kg 1,4-DB eq	2.87E-02	33.16	5.54E-02	64.04	2.40E-03	2.78	1.98E-05	0.02	8.65E-02
Marine ecotoxicity (MET)	kg 1,4-DB eq	3.54E-02	33.38	6.77E-02	63.87	2.89E-03	2.72	2.48E-05	0.02	1.06E-01
Ionising radiation (IR)	kg U235 eq	3.72E+00	34.20	6.79E+00	62.32	3.77E-01	3.46	2.53E-03	0.02	1.09E+01
Agricultural land occupation (ALO)	m2a	1.71E-01	33.94	3.16E-01	62.75	1.65E-02	3.28	1.21E-04	0.02	5.04E-01
Urban land occupation (ULO)	m2a	1.22E-01	23.43	3.96E-01	75.83	3.84E-03	0.74	3.44E-05	0.01	5.22E-01
Natural land transformation (NLT)	m2	1.63E-03	34.14	2.99E-03	62.41	1.64E-04	3.43	1.16E-06	0.02	4.79E-03
Water depletion (WD)	m3	2.82E+01	32.47	5.73E+01	65.91	1.39E+00	1.60	2.10E-02	0.02	8.69E+01
Mineral resource depletion (MRD)	kg Fe eq	1.92E+00	31.03	4.22E+00	68.13	5.08E-02	0.82	1.41E-03	0.02	6.20E+00
Fossil fuel depletion (FD)	kg oil eq	2.59E+00	33.79	4.83E+00	63.05	2.40E-01	3.14	1.68E-03	0.02	7.67E+00

Table S 3: *ReCiPe midpoints, absolute values and shares according to life-cycle phases (Improved prod./elec.).*

ReCiPe Impact category (midpoints)		Inoculum Production	%	Cultivation	%	Biomass Concentration	%	Biogas Production/combustion	%	Sum
Climate change (CC)	kg CO2 eq	8.89E+00	41.74	1.16E+01	54.30	8.37E-01	3.93	7.35E-03	0.03	2.13E+01
Ozone depletion (OD)	kg CFC-11 eq	3.08E-07	30.75	6.72E-07	67.13	2.11E-08	2.10	1.73E-10	0.02	1.00E-06
Terrestrial acidification (TA)	kg SO2 eq	2.94E-02	41.50	3.87E-02	54.62	2.69E-03	3.80	5.01E-05	0.07	7.08E-02
Freshwater eutrophication (FE)	kg P eq	2.93E-03	42.79	3.63E-03	53.12	2.78E-04	4.06	2.00E-06	0.03	6.84E-03
Marine eutrophication (ME)	kg N eq	1.25E-03	52.45	1.01E-03	42.59	1.17E-04	4.90	1.48E-06	0.06	2.38E-03
Human toxicity (HT)	kg 1,4-DB eq	2.90E+00	41.16	3.89E+00	55.08	2.63E-01	3.72	2.01E-03	0.03	7.05E+00
Photochemical oxidant formation (POF)	kg NMVOC	1.93E-02	41.08	2.59E-02	55.19	1.71E-03	3.66	3.43E-05	0.07	4.69E-02
Particulate matter formation (PMF)	kg PM10 eq	1.15E-02	38.74	1.73E-02	58.19	9.01E-04	3.02	1.58E-05	0.05	2.98E-02
Terrestrial ecotoxicity (TET)	kg 1,4-DB eq	6.85E-04	41.20	9.15E-04	55.07	6.15E-05	3.70	4.76E-07	0.03	1.66E-03
Freshwater ecotoxicity (FET)	kg 1,4-DB eq	2.87E-02	40.15	4.03E-02	56.47	2.40E-03	3.36	1.98E-05	0.03	7.14E-02
Marine ecotoxicity (MET)	kg 1,4-DB eq	3.54E-02	40.20	4.97E-02	56.49	2.89E-03	3.28	2.48E-05	0.03	8.80E-02
Ionising radiation (IR)	kg U235 eq	3.72E+00	43.96	4.37E+00	51.56	3.77E-01	4.45	2.53E-03	0.03	8.47E+00
Agricultural land occupation (ALO)	m2a	1.71E-01	42.91	2.11E-01	52.91	1.65E-02	4.15	1.21E-04	0.03	3.98E-01
Urban land occupation (ULO)	m2a	1.22E-01	24.56	3.72E-01	74.66	3.84E-03	0.77	3.44E-05	0.01	4.98E-01
Natural land transformation (NLT)	m2	1.63E-03	43.76	1.93E-03	51.81	1.64E-04	4.40	1.16E-06	0.03	3.73E-03
Water depletion (WD)	m3	2.82E+01	35.73	4.93E+01	62.48	1.39E+00	1.76	2.10E-02	0.03	7.89E+01
Mineral resource depletion (MRD)	kg Fe eq	1.92E+00	32.04	4.03E+00	67.08	5.08E-02	0.85	1.41E-03	0.02	6.00E+00
Fossil fuel depletion (FD)	kg oil eq	2.59E+00	42.23	3.30E+00	53.82	2.40E-01	3.92	1.68E-03	0.03	6.13E+00

For comparison, in Table S 4 the ReCiPe midpoint impacts are displayed for the fossil reference of 1 MJ of burned natural gas.

Table S 4: *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, 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 5* , 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 5*, the first two phases, the inoculum production and cultivation, account for almost 100 % of the individual impacts. Biomass concentration and biogas production/use are negligible concerning their shares in environmental impacts.

Table S 5: *Contribution of midpoints, absolute values and shares, to the endpoint categories human health, ecosystems and resources, according to life-cycle phases (Original data scenario).*

Human health [DALY]	per 1 MJ algal biogas combustion	Inoculum Production	%	Cultivation	%	Biomass Concentration	%	Biogas Production/combustion	%	aggregated Endpoint
Photochemical oxidant formation	kg NMVOC	1.50E-09	33.36	2.87E-09	63.64	1.34E-10	2.97	1.34E-12	0.03	
Ozone depletion	kg CFC-11 eq	7.95E-09	33.60	1.50E-08	63.49	6.86E-10	2.90	3.12E-12	0.01	
Ionising radiation	kg U235 eq	1.22E-07	34.20	2.23E-07	62.33	1.24E-08	3.46	4.14E-11	0.01	**1.06E-04**
Particulate matter formation	kg PM10 eq	6.00E-06	32.63	1.19E-05	64.80	4.68E-07	2.55	4.10E-09	0.02	
Human toxicity	kg 1,4-DB eq	4.07E-06	33.32	7.77E-06	63.66	3.68E-07	3.01	1.40E-09	0.01	
Climate change	kg CO2 eq	2.49E-05	33.38	4.74E-05	63.47	2.34E-06	3.14	1.03E-08	0.01	
Ecosystems [species*yr]	**per 1 MJ algal biogas combustion**	**Inoculum Production**	**%**	**Cultivation**	**%**	**Biomass Concentration**	**%**	**Biogas Production/Use**	**%**	**aggregated Endpoint**
Marine ecotoxicity	kg 1,4-DB eq	1.41E-07	33.38	2.68E-07	63.47	1.33E-08	3.14	5.83E-11	0.00	
Freshwater ecotoxicity	kg 1,4-DB eq	3.41E-10	33.44	6.47E-10	63.47	3.12E-11	3.06	2.91E-13	0.00	
Terrestrial ecotoxicity	kg 1,4-DB eq	2.60E-10	34.01	4.79E-10	62.75	2.47E-11	3.23	8.87E-14	0.00	
Terrestrial acidification	kg SO2 eq	2.06E-10	33.39	3.93E-10	63.60	1.85E-11	3.00	7.17E-14	0.00	
Freshwater eutrophication	kg P eq	4.94E-11	33.16	9.54E-11	64.05	4.14E-12	2.78	1.70E-14	0.00	**5.02E-07**
Urban land occupation	m2a	1.25E-11	33.38	2.38E-11	63.88	1.02E-12	2.72	4.37E-15	0.00	
Agricultural land occupation	m2a	4.10E-09	33.94	7.59E-09	62.76	3.97E-10	3.28	1.46E-12	0.00	
Natural land transformation	m2	5.07E-09	23.43	1.64E-08	75.83	1.59E-10	0.74	7.12E-13	0.00	
Climate change	kg CO2 eq	1.10E-08	25.56	3.19E-08	74.40	1.17E-11	0.03	3.64E-12	0.00	
Resources [$]	**per 1 MJ algal biogas combustion**	**Inoculum Production**	**%**	**Cultivation**	**%**	**Biomass Concentration**	**%**	**Biogas Production/Use**	**%**	**aggregated Endpoint**
Metal depletion	kg Fe eq	8.57E-01	33.80	1.60E+00	63.05	7.96E-02	3.14	2.78E-04	0.01	**3.42E+00**
Fossil depletion	kg oil eq	2.75E-01	31.03	6.04E-01	68.14	7.27E-03	0.82	1.01E-04	0.01	

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.

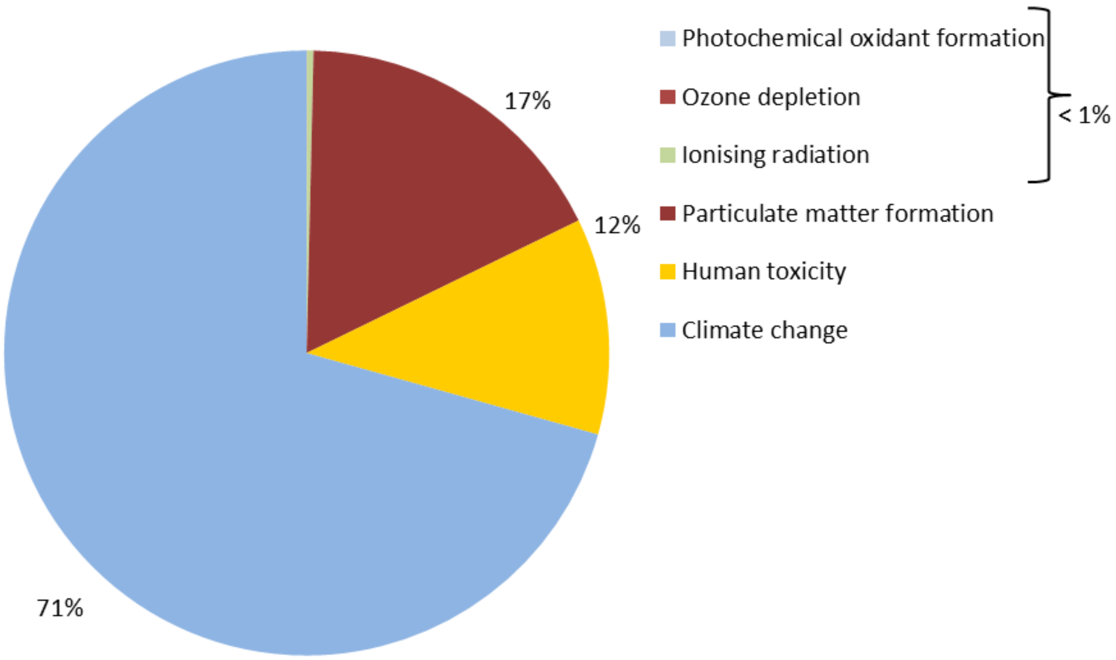


Figure S 1: *Weighted contribution of midpoint categories on the endpoint level "damage to human health".*

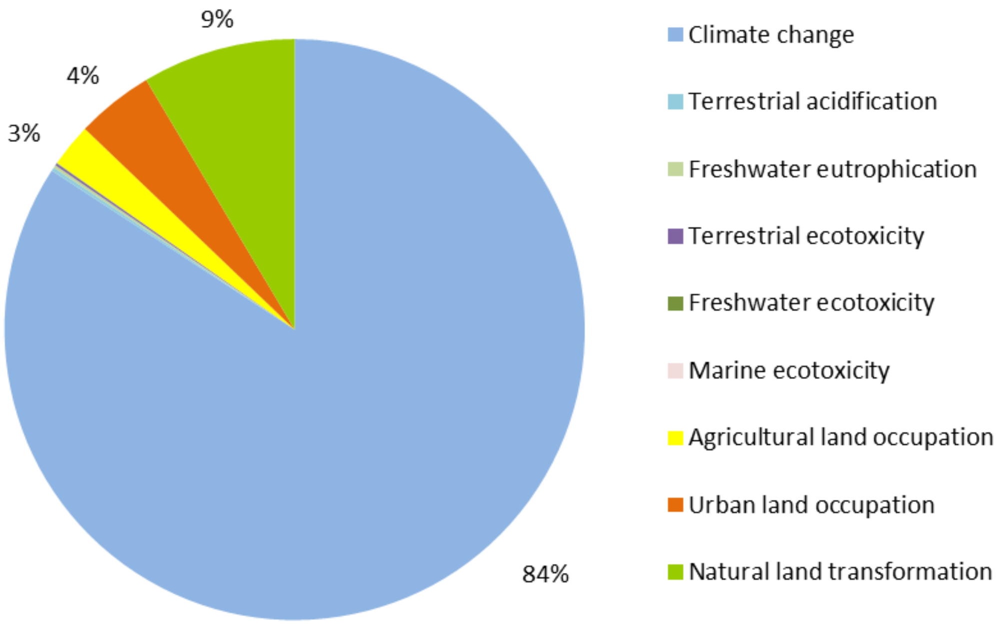


Figure S 2: *Weighted contribution of midpoint categories on the endpoint level "damage to ecosystem diversity".*

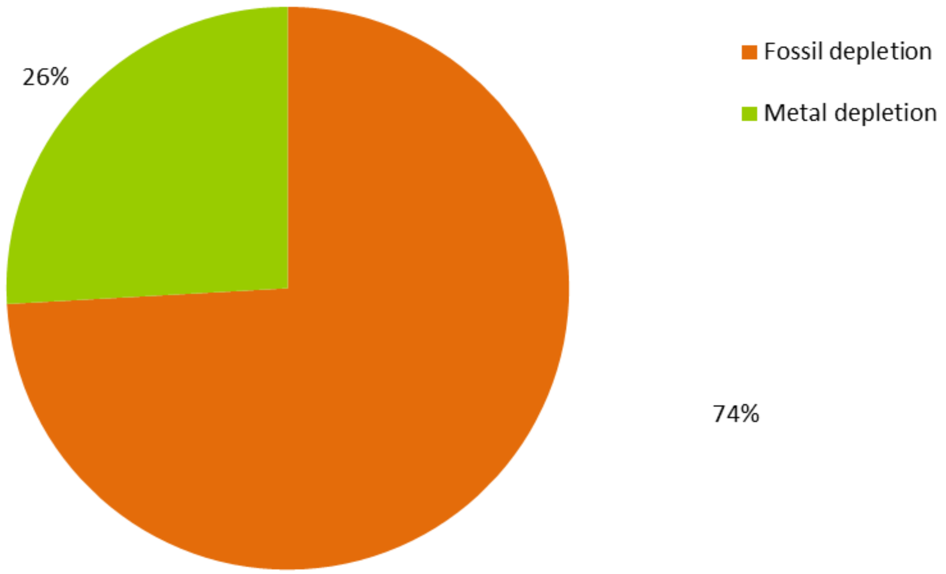
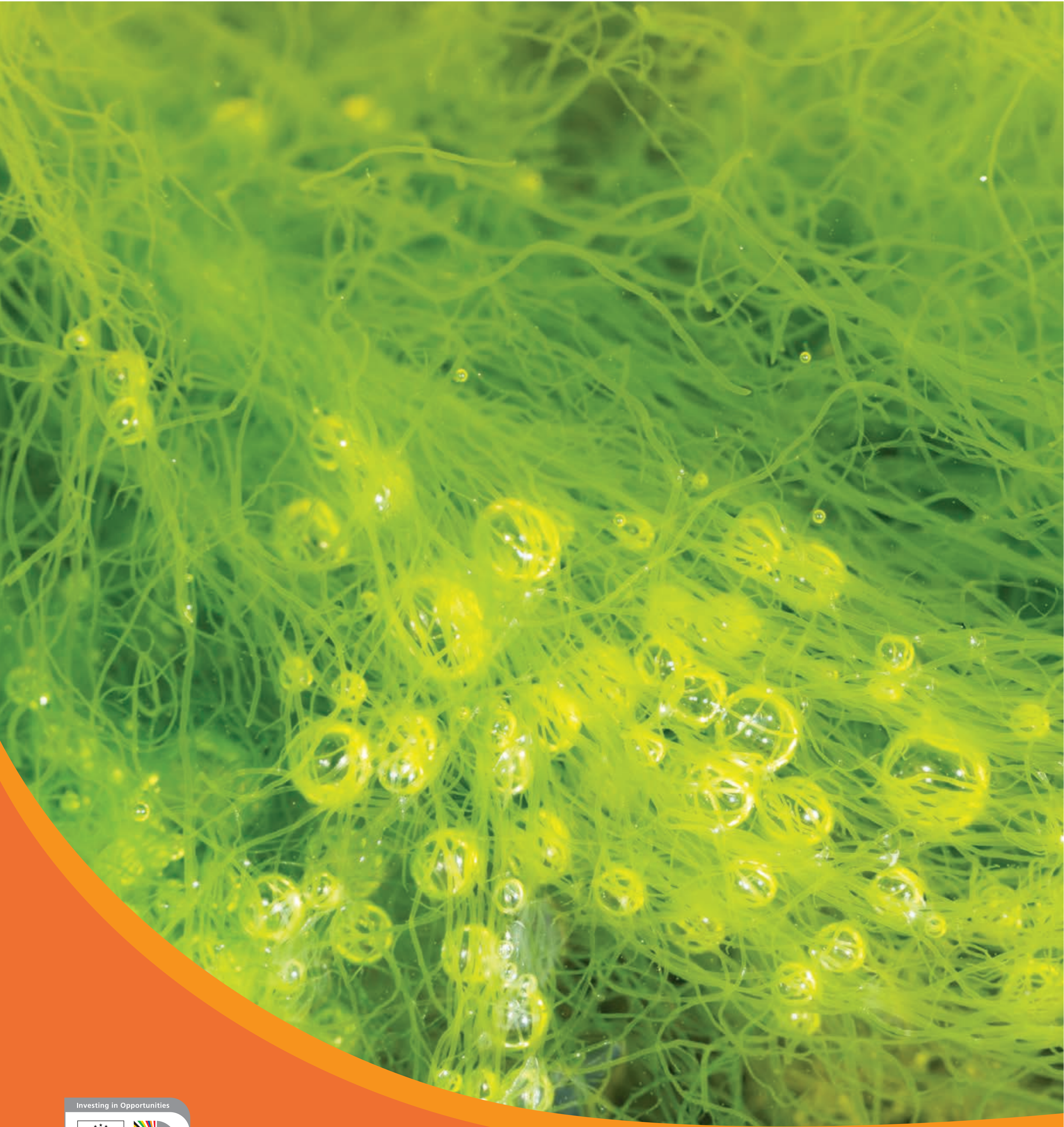


Figure S 3: *Weighted contribution of midpoint categories on the endpoint level "damage to resource availability".*



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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