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Environmental life cycle assessment (LCA) of microalgae production at Swansea University

Report WP2A11.03

Energetic Algae ('EnAlgae')

Project no. 215G

Public Output

WP2A11.03 − Environmental life cycle assessment (LCA) of microalgae production at SU

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Please cite this document as follows:
Kugler, F.; Skarka, J.; Rösch, C. 2015: *Environmental life cycle assessment (LCA) of microalgae production at SU*. Public Output report of the EnAlgae project, Swansea, December 2015, 36pp. Available online at www.enalgae.eu.

This document is an output from the Energetic Algae ('EnAlgae') project, which has received European Regional Development Funding through the INTERREG IVB NWE programme.

Environmental life cycle assessment (LCA) of microalgae production at SU

Contents

Figures

Tables

Environmental life cycle assessment (LCA) of microalgae production at SU

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 Swansea University (SU) microalgae experiments are carried out to determine physiological qualities of different algae species under different growth conditions e.g. wastewater as nutrient source. The facilities include different closed photobioreactor (PBR) types for the production of microalgae.

Within the project context, tubular reactor systems (horizontal/vertical) were built and compared according to different process parameters. Scientists at SU focused on exploring ways to grow, harvest and process microalgal biomass. The marine species *Nannochloropsis oceanica* was cultivated in a horizontal tubular reactor. Though the system did not run the whole year, data was provided based on extrapolations, for a one-year microalgae biomass production.

As there was no downstream processing available and final biomass application was defined as bioenergy production according to the project scope, 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).

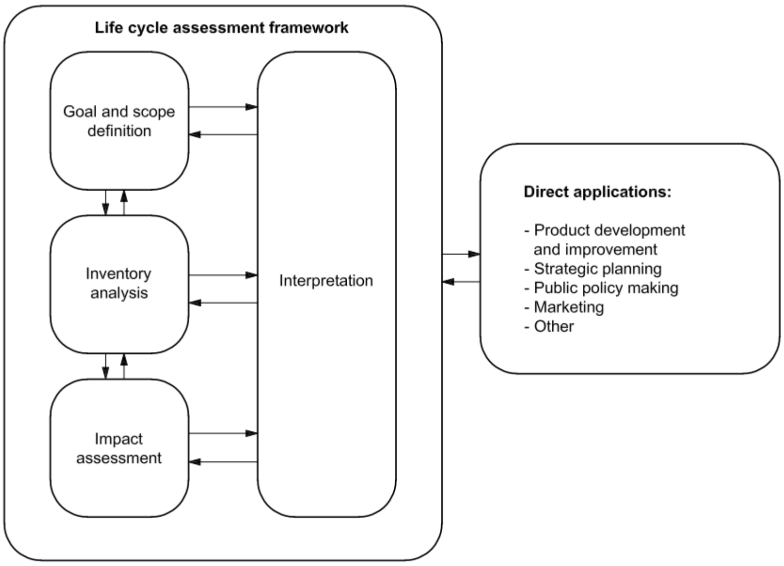

Figure 1: *LCA as a 4-phase process according to the ISO standards 14040: goal and scope definition, inventory analysis, impact assessment and interpretation (International Organization for Standardization, 2006).*

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 S6*).

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 Swansea University (SU) are located in South Wales, characterized maritime climate, with weather that is often cloudy, wet and windy but mild and moderate variations between extreme temperatures. Data for similar tubular reactors (400 L and 600 L) was provided. In this study results for the 600 reactor will be presented, as it was more likely to achieve favorable LCA results. The 400 L cultivation system was located in the basement of the lab building, equipped with central heating and artificial lighting for the whole year. Consequently high energy inputs were assumed, which are not reasonable to apply in larger scale but only for experimental purposes.

The marine species *Nannochloropsis oceanica* was cultivated. The system was operated semi-continuous, following three partial harvests per run and 12 runs per year. 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. Due to maintenance and cleaning processes a net cultivation period of about 330 days was assumed.

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

- Inoculation
- cultivation
- harvesting/dewatering and
- biogas production/combustion.

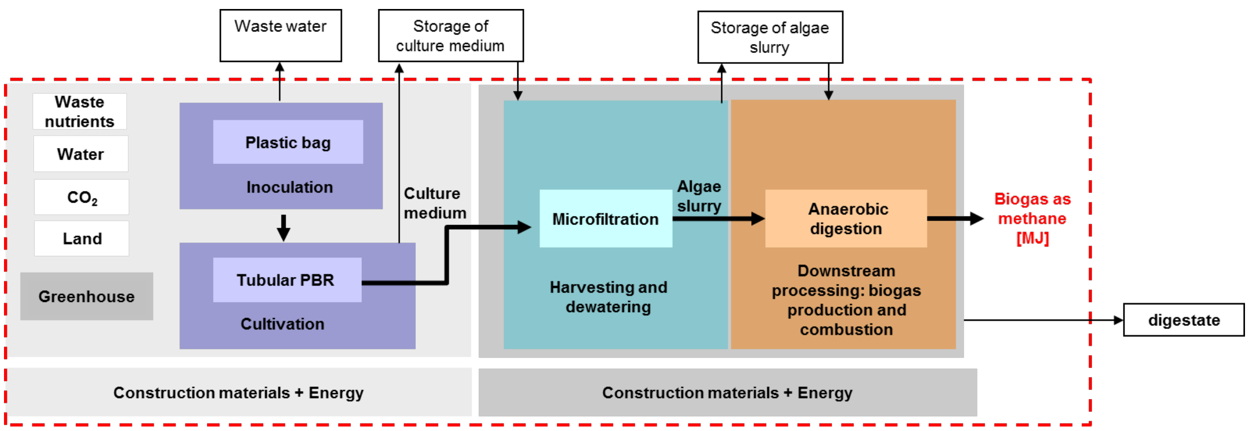

Figure 2: *System boundary and process flows included in the LCA: Processes supplied by experimental (lab) data and numbers are highlighted in light grey; processes supplied by database data and literature are highlighted in dark grey. The system boundary is displayed as red-dotted line.*

Table 1 summarizes the main cultivation parameters. As it was proved that *N. oceanica* has the potential to treat wastewater; Nutrients, e.g. nitrogen and phosphorus are taken up with an removal efficiency of 78.4 % and 52.3 %, respectively (Sirakov and Velichkova, 2014). Consequently a water treatment/cleaning credit was applied.

First, the inoculation culture has been prepared in 80 L plastic bags, being mixed by CO_2 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 1.2 g/L. With only 10 % of the final reactor volume the inoculation volume was assumed to be 60 L. The inoculation culture was transferred and diluted in the horizontal tubular closed PBR with a total volume of 600 L. After 7-10 days of cultivation, the biomass has been harvested the first time, 35 % of the culture medium (210 L) and filled up with marine tap water again. Two partial harvests with the same volume followed after three days, each. Twelve runs per year could be realized with buffer time in between for cleaning and maintenance purposes.

The 600 L reactor was located in a greenhouse nearby, equipped with central heating and artificial lighting just wintertime.

The systems were consisting of 48 polycarbonate tubes supported by a steel frame. The system was equipped with probes to measure pH, temperature, and optical density. It contains a level - and a pressure control system for automatic operation. Bottled CO_2 was supplied for pH control and energy source. An average concentration of 1.2 g/L was assumed shortly before harvesting. In total, a yearly production of 17.7 kg of dry algal biomass was estimated, resulting in an areal yield of 19.7 t/ha/a.

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 microfiltration unit. 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
Nutrient source	Waste water (cattle)
Culture volume	600 L
Average algae conc.	1.2 g/L
Total biomass yield	17.7 kg
Areal yield	19.7 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 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 3,700 kWh (lighting and gassing) plus 1,250 kWh central heating
  - Material specification/amount used for the 80 L plastic bag were obtained from the pilot operator
  - Wastewater was supplied to fulfill f/2 medium concentrations (12.4 mg/L N, 3.4 mg/L PO_4^-), without any environmental burdens
- **Cultivation**
  - During cultivation about 2,700 kWh/a were assumed for lighting in winter time and 13,300 kWh for pumping the culture
  - Material specification/amount used for the 600 L cultivation reactor as well as the supporting frame were obtained from the pilot operator
  - A standard greenhouse (materials/size) was modelled with 10 m^2 area
  - Wastewater was supplied to fulfill f/2 medium concentrations (12.4 mg/L N, 3.4 mg/L PO_4^-), without any environmental burdens
- **Biomass concentration**
  - The microfiltration unit (Dango & Dienenthal, Filtertechnik GmbH, Separator technical data sheet, 2011, specification M, 150 m^3/h capacity and 8,500 operating hours/a) was modelled to concentrate the biomass slurry for further fermentation. The material shares were taken from Weiß (2009). One unit was modelled independent of the produced biomass amount and scaled to the real throughput volume of 14.76 m^3 including "buffers". Therefore, 15 m^3 were assumed with 100% biomass recovery
  - Electricity, used to concentrate the biomass depended on the algae culture throughput and was assumed to be 1 KWh per m^3 following Gerardo et al. (2014) including a buffer of 10 % (original optimal value 0.9 KWh/m^3)
  - Biomass slurry was assumed to have a total solid content of 20 % (total biomass 17.7 kg) consequently a concentration factor of 167 (initial volume 14760 L) was assumed resulting in a slurry volume of 88.55 L; 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 *Nannochloropsis oceanica* was experimentally derived to be 0.43 m^3/kg (calculated according to personal communication Silkina, A., 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 base case is referring to the 600 L tubular reactor located in the greenhouse, just partially lighted and heated. Algal biomass concentration was assumed to be 1.2 g/L.
Additionally the cultivation was run with wastewater from cattle (nutrients were assumed to be without any burden of production) and a cleaning credit was applied. This 600 L ***base scenario*** was further modified and four sub-scenarios were developed:

- ***w/o light scenario***: Without lighting
- ***w/o light scenario+***: Without lighting + higher biomass concentration. (2 g/L)
- ***w/o light scenario++***: Without lighting + higher biomass concentration (2 g/L) + reduced pumping energy to 55 %

As production was not aiming for a specific product, except biomass, downstream processes were modelled on literature baseline and common sense. Fertilizer was 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 by now (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 Appendix (see*Table S1*- 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 600 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 four scenarios as described above are separately depicted and explained.

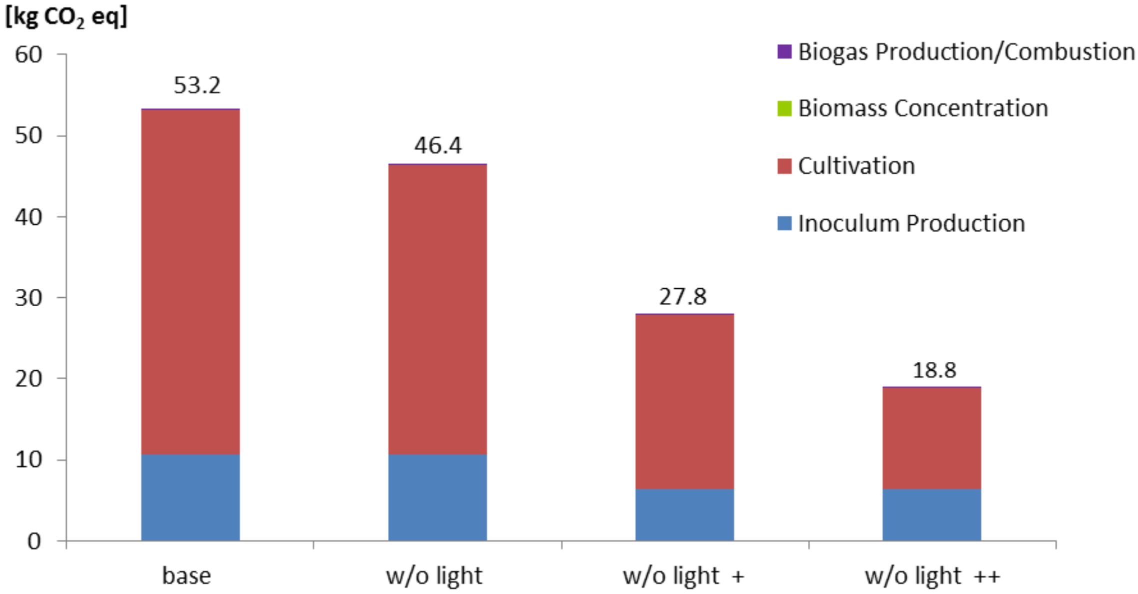

Figure 3: *Contribution of life-cycle phases to climate change for 1 MJ of burned algae-based biogas in different scenarios.*

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 base scenario most CO_2 eq resulting per MJ algae-based biogas burned. About 80 % (42.5 kg CO_2 eq) of the 53.2 kg CO_2 eq are related to the cultivation phase followed by 20% (10.6 kg CO_2 eq) related to the inoculation phase. The emissions referring to an improvement, in the w/o light scenario, are lower by 6.8 kg CO_2 eq. Still, the cultivation phase is the main contributor to climate change (77 %) followed by the inoculation with almost 23 % (10.6 kg). Without additional light inputs, biomass productivity and yield remained constant at 1.2 g/l and 17.7 kg dry algal biomass per year. Further improvements on biomass productivity are referring to the w/o light+ scenario. In this scenario 27.8 kg total CO_2 eq were calculated. The cultivation accounted for 77 % which means an absolute value of 21.4 kg. The inoculation phase made up a total value of 6.4 kg CO_2 eq.

If energy inputs for pumping were reduced to 55 % being achieved by reducing the pumping at night, the total CO_2 eq sum up to 18.8 kg – the share of cultivation was 66 %.

Aggregated process contribution to climate change per scenario

In the following the aggregated contribution was investigated and four main process types were distinguished. Process types contributing less than 1 % of the total value like biogas combustion, occupation as well as the wastewater cleaning credit were not displayed:

- Electricity, e.g. for pumping and lighting
- Water as culture medium, for cleaning and cooling purposes
- Operating supplies, like chemicals for cleaning
- Construction materials, like steel and plastics for the reactor but also the materials used for the greenhouse

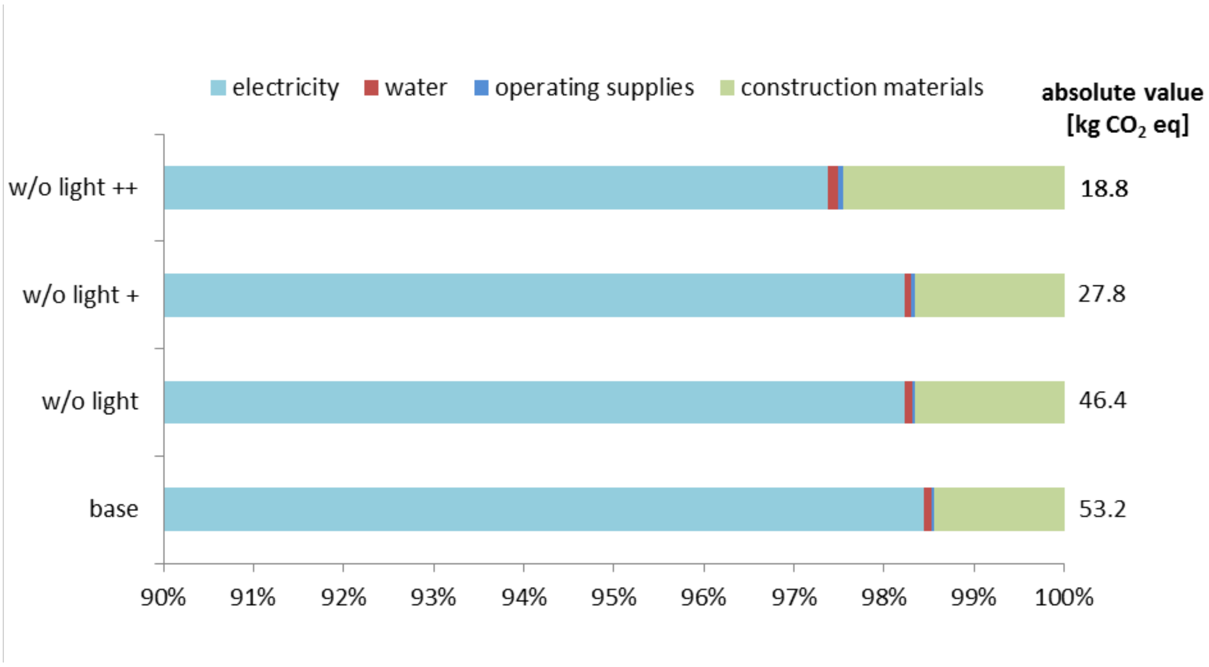

Figure 4: *Aggregated contribution of processes to climate change for 1 MJ of burned algae-based biogas in different scenarios.*

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) .

Life-cycle related impact contribution to climate change for the w/o light ++ scenario (electricity cut off)

Even in the w/o light ++ scenario the main driver for climate change was electricity. Therefore, we “zoomed in” and analysed the remaining processes with the highest shares in this phase by cutting of the electricity inputs contributions across the whole process chain. Like this, construction materials got more important with 0.46 kg CO_2 eq (see Figure 5).
The process contributors were displayed and the construction materials were separately highlighted.

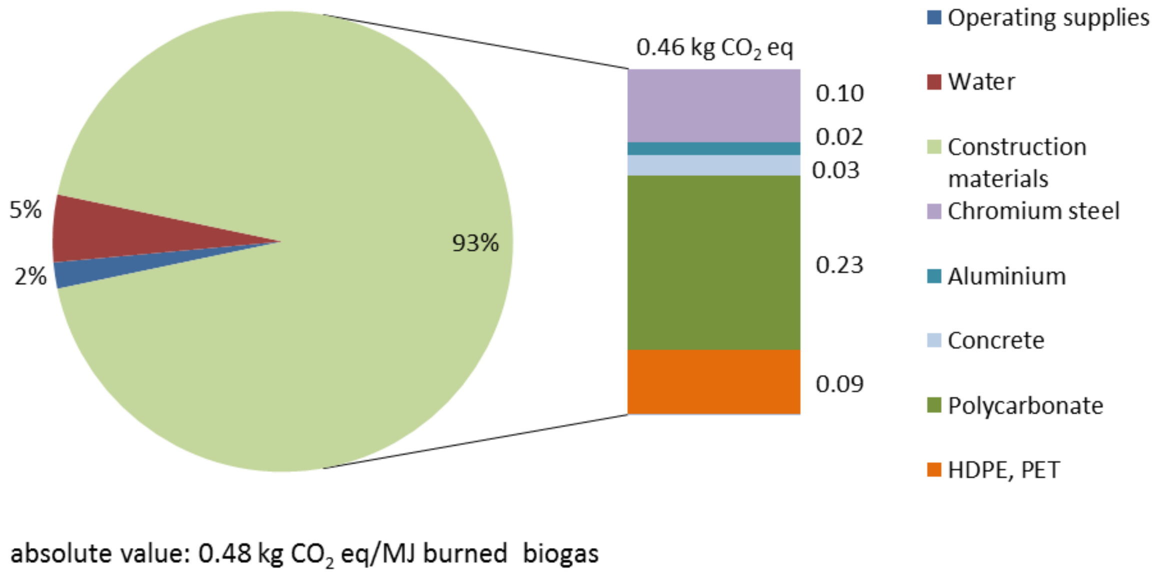

Figure 5: *Contribution to climate change for the zero electricity scenario, three process groups are displayed: construction materials (in detail), operating supplies and water (clustered).*

If electricity was cut off, it could be noticed that the construction materials made up 93 % of climate change impacts. Thereof polycarbonate for the greenhouse and reactor tubes contribute to the highest amount (48 %) followed by chromium steel used for the reactor frame, the microfiltration unit and the digester (21 %). However, the reactor set-up is still not efficient and material savings could be expected, especially in upscaled settings and optimal utilization of the greenhouse capacity.

Operating supplies and water had minor impact contribution to climate change (7 %). In the considered scale, the CO_2 eq resulting from chemical and water used are negligible.

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.

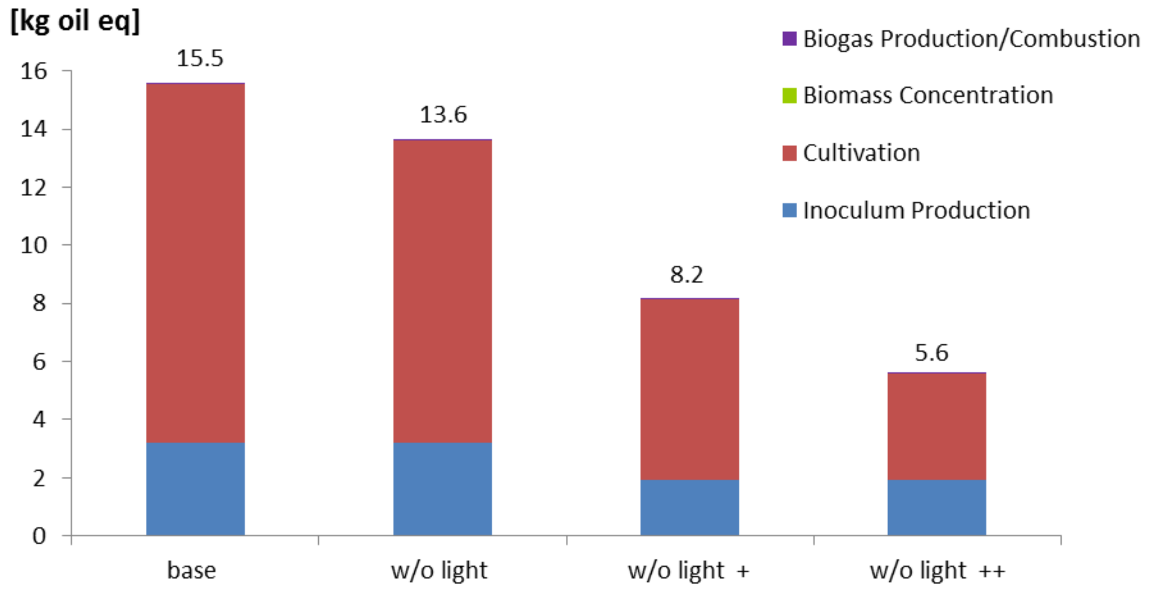

***Figure 6**: Contribution of life-cycle phases to fossil fuel depletion for 1 MJ of burned algae-based biogas in different scenarios.*

Figure 6 shows the overall result for fossil fuel depletion expressed in kg of oil equivalents. The ratio of the absolute values for the four 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 79 % of the total consumption per MJ burned algae-based biogas in base 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 the w/o light scenario, the value for fossil fuel depletion was reduced, by 12 %. Still, biomass concentration and biogas production were not visible in the phase contribution. In the further improved w/o light scenario +, the total fossil depletion decreases further by 47 % (8.2 kg oil eq), compared to the base scenario of the original data scenario. The cultivation phase had the highest contribution with 76 % of the total oil eq. The w/o light scenario ++ had the lowest impact to fossil fuel depletion with 5.6 kg oil eq per MJ algal biogas burned, however the cultivation phase represented 65 %.

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 98 % to overall fossil fuel depletion in the base scenario (see *Figure 7*). In the w/o light ++ scenario the contribution of electricity is about 97%. Contributions for water, operating supplies and construction materials were quite low. Nevertheless, in a next step we tried to further display their share more detailed.

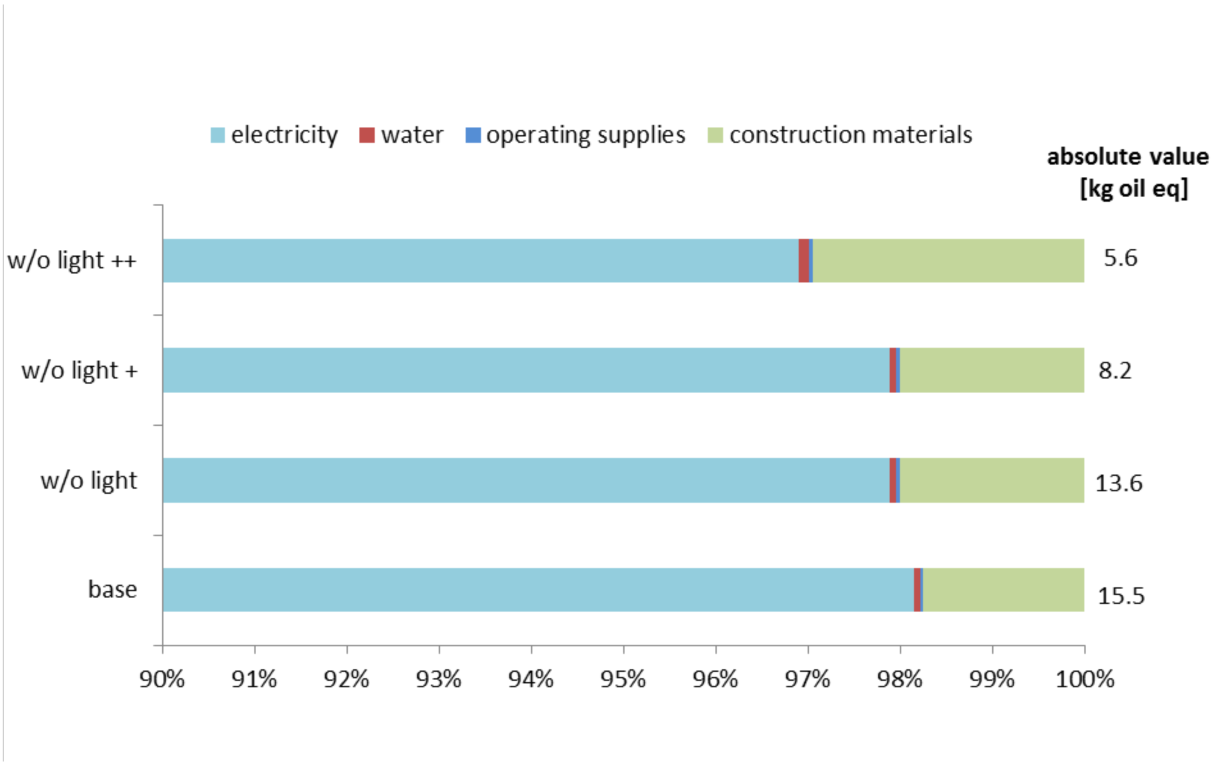

Figure 7: *Aggregated contribution of processes to fossil fuel depletion for 1 MJ of burned algae-based biogas in different scenarios.*

Life-cycle related impact contribution to fossil fuel fuel depletion for the w/o light ++ scenario (electricity cut off)

As was demonstrated, the cultivation phase made up the highest contribution to fossil fuel depletion (compare Figure 6).

Consequently, we analyzed the remaining processes according to their contribution to this impact category, on the "+" scenario baseline. As electricity was cut off the impacts the construction materials were identified as the second main contributor. Without electricity inputs 95 % of the fossil fuel depletion is related to the construction materials (see Figure 8). All these materials were separately expressed.

It could be demonstrated that polycarbonate, which was used for the greenhouse construction, contributed most, with 0.07 kg (41 %) oil eq/MJ burned algae-based biogas. Polycarbonate is followed by HDPE and PET (35 %) used for plastic bags of inoculation as well as the reactor dark tank to maintain a day-night cycle. For these materials fossil fuels are used, either directly as carbon source or for production processes.

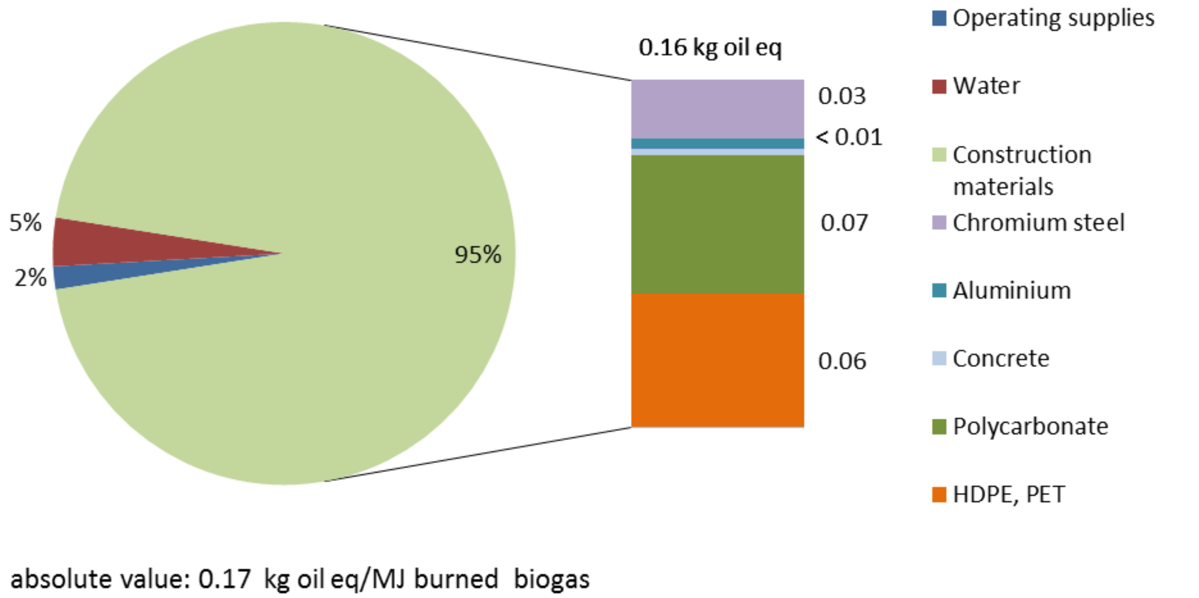

Figure 8: Contribution to fossil fuel depletion for the zero electricity scenario, three process groups are displayed: construction materials (in detail), operating supplies and water (clustered)

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 depending on the high-tech equipment used.

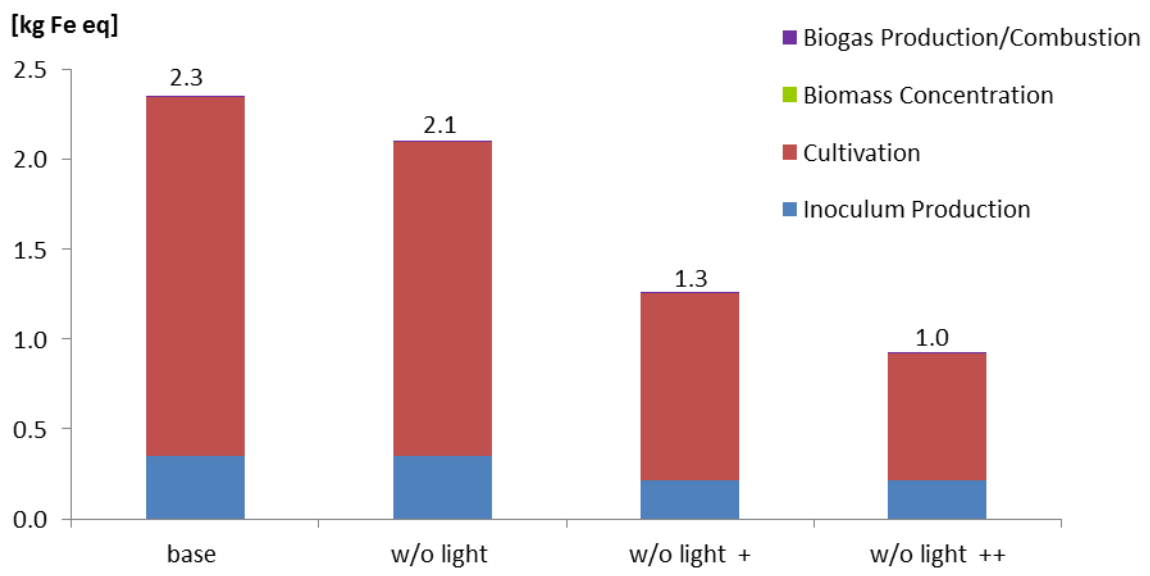

Figure 9: *Contribution of life-cycle phases to mineral resource depletion for 1 MJ of burned algae-based biogas in different scenarios.*

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 85 %, for the base scenario, showing an absolute total value of 2.3 kg Fe eq. In contrast, the production and combustion of natural gas accounted for only 0.06 g Fe eq.

In the w/o light ++ scenario, results for lower energy inputs during cultivation and reduced steel for the reactor frame are presented. Still, this impact is mainly related to the cultivation phase (84 %) as here most steel-consuming equipment (per output) was used. However, the absolute value of kg Fe eq used decreased to 1.0 kg.

Compared to climate change and fossil depletion the improvements in the w/o light ++ scenario lead to lower improvements in mineral resource depletion by about 56 %.

<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 base scenario the construction materials make up a share of 22 %. Complemented by electricity with about 78 % almost the total Fe eq are depleted by these inputs. The improvement from the w/o light scenario to the w/o light + scenario leads to a lower absolute Fe eq depletion (2.1 kg Fe eq and 1.3 kg Fe eq, respectively). Comparing these two scenarios, the absolute values differ strongly whereas the shares of the aggregated process contributors remain constant (share of electricity 76 %, construction materials 24 %, water and operating supplies negligible). In the w/o light ++ even more Fe eq were dedicated to the direct input of construction materials.

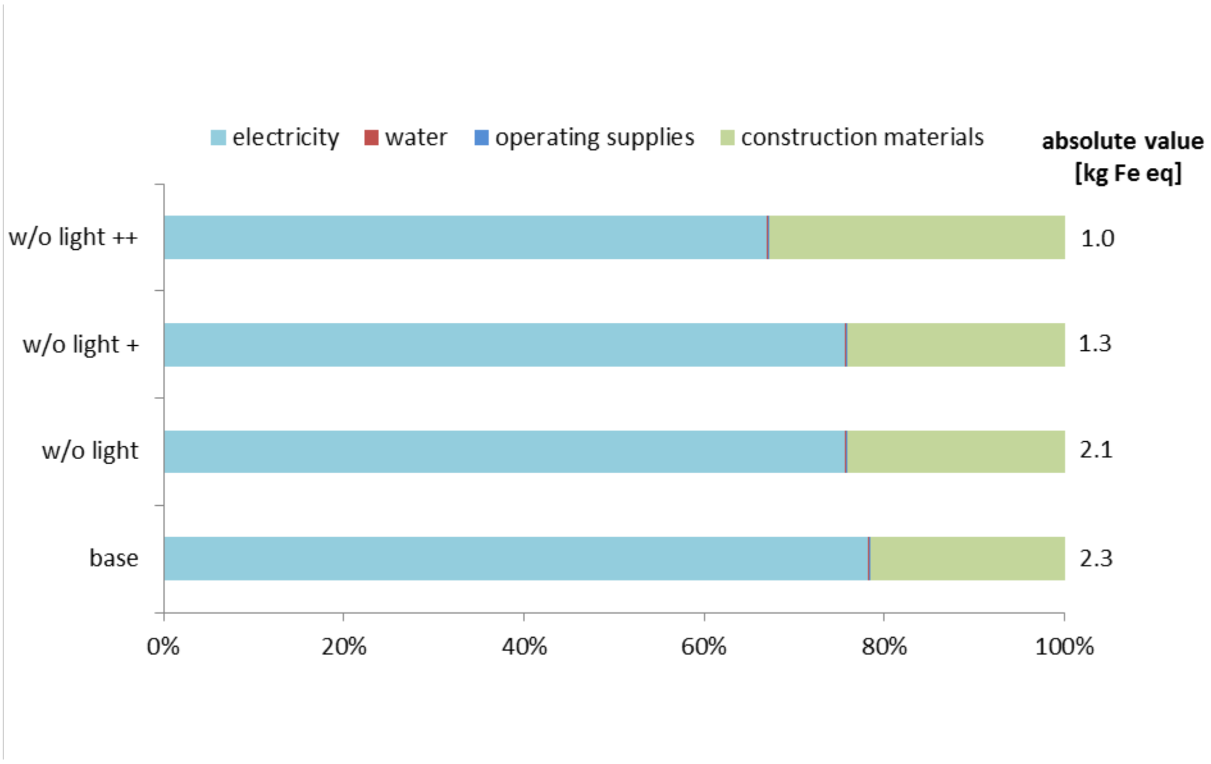

Figure 10: *Aggregated contribution of processes to mineral resource depletion for 1 MJ of burned algae-based biogas in different scenarios.*

<u>Life-cycle related impact contribution to mineral resource depletion for the w/o light ++ scenario (electricity cut off)</u>

Like the other impacts electricity is the main contributor. 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.

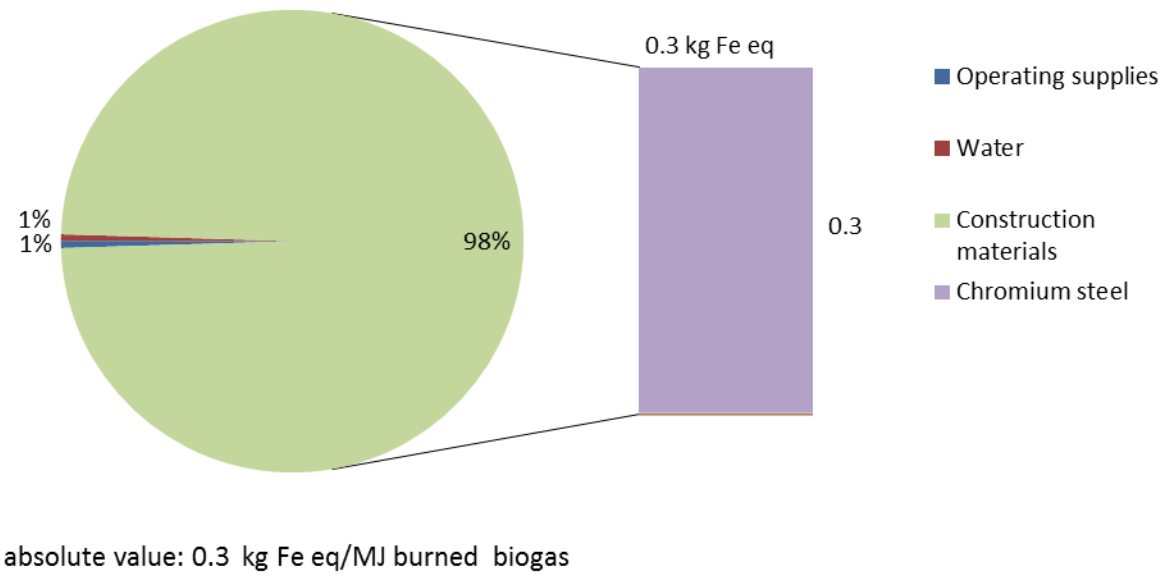

Figure 11: *Contribution to mineral resource depletion for the zero electricity scenario, three process groups are displayed: construction materials (in detail), operating supplies and water (clustered).*

5.1.4 Particulate matter formation

Particulate matter formation was investigated in detail as it had significant contribution, 14%, 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.

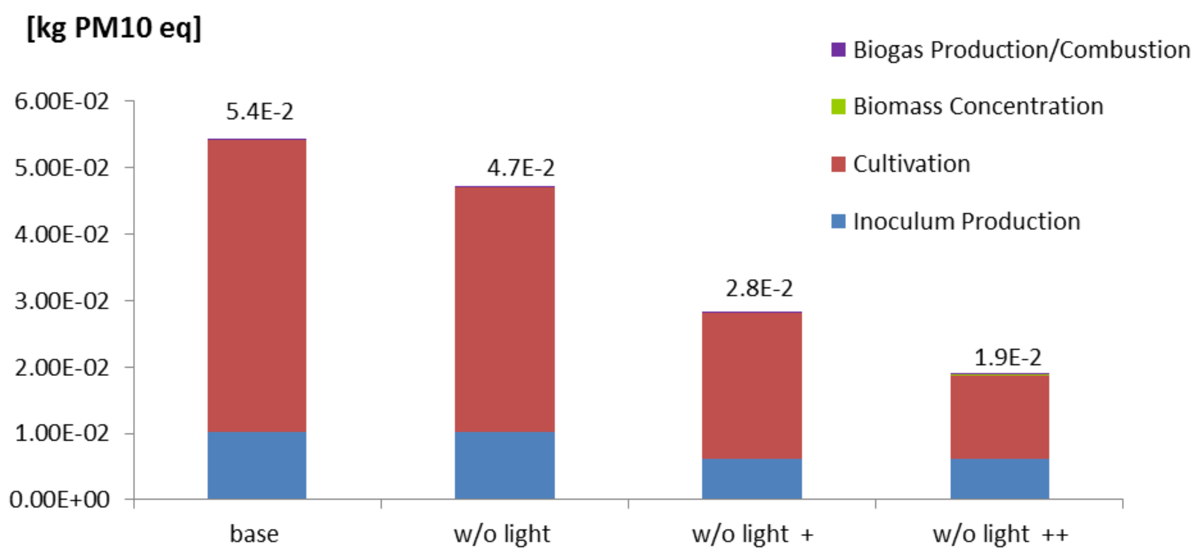

Figure 12: *Contribution of life-cycle phases to particulate matter formation for 1 MJ of burned algae-based biogas for different scenarios.*

The cultivation phase could be determined to be main contributor in all scenarios. In the base scenario 81 % the PM10 eq are related to the phase of cultivation representing an absolute value of 0.04 kg PM10 eq per MJ algae-based biogas burned. The absolute value decreased step by step as energy inputs were reduced and productivity increased per scenario. In the w/o light ++ scenario the share of the cultivation phase accounted for 67 % equivalent to 0.01 kg PM10 eq.

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*.

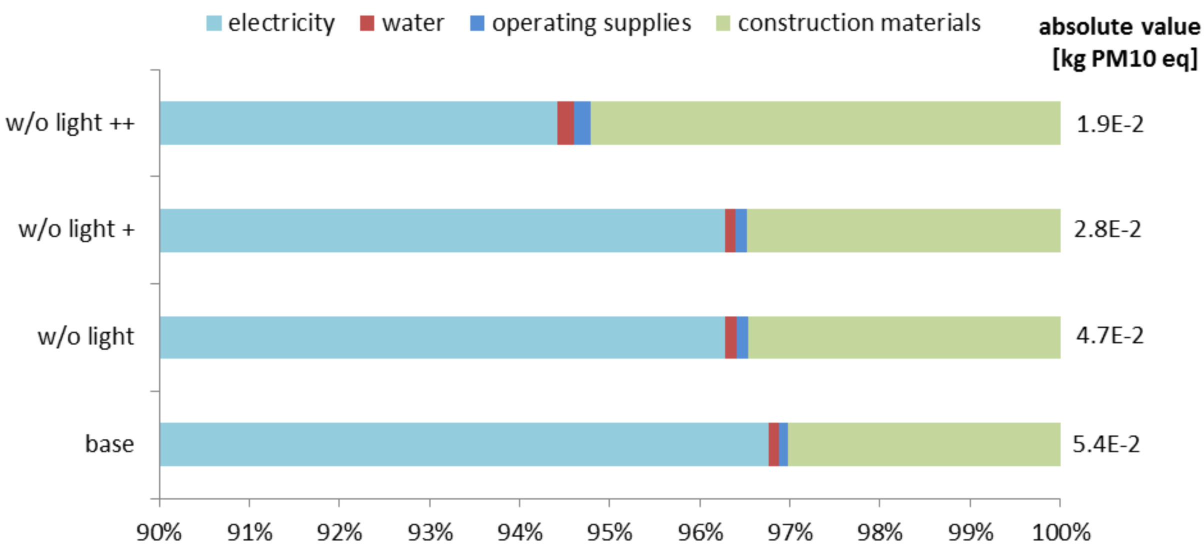

Figure 13: *Aggregated contribution of processes to particulate matter formation for 1 MJ of burned algae-based biogas in different scenarios.*

Among the whole life cycle electricity was identified as the driver of particulate matter formation in all four scenarios varying between 94 % (w/o light ++ scenario) and 96 % (base scenario). Among the scenario series the contribution of water, operating supplies and construction materials increases as simultaneously the absolute value decreases. However these shares are rather low, compared to the electricity.

Life-cycle related impact contribution to PMF for the w/o light ++ scenario (electricity cut off)

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

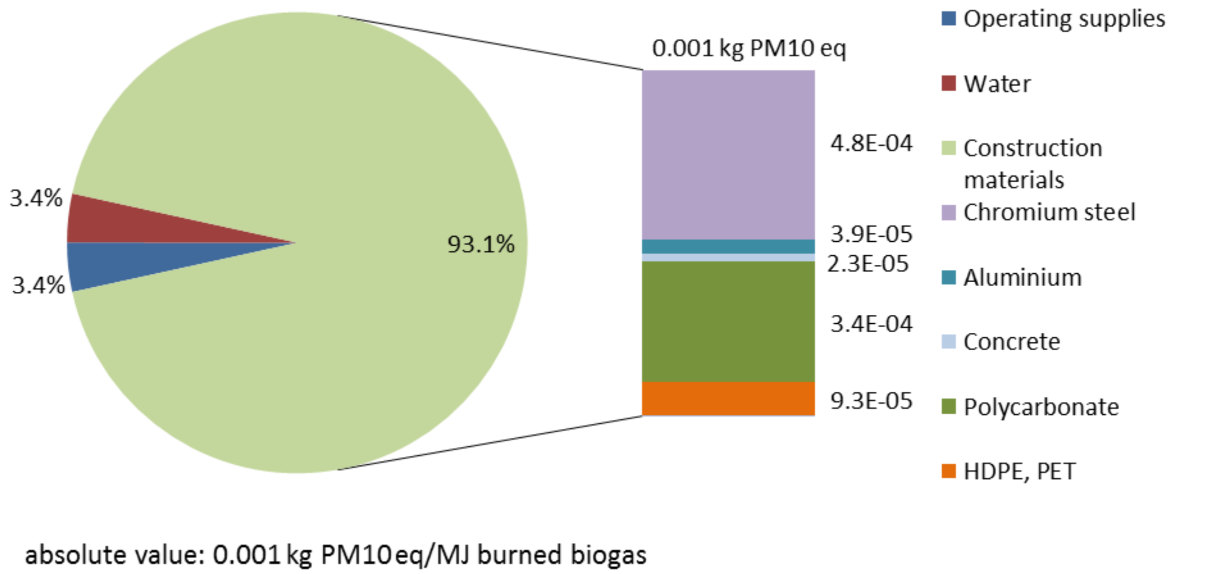

Figure 14: *Contribution to particulate matter formation for the zero electricity scenario, three process groups are displayed: construction materials (in detail), operating supplies and water (clustered).*

In Figure 14 the single material contributions are displayed, as the construction had an overall impact of 93 % if electricity was cut off. Chromium steel, which is abundant on mining processes and consequently indirectly on electricity, represented the highest share in materials, 4.8E-4 kg PM10 eq (48 %) per MJ of algae-based biogas burned. Another main contributor was polycarbonate with 3.9E-4 kg PM10 eq (39 %). With together about 7 % contribution share the other process groups, water and operating supplies had just marginal impact.

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.

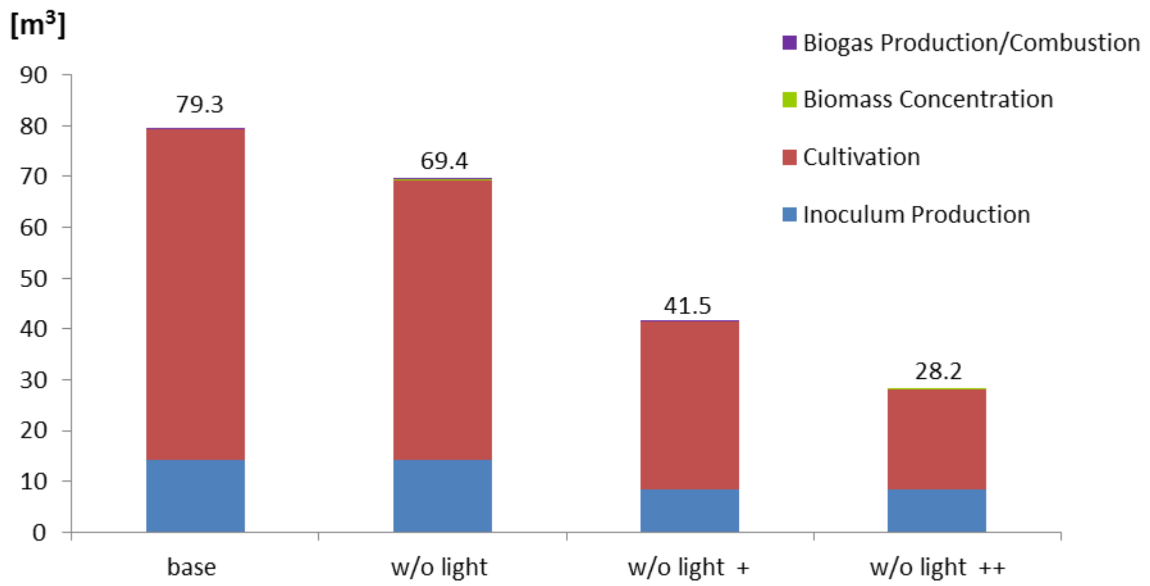

Figure 15: *Contribution of life-cycle phases to water depletion for 1 MJ of burned algae-based biogas for different scenarios.*

Figure 15 shows the results for the impact category water depletion in different scenarios. Main contribution within the base scenario (82 %) was related to the phase of cultivation. Almost all the rest (18 %) 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.

In the w/light ++ scenario the total impact was reduced by about 65% and an absolute value of 28.2 m^3 was calculated. Still the cultivation was dominating the results with a share of 70 %.

<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 electricity. This fact can be explained by the water used in turbines, related to electricity production processes, specifically hydropower generation. 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. Processes like occupation, biogas production and wastewater cleaning (credit) were not displayed, as they had contributions less than 0.5% in the considered impact categories, however these values are included.

In the base scenario for example 98 % 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 79.3m^3. In w/o light ++ scenario the main direct contribution we could derive an absolute water depletion value of 0.6 m^3, if turbine water was not considered.

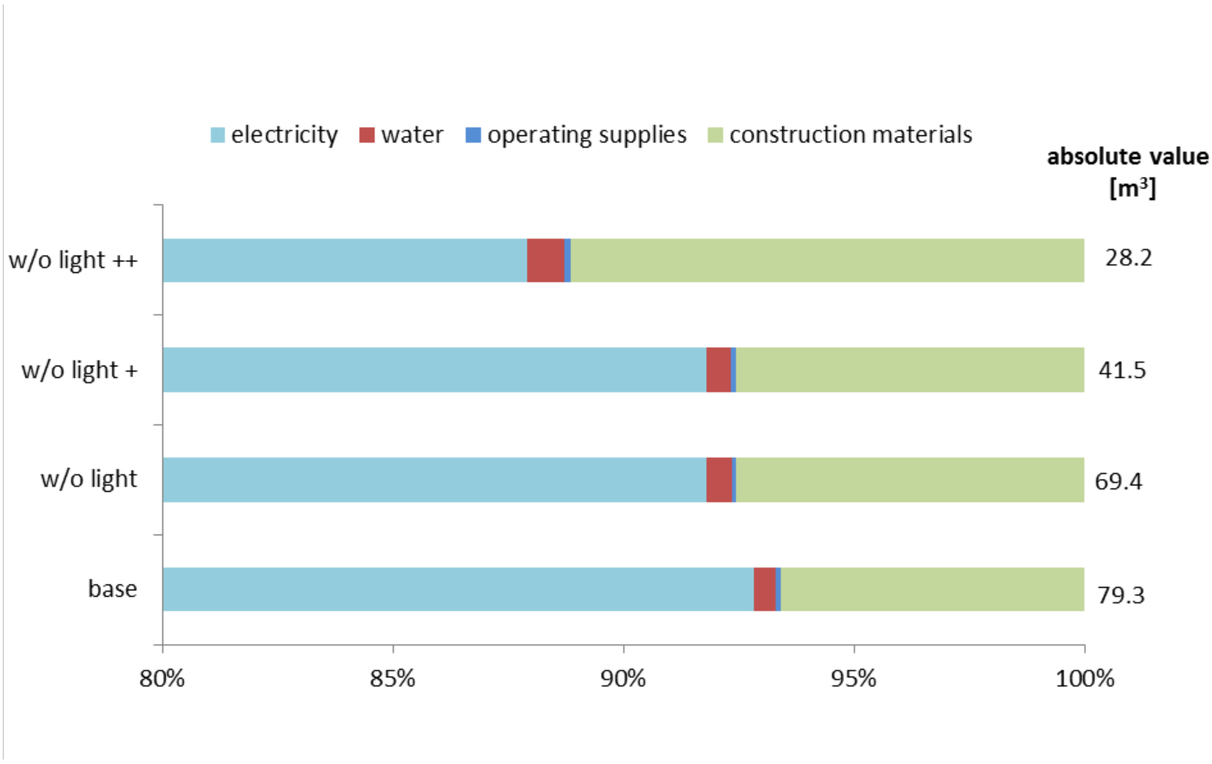

Figure 16: *Aggregated contribution of processes to water depletion for 1 MJ of burned algae-based biogas in different scenarios.*

Life-cycle related impact contribution to water depletion for the w/o light ++ scenario (electricity cut off)

Even if electricity is not considered, the direct water inputs do not represent the highest share in water depletion (see *Figure 17*). Upstream electricity inputs among other things like production processes for materials still cover the direct water contributions. Water accounted for only 2 %. Within this group the cultivation medium had a minor contribution; Cleaning and cooling water were dominating the water impact group. In this scenario the highest wastewater cleaning credit was applied with 0.16 m^3 per MJ algal biogas burned.

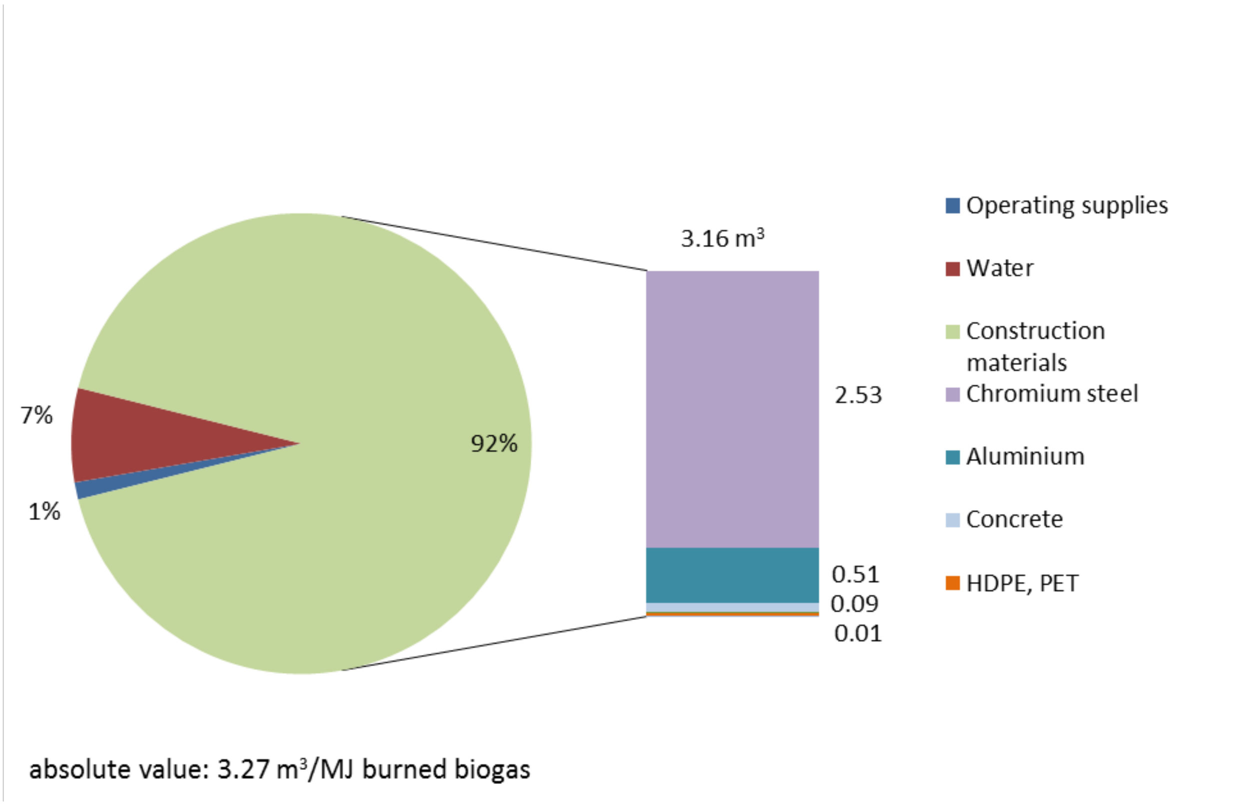

Figure 17: *Contribution to water depletion for the zero electricity scenario, three process groups are displayed: construction materials (in detail), operating supplies and water (clustered).*

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.

Impact contribution to CEENE per life-cycle phase

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 w/o light + scenario a value of 544 MJ_{ex} was calculated. This means with switching of the additional lighting improving the productivity, savings of 48% could be achieved. 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.

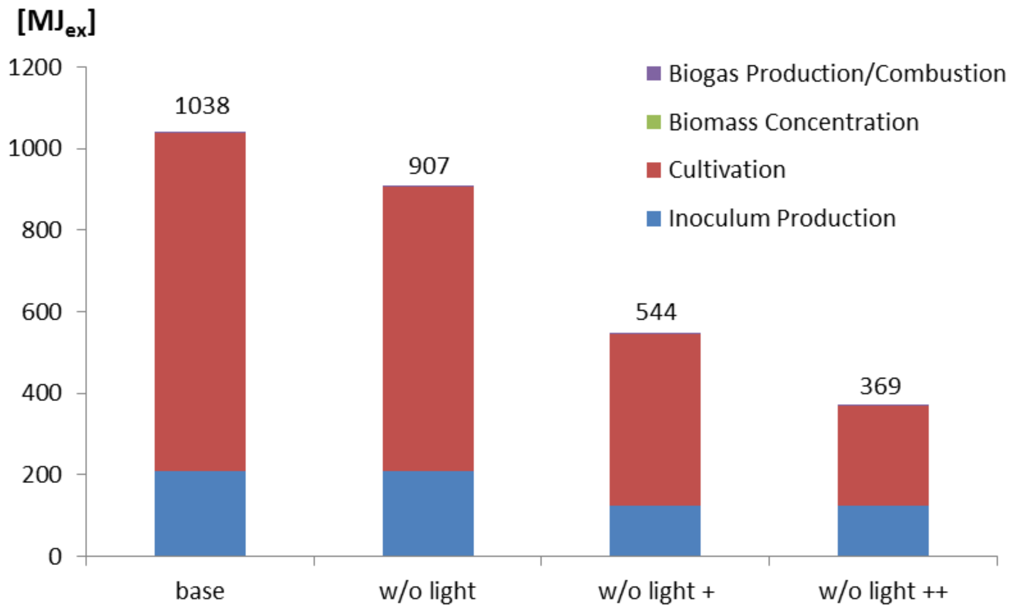

Figure 18: *Contribution of life-cycle phases to the CEENE footprint for 1 MJ of burned algae-based biogas for different scenarios.*

Impact contribution of the resource categories to CEENE per scenario

The results according to resource categories of the four scenarios are presented in *Figure 19*. The highest share of the total CEENE impact for all scenarios is related to fossil fuel consumption, between 78 % and 79 %. Fossil fuels were followed by nuclear energy representing the main shares of the British electricity mix. Water resources were also remarkable with a contribution of about 9 % resulting from indirect water for energy production but also for the material processing as well as direct water inputs as culture medium, added by water for cleaning purposes. 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.

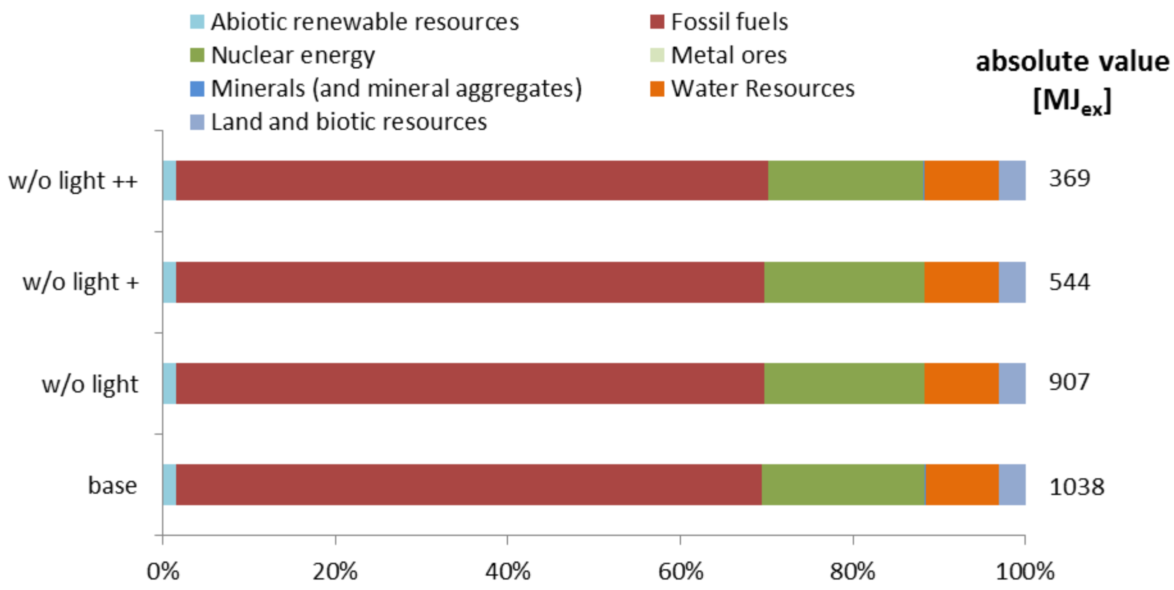

Figure 19: *Impact contribution to CEENE for different resource categories for 1 MJ of burned algae-based biogas.*

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, polycarbonate and HDPE/PET.

To reduce the environmental impacts, Construction/reactor materials with lower footprints could be used in order to substitute materials with higher ones. It has to be mentioned that a lower impact in one category could have a higher one in another, e.g. glass has a relatively high impact in mineral resource depletion but low impact regarding fossil fuel depletion.

If operated continuously in a fed-batch mode, energy savings can either be expected due to the lower inoculum production or if the system is run regularly on an equal production level, low pumping energy and lower flow velocity might result. Moreover, a single output system was presented. The credit, that was applied for wastewater treatment was negligible, as the amount of water processed was marginal. Co-production and resulting credits e.g. for digestate use as soil conditioner/fertilizer could potentially improve the findings. Nevertheless, proceedings like this have to be evaluated precisely.

7 Conclusions

Although one of the largest systems in the University sector in the UK, the SU microalgae production runs on semi-pilot scale. Technical equipment and materials used are optimized for scientific investigation and not for maximum energy efficiency. Consequently, improvements can be expected if correctly scaled and balanced equipment was used with the sole focus on efficiency. The relatively small scale prevented theoretical upscaling approaches, as the data baseline was not suitable to be abstracted.

The LCA results give hints on 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.

References

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

Brennan, L., Owende, P., 2010. Biofuels from microalgae—A review of technologies for production, processing, and extractions of biofuels and co-products. Renew. Sustain. Energy Rev. 14, 557–577. doi:10.1016/j.rser.2009.10.009

Chisti, Y., 2007. Biodiesel from microalgae. Biotechnol. Adv. 25, 294–306. doi:10.1016/j.biotechadv.2007.02.001

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

Dango & Dienenthal, Filtertechnik GmbH, Separator technical data sheet, 2011.

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.

Gerardo, M.L., Oatley-Radcliffe, D.L., Lovitt, R.W., 2014. Minimizing the energy requirement of dewatering Scenedesmus sp. by microfiltration: Performance, costs, and feasibility. Environ. Sci. Technol. 48, 845–853. doi:10.1021/es4051567

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.

Olesen, J.E., Bindi, M., 2002. Consequences of climate change for European agricultural productivity, land use and policy. Eur. J. Agron. 16, 239–262. doi:10.1016/S1161-0301(02)00004-7

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

Schröter, D., Cramer, W., Leemans, R., Prentice, I.C., Araújo, M.B., Arnell, N.W., Bondeau, A., Bugmann, H., Carter, T.R., Gracia, C. a, de la Vega-Leinert, A.C., Erhard, M., Ewert, F., Glendining, M., House, J.I., Kankaanpää, S., Klein, R.J.T., Lavorel, S., Lindner, M., Metzger, M.J., Meyer, J., Mitchell, T.D., Reginster, I., Rounsevell, M., Sabaté, S., Sitch, S., Smith, B., Smith, J., Smith, P., Sykes, M.T., Thonicke, K., Thuiller, W., Tuck, G., Zaehle, S., Zierl, B., 2005. Ecosystem service supply and vulnerability to global change in Europe. Science 310, 1333–1337. doi:10.1126/science.1115233

Sirakov, I.N., Velichkova, K.N., 2014. Bioremediation of wastewater originate from aquaculture and biomass production from microalgae species - Nannochloropsis oculata and Tetraselmis chuii 20, 66–72.

Spruijt, J., Schipperus, R., Kootstra, M., de Visser, C., Parker, B., 2015. AlgaEconomics: bioeconomic production models of micro-algae and downstream processing to produce bio energy carriers. Public Output report of the EnAlgae project, Swansea, June 2015, 67 pp. www.enalgae.eu

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. Resoures, Conservation & Recycling. 91, 1–10. doi:10.1016/j.resconrec.2014.07.009

Wall, G., 1977. Exergy - A useful concept. PhD Thesis, Chalmers Univ. Technol. Univ. Göteborg. URL 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 according to the four scenarios in *Table S1*- S4. However, for detailed investigation, only five categories have been selected.

Table S1: *ReCiPe midpoints, absolute values and shares according to life-cycle phases (base scenario).*

ReCiPe Impact category (midpoints)		Inoculum Production	%	Cultivation	%	Biomass Concentration	%	Biogas Production/combustion	%	Sum
Climate change (CC)	kg CO2 eq	1.06E+01	20.01	4.25E+01	79.91	3.71E-02	0.07	7.35E-03	0.01	5.32E+01
Ozone depletion (OD)	kg CFC-11 eq	3.95E-07	22.18	1.38E-06	77.76	9.25E-10	0.05	1.73E-10	0.01	1.78E-06
Terrestrial acidification (TA)	kg SO2 eq	3.13E-02	19.15	1.32E-01	80.75	1.19E-04	0.07	5.01E-05	0.03	1.64E-01
Freshwater eutrophication (FE)	kg P eq	3.14E-03	18.98	1.34E-02	80.93	1.22E-05	0.07	2.00E-06	0.01	1.65E-02
Marine eutrophication (ME)	kg N eq	1.34E-03	22.64	4.59E-03	77.25	5.14E-06	0.09	1.48E-06	0.02	5.94E-03
Human toxicity (HT)	kg 1,4-DB eq	2.96E+00	18.81	1.27E+01	81.10	1.15E-02	0.07	2.01E-03	0.01	1.57E+01
Photochemical oxidant formation (POF)	kg NMVOC	2.07E-02	19.53	8.50E-02	80.36	7.54E-05	0.07	3.43E-05	0.03	1.06E-01
Particulate matter formation (PMF)	kg PM10 eq	1.02E-02	18.88	4.39E-02	81.02	3.87E-05	0.07	1.58E-05	0.03	5.41E-02
Terrestrial ecotoxicity (TET)	kg 1,4-DB eq	7.07E-04	19.06	3.00E-03	80.85	2.70E-06	0.07	4.76E-07	0.01	3.71E-03
Freshwater ecotoxicity (FET)	kg 1,4-DB eq	2.68E-02	18.73	1.16E-01	81.18	1.04E-04	0.07	1.98E-05	0.01	1.43E-01
Marine ecotoxicity (MET)	kg 1,4-DB eq	3.22E-02	18.81	1.39E-01	81.10	1.25E-04	0.07	2.48E-05	0.01	1.71E-01
Ionising radiation (IR)	kg U235 eq	4.28E+00	18.96	1.83E+01	80.95	1.68E-02	0.07	2.53E-03	0.01	2.26E+01
Agricultural land occupation (ALO)	m2a	1.87E-01	18.91	8.00E-01	81.01	7.31E-04	0.07	1.21E-04	0.01	9.87E-01
Urban land occupation (ULO)	m2a	8.00E-02	24.88	2.41E-01	75.05	1.67E-04	0.05	3.44E-05	0.01	3.21E-01
Natural land transformation (NLT)	m2	2.10E-03	20.15	8.32E-03	79.77	7.30E-06	0.07	1.16E-06	0.01	1.04E-02
Water depletion (WD)	m3	1.42E+01	17.86	6.52E+01	82.04	5.51E-02	0.07	2.10E-02	0.03	7.94E+01
Mineral resource depletion (MRD)	kg Fe eq	3.53E-01	15.05	1.99E+00	84.83	1.38E-03	0.06	1.41E-03	0.06	2.35E+00
Fossil fuel depletion (FD)	kg oil eq	3.20E+00	20.59	1.23E+01	79.33	1.06E-02	0.07	1.68E-03	0.01	1.55E+01

Table S2: *ReCiPe midpoints, absolute values and shares according to life-cycle phases (w/o light scenario).*

ReCiPe Impact category (midpoints)		Inoculum Production	%	Cultivation	%	Biomass Concentration	%	Biogas Production/combustion	%	Sum
Climate change (CC)	kg CO2 eq	1.06E+01	22.92	3.57E+01	76.98	3.71E-02	0.08	7.35E-03	0.02	4.64E+01
Ozone depletion (OD)	kg CFC-11 eq	3.95E-07	24.50	1.22E-06	75.43	9.25E-10	0.06	1.73E-10	0.01	1.61E-06
Terrestrial acidification (TA)	kg SO2 eq	3.13E-02	22.07	1.10E-01	77.81	1.19E-04	0.08	5.01E-05	0.04	1.42E-01
Freshwater eutrophication (FE)	kg P eq	3.14E-03	21.94	1.11E-02	77.96	1.22E-05	0.09	2.00E-06	0.01	1.43E-02
Marine eutrophication (ME)	kg N eq	1.34E-03	26.87	3.65E-03	73.00	5.14E-06	0.10	1.48E-06	0.03	5.00E-03
Human toxicity (HT)	kg 1,4-DB eq	2.96E+00	21.71	1.06E+01	78.19	1.15E-02	0.08	2.01E-03	0.01	1.36E+01
Photochemical oxidant formation (POF)	kg NMVOC	2.07E-02	22.45	7.13E-02	77.44	7.54E-05	0.08	3.43E-05	0.04	9.20E-02
Particulate matter formation (PMF)	kg PM10 eq	1.02E-02	21.70	3.68E-02	78.18	3.87E-05	0.08	1.58E-05	0.03	4.71E-02
Terrestrial ecotoxicity (TET)	kg 1,4-DB eq	7.07E-04	21.97	2.51E-03	77.93	2.70E-06	0.08	4.76E-07	0.01	3.22E-03
Freshwater ecotoxicity (FET)	kg 1,4-DB eq	2.68E-02	21.60	9.72E-02	78.30	1.04E-04	0.08	1.98E-05	0.02	1.24E-01
Marine ecotoxicity (MET)	kg 1,4-DB eq	3.22E-02	21.69	1.16E-01	78.21	1.25E-04	0.08	2.48E-05	0.02	1.48E-01
Ionising radiation (IR)	kg U235 eq	4.28E+00	21.93	1.52E+01	77.97	1.68E-02	0.09	2.53E-03	0.01	1.95E+01
Agricultural land occupation (ALO)	m2a	1.87E-01	21.85	6.67E-01	78.05	7.31E-04	0.09	1.21E-04	0.01	8.54E-01
Urban land occupation (ULO)	m2a	8.00E-02	27.49	2.11E-01	72.44	1.67E-04	0.06	3.44E-05	0.01	2.91E-01
Natural land transformation (NLT)	m2	2.10E-03	23.10	6.99E-03	76.81	7.30E-06	0.08	1.16E-06	0.01	9.10E-03
Water depletion (WD)	m3	1.42E+01	20.44	5.52E+01	79.45	5.51E-02	0.08	2.10E-02	0.03	6.94E+01
Mineral resource depletion (MRD)	kg Fe eq	3.53E-01	16.84	1.74E+00	83.03	1.38E-03	0.07	1.41E-03	0.07	2.10E+00
Fossil fuel depletion (FD)	kg oil eq	3.20E+00	23.52	1.04E+01	76.39	1.06E-02	0.08	1.68E-03	0.01	1.36E+01

Table S3: *ReCiPe midpoints, absolute values and shares according to life-cycle phases (w/o light + scenario).*

ReCiPe Impact category (midpoints)		Inoculum Production		Cultivation	%	Biomass Concentration	%	Biogas Production/combustion	%	Sum
Climate change (CC)	kg CO2 eq	6.38E+00	22.92	2.14E+01	76.97	2.22E-02	0.08	7.35E-03	0.03	2.78E+01
Ozone depletion (OD)	kg CFC-11 eq	2.37E-07	24.51	7.29E-07	75.42	5.55E-10	0.06	1.73E-10	0.02	9.67E-07
Terrestrial acidification (TA)	kg SO2 eq	1.88E-02	22.08	6.62E-02	77.78	7.12E-05	0.08	5.01E-05	0.06	8.51E-02
Freshwater eutrophication (FE)	kg P eq	1.88E-03	22.00	6.67E-03	77.89	7.35E-06	0.09	2.00E-06	0.02	8.56E-03
Marine eutrophication (ME)	kg N eq	8.07E-04	31.45	1.75E-03	68.37	3.09E-06	0.12	1.48E-06	0.06	2.57E-03
Human toxicity (HT)	kg 1,4-DB eq	1.77E+00	21.73	6.38E+00	78.16	6.92E-03	0.08	2.01E-03	0.02	8.16E+00
Photochemical oxidant formation (POF)	kg NMVOC	1.24E-02	22.46	4.27E-02	77.40	4.52E-05	0.08	3.43E-05	0.06	5.52E-02
Particulate matter formation (PMF)	kg PM10 eq	6.13E-03	21.72	2.21E-02	78.14	2.32E-05	0.08	1.58E-05	0.06	2.82E-02
Terrestrial ecotoxicity (TET)	kg 1,4-DB eq	4.24E-04	22.02	1.50E-03	77.88	1.62E-06	0.08	4.76E-07	0.02	1.93E-03
Freshwater ecotoxicity (FET)	kg 1,4-DB eq	1.61E-02	21.61	5.83E-02	78.28	6.27E-05	0.08	1.98E-05	0.03	7.45E-02
Marine ecotoxicity (MET)	kg 1,4-DB eq	1.93E-02	21.71	6.95E-02	78.18	7.48E-05	0.08	2.48E-05	0.03	8.90E-02
Ionising radiation (IR)	kg U235 eq	2.57E+00	21.94	9.12E+00	77.95	1.01E-02	0.09	2.53E-03	0.02	1.17E+01
Agricultural land occupation (ALO)	m2a	1.12E-01	21.85	4.00E-01	78.04	4.38E-04	0.09	1.21E-04	0.02	5.13E-01
Urban land occupation (ULO)	m2a	4.80E-02	27.51	1.26E-01	72.41	1.00E-04	0.06	3.44E-05	0.02	1.74E-01
Natural land transformation (NLT)	m2	1.26E-03	23.10	4.19E-03	76.80	4.38E-06	0.08	1.16E-06	0.02	5.46E-03
Water depletion (WD)	m3	8.51E+00	20.46	3.30E+01	79.41	3.30E-02	0.08	2.10E-02	0.05	4.16E+01
Mineral resource depletion (MRD)	kg Fe eq	2.12E-01	16.86	1.04E+00	82.96	8.28E-04	0.07	1.41E-03	0.11	1.26E+00
Fossil fuel depletion (FD)	kg oil eq	1.92E+00	23.52	6.23E+00	76.38	6.38E-03	0.08	1.68E-03	0.02	8.16E+00

Table S4: *ReCiPe midpoints, absolute values and shares according to life-cycle phases (w/o light ++ scenario).*

ReCiPe Impact category (midpoints)		Inoculum Production		Cultivation	%	Biomass Concentration	%	Biogas Production/combustion	%	Sum
Climate change (CC)	kg CO2 eq	6.38E+00	33.91	1.24E+01	65.94	2.22E-02	0.12	7.35E-03	0.04	1.88E+01
Ozone depletion (OD)	kg CFC-11 eq	2.37E-07	31.95	5.04E-07	67.95	5.55E-10	0.07	1.73E-10	0.02	7.42E-07
Terrestrial acidification (TA)	kg SO2 eq	1.88E-02	33.42	3.73E-02	66.37	7.12E-05	0.13	5.01E-05	0.09	5.62E-02
Freshwater eutrophication (FE)	kg P eq	1.88E-03	33.75	3.69E-03	66.08	7.35E-06	0.13	2.00E-06	0.04	5.58E-03
Marine eutrophication (ME)	kg N eq	8.07E-04	61.40	5.03E-04	38.26	3.09E-06	0.23	1.48E-06	0.11	1.31E-03
Human toxicity (HT)	kg 1,4-DB eq	1.77E+00	33.12	3.57E+00	66.72	6.92E-03	0.13	2.01E-03	0.04	5.36E+00
Photochemical oxidant formation (POF)	kg NMVOC	1.24E-02	33.64	2.44E-02	66.15	4.52E-05	0.12	3.43E-05	0.09	3.69E-02
Particulate matter formation (PMF)	kg PM10 eq	6.13E-03	32.60	1.26E-02	67.19	2.32E-05	0.12	1.58E-05	0.08	1.88E-02
Terrestrial ecotoxicity (TET)	kg 1,4-DB eq	4.24E-04	33.40	8.44E-04	66.44	1.62E-06	0.13	4.76E-07	0.04	1.27E-03
Freshwater ecotoxicity (FET)	kg 1,4-DB eq	1.61E-02	32.81	3.29E-02	67.02	6.27E-05	0.13	1.98E-05	0.04	4.90E-02
Marine ecotoxicity (MET)	kg 1,4-DB eq	1.93E-02	32.94	3.92E-02	66.89	7.48E-05	0.13	2.48E-05	0.04	5.86E-02
Ionising radiation (IR)	kg U235 eq	2.57E+00	33.70	5.04E+00	66.13	1.01E-02	0.13	2.53E-03	0.03	7.62E+00
Agricultural land occupation (ALO)	m2a	1.12E-01	33.46	2.22E-01	66.37	4.38E-04	0.13	1.21E-04	0.04	3.35E-01
Urban land occupation (ULO)	m2a	4.80E-02	35.88	8.56E-02	64.02	1.00E-04	0.08	3.44E-05	0.03	1.34E-01
Natural land transformation (NLT)	m2	1.26E-03	34.24	2.42E-03	65.61	4.38E-06	0.12	1.16E-06	0.03	3.68E-03
Water depletion (WD)	m3	8.51E+00	30.17	1.97E+01	69.64	3.30E-02	0.12	2.10E-02	0.07	2.82E+01
Mineral resource depletion (MRD)	kg Fe eq	2.12E-01	22.94	7.10E-01	76.81	8.28E-04	0.09	1.41E-03	0.15	9.24E-01
Fossil fuel depletion (FD)	kg oil eq	1.92E+00	34.43	3.65E+00	65.43	6.38E-03	0.11	1.68E-03	0.03	5.57E+00

For comparison, in Table S4 the ReCiPe midpoint impacts are displayed for the fossil reference of 1 MJ of burned natural gas.

Table S5: *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 S6*, 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 S6*, 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 S6: *Contribution of midpoints, absolute values and shares, to the endpoint categories human health, ecosystems and resources, according to life-cycle phases (base scenario).*

Human health [DALY]	per 1 MJ biogas combustion	Inoculum Production	%	Cultivation	%	Biomass Concentration	%	Biogas Production/combustion	%	aggregated Endpoint
Photochemical oxidant formation	kg NMVOC	8.06E-10	19.53	3.32E-09	80.36	2.94E-12	0.07	1.34E-12	0.03	
Ozone depletion	kg CFC-11 eq	6.29E-09	23.68	2.03E-08	76.25	1.50E-11	0.06	3.12E-12	0.01	
Ionising radiation	kg U235 eq	7.02E-08	18.96	3.00E-07	80.95	2.75E-10	0.07	4.14E-11	0.01	
Particulate matter formation	kg PM10 eq	2.66E-06	18.88	1.14E-05	81.02	1.01E-08	0.07	4.10E-09	0.03	**9.99E-05**
Human toxicity	kg 1,4-DB eq	2.07E-06	18.81	8.92E-06	81.10	8.07E-09	0.07	1.40E-09	0.01	
Climate change	kg CO2 eq	1.49E-05	20.01	5.95E-05	79.91	5.19E-08	0.07	1.03E-08	0.01	
Ecosystems [species*yr]	per 1 MJ biogas combustion	Inoculum Production	%	Cultivation	%	Biomass Concentration	%	Biogas Production/Use	%	aggregated Endpoint
Climate change	kg CO2 eq	8.43E-08	20.01	3.37E-07	79.91	2.94E-10	0.07	5.83E-11	0.00	
Terrestrial acidification	kg SO2 eq	1.82E-10	19.15	7.66E-10	80.75	6.88E-13	0.07	2.91E-13	0.00	
Freshwater eutrophication	kg P eq	1.39E-10	18.98	5.94E-10	80.93	5.44E-13	0.07	8.87E-14	0.00	
Terrestrial ecotoxicity	kg 1,4-DB eq	1.07E-10	19.06	4.52E-10	80.85	4.07E-13	0.07	7.17E-14	0.00	
Freshwater ecotoxicity	kg 1,4-DB eq	2.31E-11	18.73	1.00E-10	81.18	8.99E-14	0.07	1.70E-14	0.00	**4.80E-07**
Marine ecotoxicity	kg 1,4-DB eq	5.67E-12	18.81	2.44E-11	81.10	2.20E-14	0.07	4.37E-15	0.00	
Agricultural land occupation	m2a	2.24E-09	18.91	9.59E-09	81.01	8.76E-12	0.07	1.46E-12	0.00	
Urban land occupation	m2a	1.66E-09	24.88	5.00E-09	75.05	3.46E-12	0.05	7.12E-13	0.00	
Natural land transformation	m2	6.03E-09	15.89	3.19E-08	84.07	1.17E-11	0.03	3.64E-12	0.00	
Resources [$]	per 1 MJ biogas combustion	Inoculum Production	%	Cultivation	%	Biomass Concentration	%	Biogas Production/Use	%	aggregated Endpoint
Fossil depletion	kg Fe eq	5.29E-01	20.59	2.04E+00	79.33	1.76E-03	0.07	2.78E-04	0.01	**2.74E+00**
Metal depletion	kg oil eq	2.53E-02	15.05	1.42E-01	84.83	9.86E-05	0.06	1.01E-04	0.06	

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 S1*-S3) show the aggregated contribution of impact categories to the endpoint levels damage of human health, damage of ecosystem diversity and damage of resource availability.

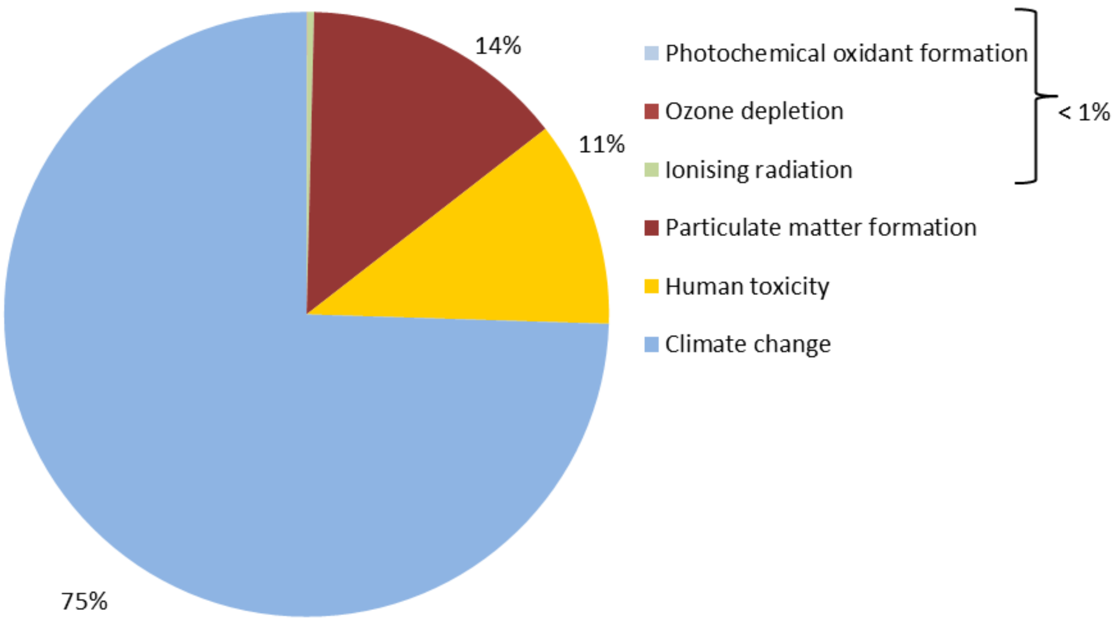

Figure S1: *Weighted contribution of midpoint categories on the endpoint level "damage to human health".*

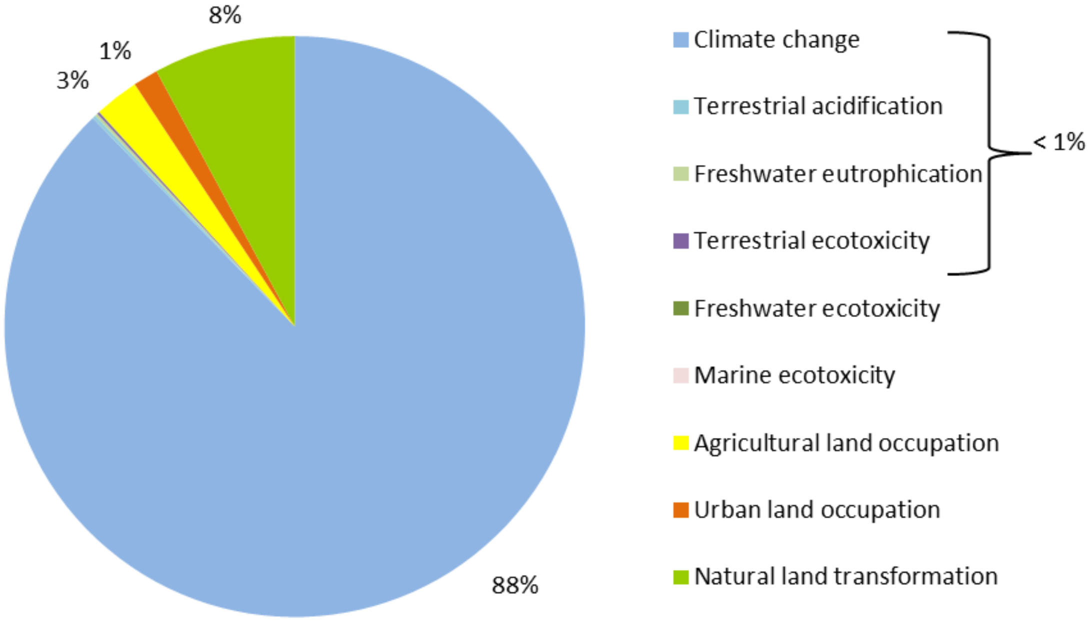

Figure S2: *Weighted contribution of midpoint categories on the endpoint level “damage to ecosystem diversity”.*

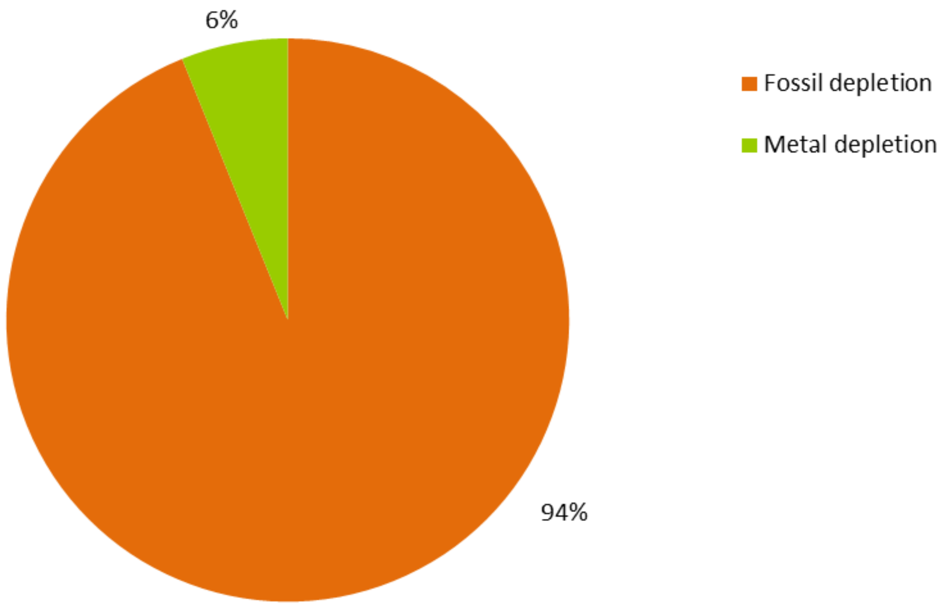

Figure S3: *Weighted contribution of midpoint categories on the endpoint level “damage to resource availability”.*

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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