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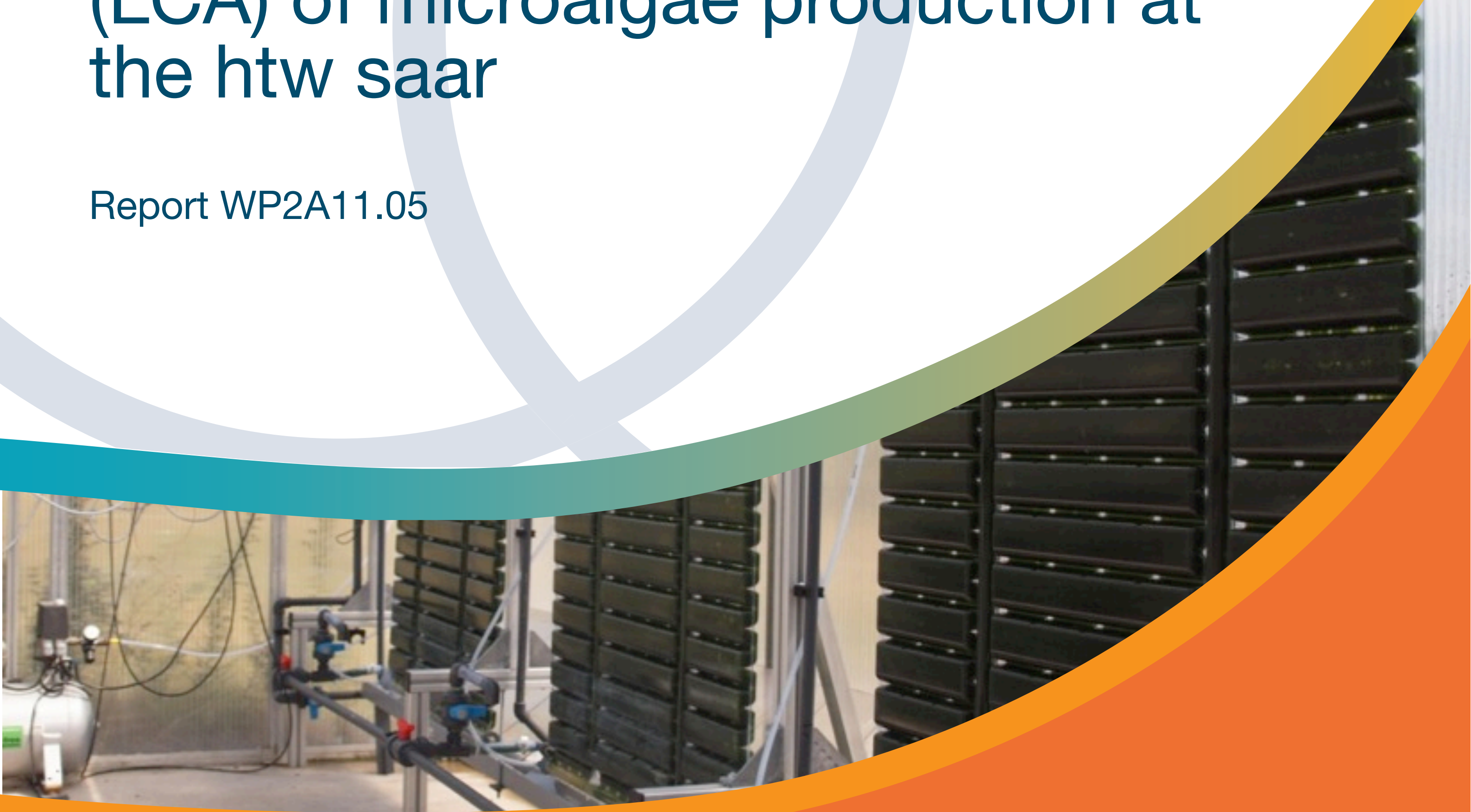
# Environmental life cycle assessment (LCA) of microalgae production at the htw saar

Report WP2A11.05



**Energetic Algae ('EnAlgae')**

Project no. 215G

**Public Output**

# WP2.A11.05 − Environmental life cycle assessment (LCA) of microalgae production at the htw saar

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# Environmental life cycle assessment (LCA) of microalgae production at the htw saar

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# Environmental life cycle assessment (LCA) of microalgae production at the htw saar

## 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 Hochschule für Technik und Wirtschaft des Saarlandes (htw saar), experiments focus on microalgae production in closed loop aquatic systems. The facilities include several recirculation aquaculture systems (RAS) for marine fish and crustacean that were supposed to be coupled with photobioreactors (PBRs) for the production of microalgae. At the time of evaluation, however, the algae batch cultivation was not integrated in a recirculating system but considered as a "stand alone" production at lab scale. The microalgae species *Nannochloropsis salina* was cultivated in a closed tubular PBR located in a greenhouse. Though the considered system did not run the whole year, data was provided based on extrapolations, for a one year microalgae biomass production of the saline species *Nannochloropsis salina.* As there was no downstream processing available and final biomass application was defined as bioenergy production according to the overall project scope, we decided to model the production and 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 algae production system (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***).

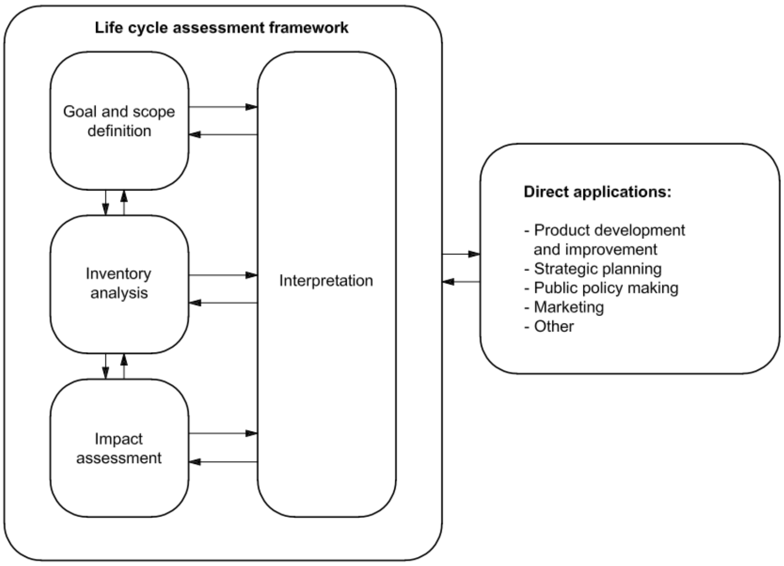


***Figure 1:*** *LCA as a 4-phase process according to the ISO standards 14040: goal and scope definition, inventory analysis, impact assessment and interpretation (International Organization for Standardization, 2006).*

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.

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).

# 3 Scope of the study

The microalgae pilot facilities of the htw saar are located in South West Germany, characterized as oceanic climate with rather moderate variations between extreme temperatures and regular rainfall and a global radiation of 3,825 $MJ/m^2/a$ (Súri et al., 2007). Main materials and their production were considered in the system, transport and manufacturing processes were not taken into account. Waste water from the production and cleaning processes was simply diluted and drained untreated and is therefore not considered in the LCA system, downstream processes were modelled on a one year baseline. Due to maintenance and cleaning processes a net cultivation period of 300 days was assumed.

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

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

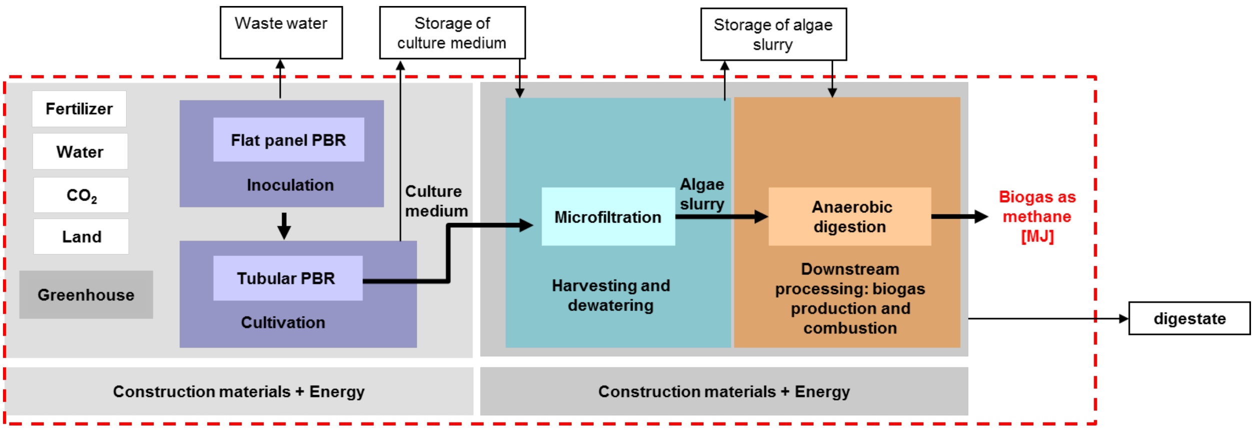


***Figure 2:*** *System boundary and process flows included in the LCA: Processes supplied by experimental (lab) data and numbers are highlighted in light grey; processes supplied by database data and literature are highlighted in dark grey. The system boundary is displayed as red-dotted line.*

The main cultivation parameters are summarized in *Table 1*. First, the inoculation culture has been prepared in a 5 L flat panel photobioreactor (PBR). Parallel to the cultivation the inoculation system was operated in fed-batch mode to maintain and provide starting cultures for flexible experimental purposes during the period of production. For the inoculation of the cultivation system, 4 L of high density (3 g/L) culture was required to be diluted in the horizontal tubular closed PBR with a total volume of 100 L. The high density was reached after 1-2 weeks resulting in 40 dilutions (replacements à 3 L) per year either being partially (4 L) transferred to the cultivation reactor or drained.

The cultivation reactor was set up on a mobile steel platform (0.8m x 2m) in a greenhouse. To minimize space, two glass tube modules were mounted as helical solar collectors with 24 U turns on the platform. A pump circulated the suspension through the helical modules (height 130cm). Algae were cultivated in batch mode, meaning one harvest of the entire volume (100 L) per month; ten cultivation months per year were assumed. During summer temperature was controlled by spray cooling. 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. Bottled $CO_2$ was supplied for pH control and as carbon source. The process water, the artificial seawater, was prepared from tap water and supplemented salts. For the life cycle inventory calculation it was assumed that only sodium chloride was added which usually contributes to the greatest share of seawater salt composition. An average algal biomass concentration of 3 g/L was assumed shortly before harvesting. In total, a yearly production of 4.4 kg of dry algal biomass was achieved, resulting in an areal yield of 29 t/ha/a.

Biomass was “harvested” by draining the reactor. 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 harvested and concentrated by a microfiltration unit. The harvested algal biomass was modelled to be digested and processed to biogas and burned in a cogeneration unit. Biogas was modelled as single output of the system without any losses; utilization of digestate was not considered.

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.*

| Parameter | Description |
|---|---|
| Reactor Type | Horizontal tubular PBR |
| Nutrient source | Chemical fertilizer |
| Culture volume | 100 L |
| Average algae conc. | 3 g/L |
| Total biomass yield | 4.4 kg |
| Areal yield | 29 t/ha/a |

At the htw saar, the oil-rich species *Nannochloropsis salina* is cultivated on experimental level. Production objectives and conditions were not aiming for high lipid content or another specific product, except biomass. Thus, fertilizer was sufficiently supplied and cells were not forced by nitrogen starvation to accumulate lipids.

In this study, it was assumed that the harvested biomass is converted into biogas because it is the most simple downstream energy process and the whole biomass is used. Besides, biogas can be processed without prior fractionation steps.

Therefore, biogas production and combustion were modelled to allow for a direct comparison to the other pilot case studies. 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*.

# 4 Life cycle inventory

Main data for the life cycle inventory was collated, using a standardized questionnaire based on MS excel. In close contact with the pilot operator, the spreadsheet was adapted to the specific system of the lab facility. To get an impression of the reactor setup and to ensure the same understanding of processes a guided facility visit was organized. Additionally, personal interviews as well as skype calls were carried out to gather or assess missing data.

The challenge to use the collected data for the life cycle inventory is that the considered cultivation system was used for lab experiments. Therefore, 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 were provided according to the experimental setup translated to a one year baseline.

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

- **Inoculation**
  - The inoculum was produced, using about 565 kWh/a for gassing, lighting, sterilization and pumping processes,
  - Material specification/amount used for the 5 L flat panel PBR were obtained from the pilot operator
  - Chemical fertilizer sufficiently supplied, estimated for (2.3 g/L $NaNO_3$, 0.33 g/L $KH_2PO_4$)
- **Cultivation**
  - During cultivation about 2300 kWh/a were assumed for pumping of 10 batch runs
  - Material specification/amount used for the 100 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
  - Chemical fertilizer sufficiently supplied, estimated for (2.3 g/L $NaNO_3$, 0.33 g/L $KH_2PO_4$)
- **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 independently of the produced biomass amount and scaled to the real throughput volume of 1.5 $m^3$ (1 $m^3$ + 0.5 $m^3$ "buffer"). 100% biomass recovery was assumed
  - The amount of 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 4.4 kg) consequently a concentration factor of 45 (initial volume 1,000 L) was assumed resulting in a slurry volume of 22 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 salina* was calculated to be 0.19 $m^3$/kg dry biomass according to Schwede (2013); the lower heating value of biomethane was assumed to be 35.78 MJ/$m^3$ obtained from experimental data corresponding to Collet et al. (2011)

- The combustion process was modelled equivalent to the fossil reference (modified database process)

# 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 three scenarios were defined.

- **Original data scenario:** The flows and impacts were computed with the original data according to the pilot setup.
- **Improved data scenario:** In this scenario it was assumed that the pumping energy needed for the cultivation can be reduced to a third. Additionally, steel inputs for the reactor setup were assumed to be reduced to one third. This could be achieved easily by changing the design of the cultivation system. For example: A smaller pump can be used for circulating the culture during daytime. The one used in the experiment was available at the pilot operator, but oversized. From the experience of the pilot operator, these scenario assumptions were considered to be realistically translated into reality. All inputs for the inoculation remained as in the original data scenario.
- **Zero electricity scenario:** In this scenario it was assumed that no electricity is needed for the inoculation and cultivation of the microalgae. This scenario was developed for analytical reasons, only. This hypothetical assumption was made to investigate the contributions of other flows than electricity. The indirect electricity demand, i.e. for the steel inputs remained at the improved value of one third of the improved data scenario. Assuming that the downstream processes microfiltration and biogas production and combustion represent mature technologies with only minor optimization potential and optimal scaling and capacity, the data for the state-of-the-art was not changed.

## 5.1 ReCiPe

In the following the results of selected ReCiPe midpoints are presented. The most relevant impact categories have been graphically displayed; a table of the results for all 18 midpoint impact categories can be found in the Supplement. 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 (*Table S 1*– S 3). Likewise, midpoint impacts are displayed for the fossil reference (*Table S 4*).

Separated in the four process phases the endpoint results indicated that mainly the first two phases namely the 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 (*Figure S 1* – S 3).

Climate change and fossil depletion are highly interconnected and represent the highest shares in the environmental impacts on endpoint level (*Table S 5*). Therefore, those two 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, human toxicity was considered to be important for further detail examination. Although, the water impacts hardly showed up in the endpoint results, because two water categories (marine eutrophication and water depletion) are simply not considered within the endpoint methodology, water depletion was consulted on midpoint level.

### 5.1.1 Climate change

The impact category climate change (CC) 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 results for the three scenarios as described above are depicted and explained.

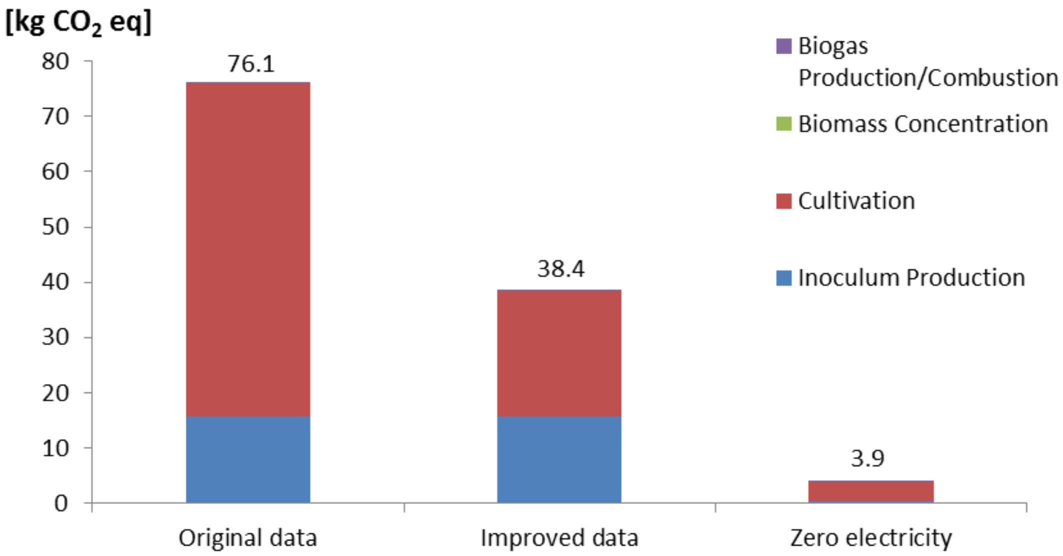


***Figure 3:*** *Contribution of life-cycle phases to climate change for 1 MJ of burned algae-based biogas in different scenarios.*

Figure 3 shows the overall results for climate change expressed in kg of $CO_2$ equivalents (eq). The LCIA with the original data reveal that is a high contribution to climate change compared to the fossil reference natural gas. This is on the one hand related to the high electricity demand and the mainly fossil fuel based energy mix for the electricity supply in Germany. On the other hand the chosen reference natural gas has a significantly smaller environmental burden than other fossil energy carriers such as coal. The resulting $CO_2$ eq are mainly related to the phase of cultivation for all three scenarios. For the original data scenario 79 % of the total emissions per MJ burned biogas, are related to this phase. The upstream inoculation and the cultivation phase represent almost the total contributors to climate change, in all three scenarios.

A reduction of electricity and a reduced consumption of chromium steel for the construction of the reactor according to the improved data scenario would lead to a decrease of impact in climate change by about 50 % compared to the original data. This reduction can be observed in all the impact categories and not only for climate change.

Even in the zero electricity scenario the main contribution to climate change was during the cultivation phase. However, the absolute value decreased to 3.9 kg $CO_2$ eq per MJ burned algae based biogas compared to 76.1 kg $CO_2$ eq of the original data. In comparison to the original data scenario, the contribution to climate change related to the fossil reference accounts for 0.06 kg $CO_2$ eq per MJ natural gas.

Aggregated process contribution to climate change per scenario

In the following the aggregated contribution was investigated and four main process types were distinguished:

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

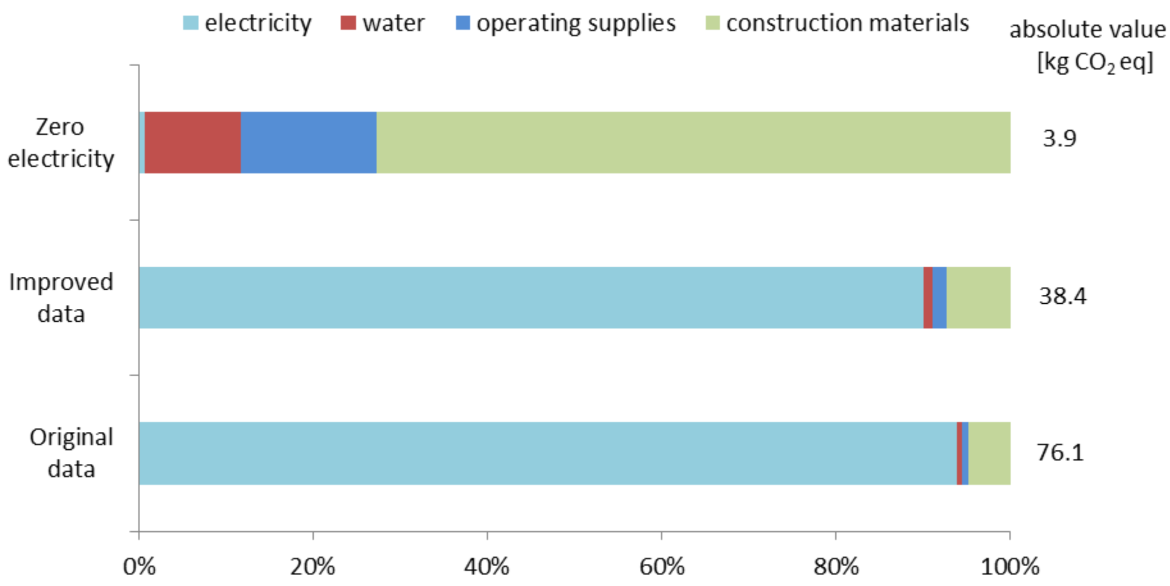


***Figure 4:*** *Aggregated contribution of processes to climate change for 1 MJ of burned algae-based biogas in different scenarios.*

As can be extracted from the bar chart, the main contribution to climate change was due to the consumption of electricity for the original data scenario and the improved data scenario. A German standard electricity mix was applied, which is among others (e.g. nuclear power and renewables) composed of power generation of lignite (25 %), hard coal (23 %), and natural gas (10 %), resulting in a carbon footprint of 0.74 kg $CO_2$ eq per kWh (Frischknecht et al., 2007).

Impact contribution to climate change during cultivation in the zero electricity scenario

Even in the zero electricity scenario the cultivation phase seemed to be the main driver to climate change (89 %). Therefore, we “zoomed in” and analyzed the remaining processes with the highest shares in this phase (see Figure 5).

Again the process contributors were displayed and the construction materials were separately highlighted. Material inputs were based on the improved data scenario, meaning one third of chromium steel used compared to the original data.

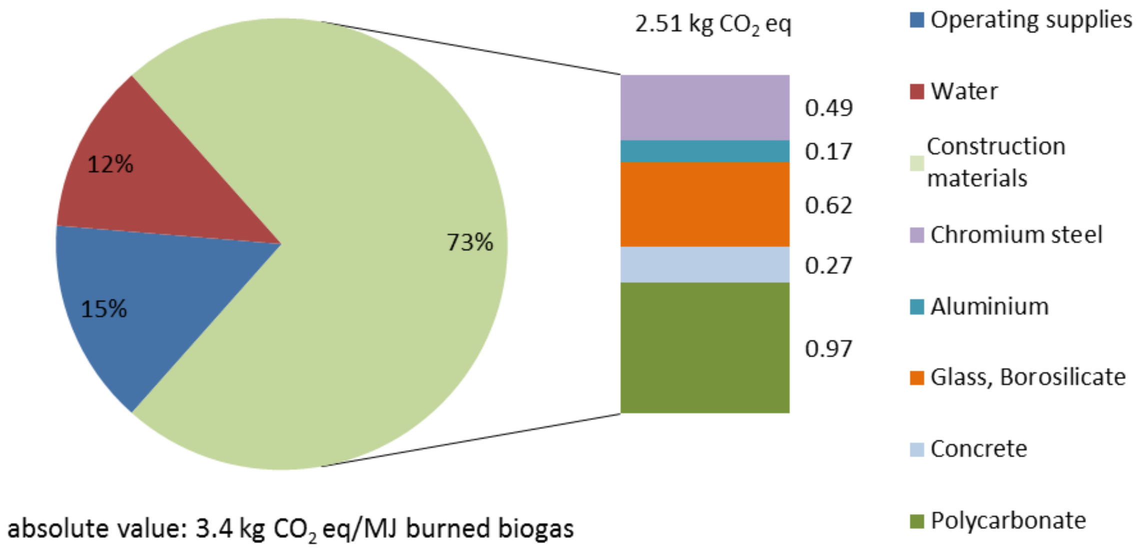


***Figure 5:** Contribution to climate change in the cultivation phase for the zero electricity scenario, three process groups are displayed: construction materials (in detail), operating supplies and water (clustered).*

If electricity was not considered, it can be noticed that the construction materials made up 73 % of climate change impacts. Thereof polycarbonate for the greenhouse and the glass tubes contribute to the highest amount (47 %). 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. The mobility of the reactor caused high material demand (chromium steel) as well, because glass tubes had to be much more fixed in order to avoid transport damages which might be further optimized and reduced.

Operating supplies and water had similar, but moderate contribution to climate change. At this scale, the $CO_2$ eq due to chemicals/ fertilizer and water used are negligible with 0.5 kg $CO_2$ eq and 0.4 kg $CO_2$ eq, respectively.

### 5.1.2 Fossil fuel depletion

The following section is dedicated to the presentation of the results for the impact category fossil depletion. Since fossil depletion is mainly related to the consumption of fossil energy (carriers) like coal, representing a large fraction of the German electricity mix, it could be shown that the results strictly follow the ones for climate change (compare Figure 6)

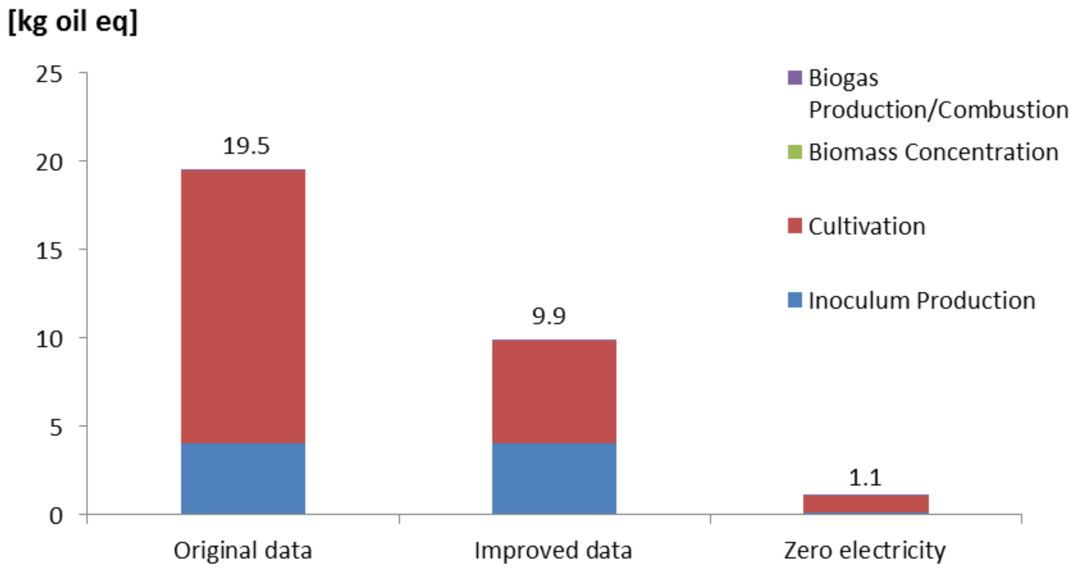


***Figure 6:*** *Contribution of life-cycle phases to fossil fuel depletion for 1 MJ of burned algae-based biogas in different scenarios.*

Figure 6 shows the overall result for fossil fuel depletion (FD) expressed in kg of oil equivalents per MJ of burned biogas. The ratio of the absolute values for the both 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 biogas in the original data. 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 improved data scenario, the value for fossil fuel depletion was reduced, by 50 %. Still, biomass concentration and biogas production were not visible in the phase contribution.

In the zero electricity scenario, the total fossil depletion decreases to about 5 % (1.1 kg oil eq) of the original data scenario. The cultivation phase had the highest contribution with 88 % of oil eq. Now, the materials and their fossil fuel footprint dominate the results during that phase.

Aggregated process contribution to fossil fuel depletion per scenario

The results clearly 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 93 % to overall fossil fuel depletion in the original data scenario and to 89 % in the improved data scenario (see Figure 7). In the zero electricity scenario the contribution of construction materials accounts for 73 %. Here, also operating supplies (16 %) and water (11 %) represent a remarkable share, but the absolute value is quite low.

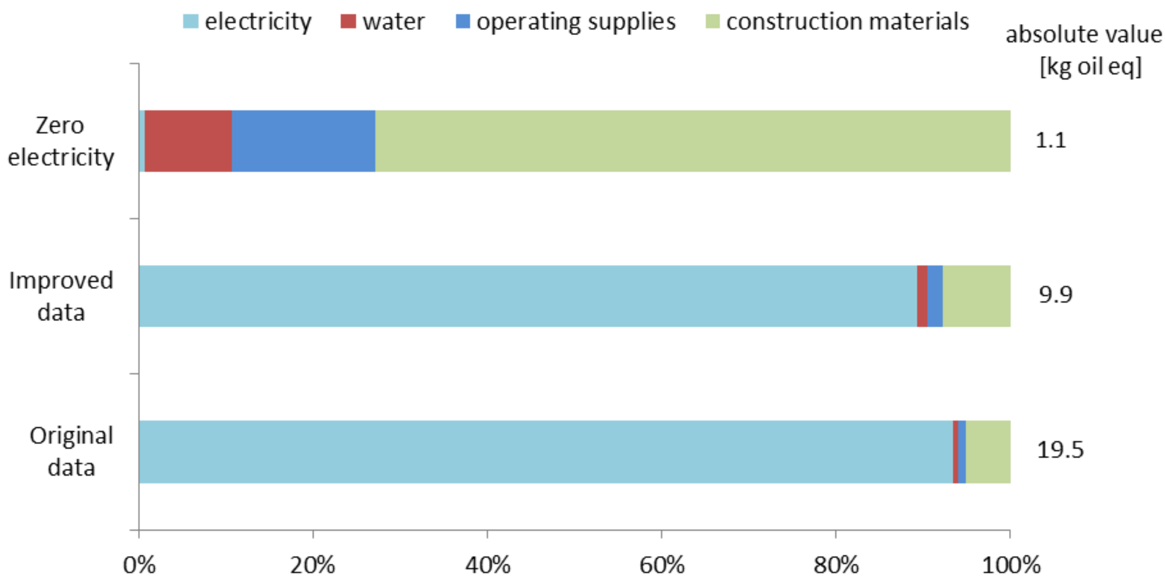


***Figure 7:** Aggregated contribution of processes to fossil fuel depletion for 1 MJ of burned algae-based biogas in different scenarios.*

<u>Impact contribution to fossil fuel depletion during cultivation in the zero electricity scenario</u>

The cultivation phase made up the highest contribution to the fossil fuel depletion, even in the zero electricity scenario (compare Figure 7).

Consequently, we analyzed the remaining processes according to their contribution to this impact category, focusing on construction materials (see ***Figure 8***). Without electricity inputs 73 % of the fossil fuel depletion during cultivation is related to the construction materials. All these materials were separately expressed.

It could be demonstrated that polycarbonate, which was used for the greenhouse construction, contributed most, with 0.27 kg oil eq/MJ (30 %) burned biogas in the improved data scenario. Polycarbonate is followed by glass (21 %) used for the reactor tubes and chromium steel (16 %) which was used for the reactor support-frame as well as for the pumps. For these three materials fossil fuels are used, either directly as carbon source in the case of polycarbonate or for melting (glass) and smelting (chromium steel). Even though about twice the amount of glass is needed, polycarbonate shows a larger impact. However, only the production of the materials was considered and a recycling of polycarbonate that would reduce the impacts was not taken into account.

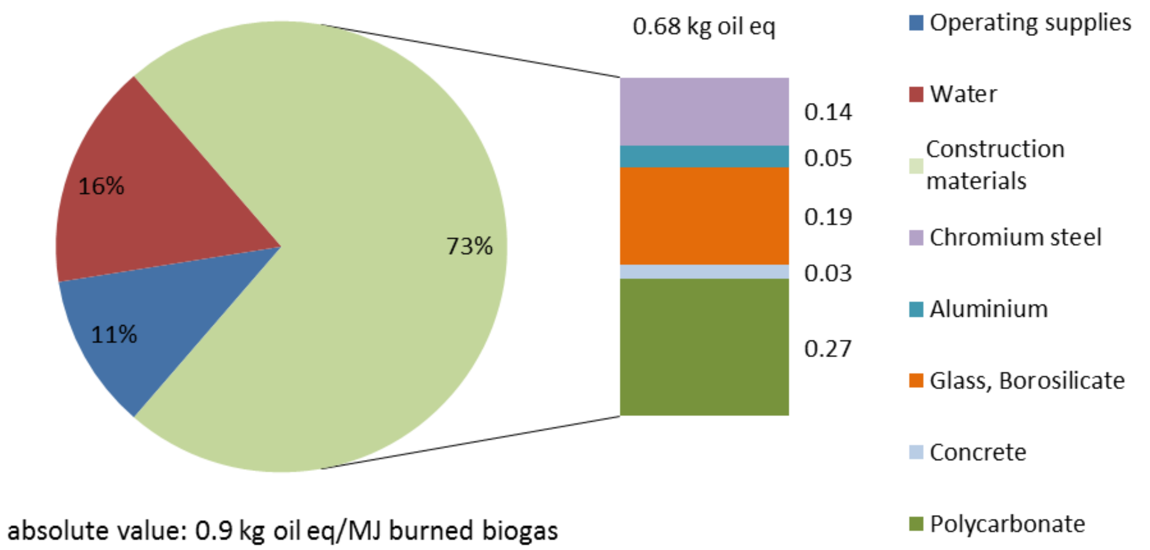


***Figure 8:*** *Contribution to fossil fuel depletion in the cultivation phase for the zero electricity scenario, three process groups are displayed: construction materials (in detail), operating supplies and water (clustered).*

### 5.1.3 Mineral resource depletion

Mineral resources are extracted from deposits via mining processes. They are feedstock for industrial processes with steel being 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 consequently consider this impact category as it is highly depending on the high-tech equipment used.

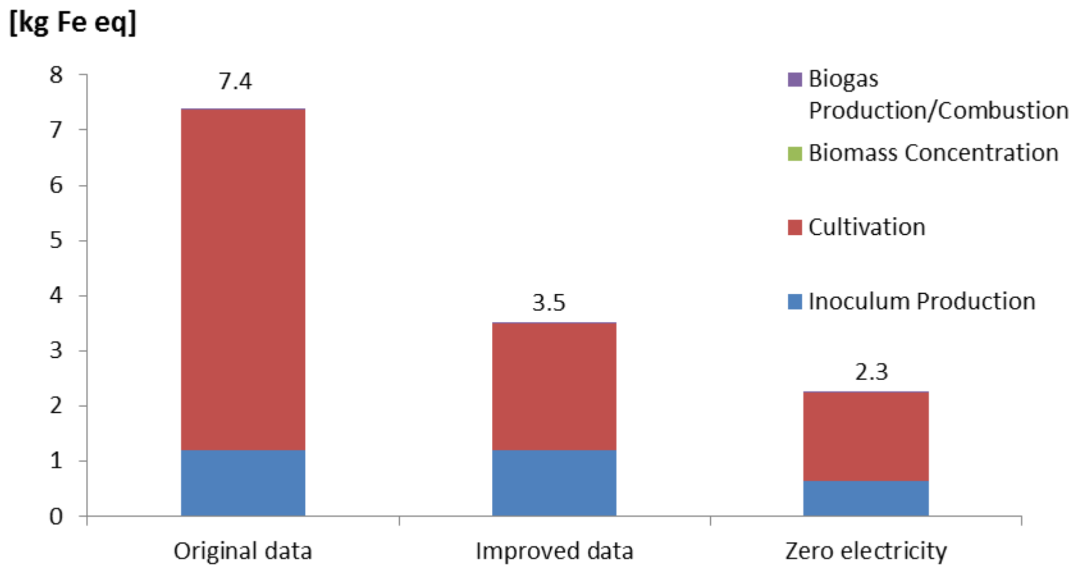


***Figure 9:*** *Contribution of life-cycle phases to mineral resource depletion for 1 MJ of burned algae-based biogas in different scenarios.*

*Figure 9* shows the overall result for mineral resource depletion (MRD) expressed in kg of Fe equivalents. As high-tech equipment was used during cultivation, this process step contributes 84 %, to the original data, showing an absolute value of 7.4 kg Fe eq. In contrast, the production and combustion of natural gas accounted for 0.06 g Fe eq only.

In the improved data scenario, results for lower energy inputs during cultivation and a reduced demand of steel for the reactor frame are presented. Still, this impact is mainly related to the cultivation phase (66 %) as here most equipment and auxiliary materials were used. However, the inoculum phase got more important as this phase was still referring to the original data baseline.

The cultivation phase in the zero electricity scenario represented with 72 % the highest impact. Compared to climate change and fossil depletion the reduction of electricity inputs to zero, leads to only minor improvements since the mineral resource depletion impact category is mainly driven by material inputs (see Figure 10).

Aggregated process contribution to mineral resource depletion per scenario

The results show that the impact category mineral resource depletion is driven by the construction materials used over the life cycle (see Figure 10). In the original data scenario the construction materials make up a share of 63 %. Complemented by electricity with 35 % almost the total Fe eq are depleted by these inputs. In the improved data scenario the relative shares of construction materials and electricity changes just slightly, leading to a relatively higher contribution of the operating supplies. In the zero electricity scenario 93 % of Fe eq were dedicated to the direct input of construction materials. Again the relative importance of operating supplies and water increased to 4 % and 1 % respectively.

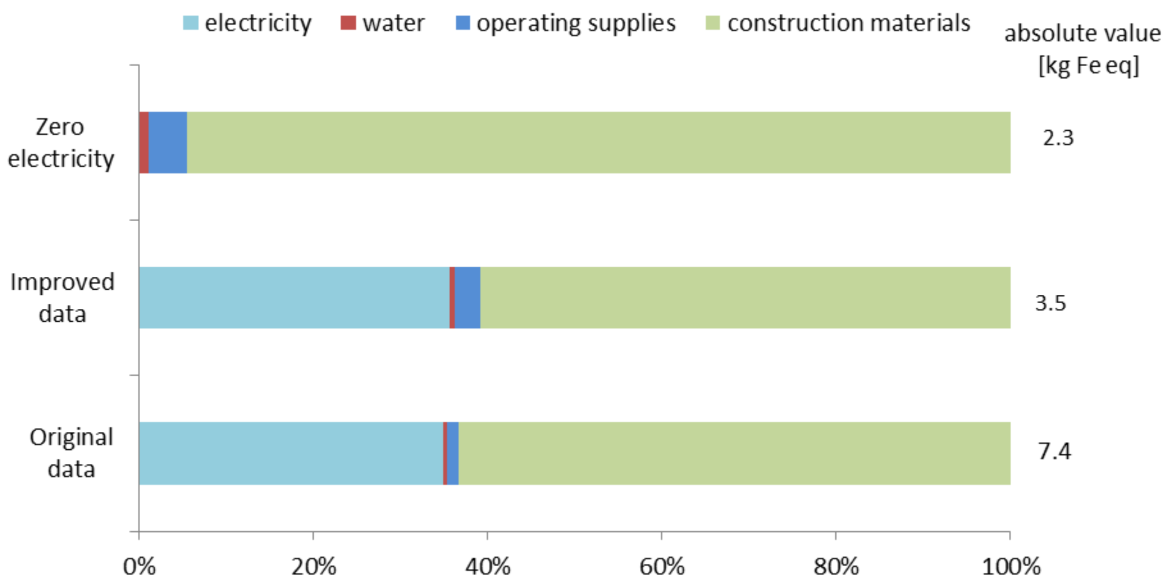


***Figure 10:*** *Aggregated contribution of processes to mineral resource depletion depletion for 1 MJ of burned algae-based biogas in different scenarios.*

Impact contribution to mineral resource depletion during cultivation in the zero electricity scenario

Like the other impacts, mineral resource depletion is driven by the cultivation phase (72 %). Therefore, single relevant inputs were identified and depicted according to their shares. The results can be seen in Figure 11. Chromium steel is the most important input in this impact category with a share of 92 % of total mineral resource depletion. Other contributors like water, and operating supplies were negligible. Consequently, processes that consume a lot of iron, like steel production, amplify the impact of this category.

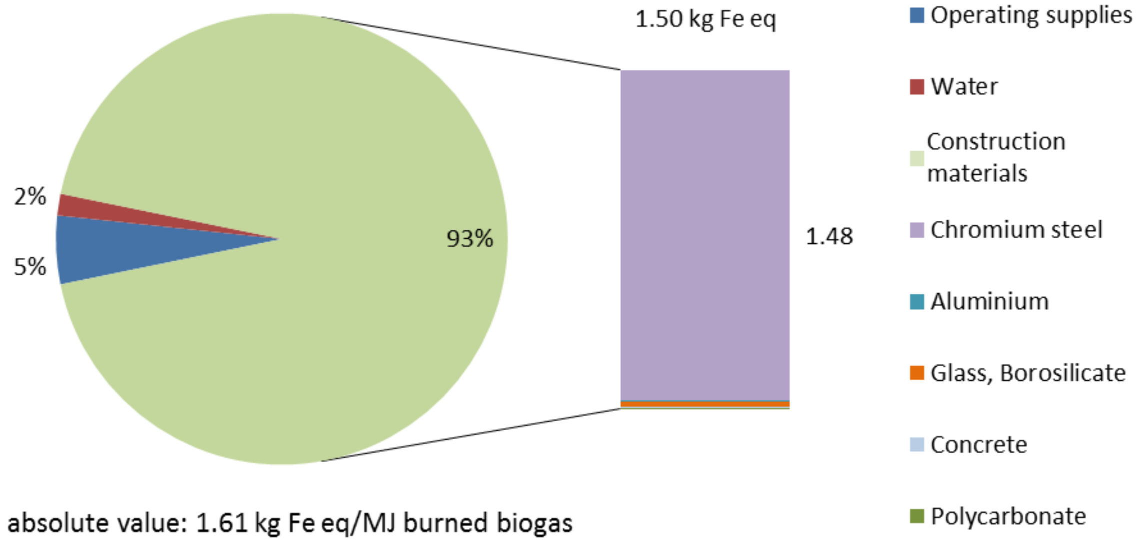


***Figure 11:*** *Contribution to mineral resource depletion in the cultivation phase for the zero electricity scenario, three process groups are displayed: construction materials (in detail), operating supplies and water (clustered).*

### 5.1.4 Human toxicity

Human toxicity describes the potential of harming chemicals (pollutants) that are released into the environment. It is expressed in 1,4-Dichlorobenzene equivalents (1,4-DB eq). Human toxicity is often displayed in LCA studies since it directly influences human health.

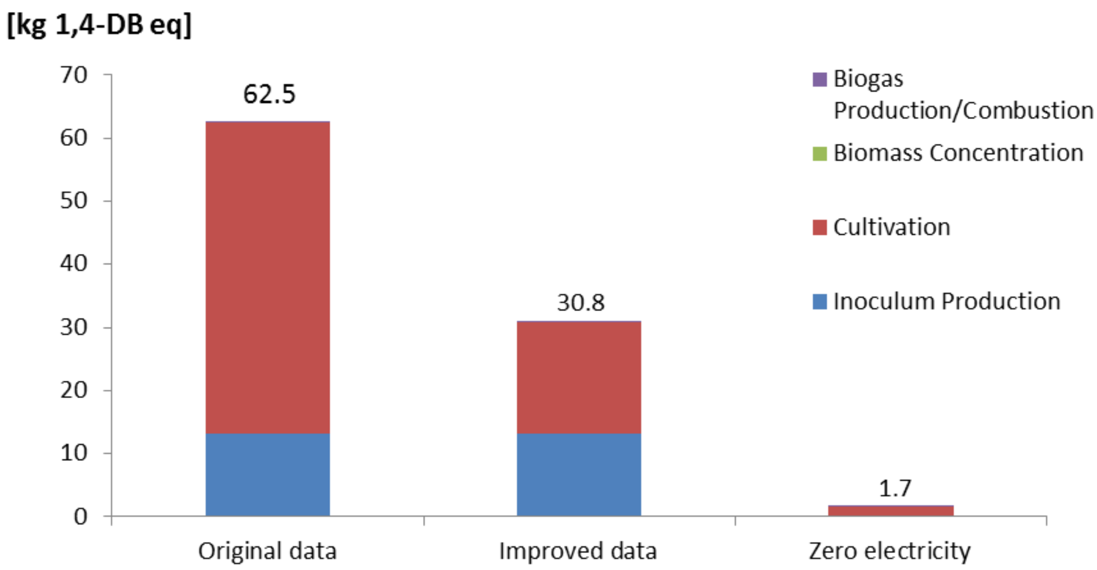


***Figure 12:*** *Contribution of life-cycle phases to Human toxicity for 1 MJ of burned algae-based biogas for different scenarios.*

Figure 12 shows the results for the impact category human toxicity. In the original data scenario the cultivation phase contributes 79 % to the impacts on human toxicity. Almost all the rest was due to the inoculum production phase. Compared to the life-cycle impact of natural gas the total absolute value in this scenario is much higher.

If inputs for steel and electricity were improved, the overall impact decreased to 30.8 kg 1,4-DB eq per MJ biogas burned. The cultivation phase was still dominating the results with 57 %, followed by the inoculum phase.

In the zero electricity scenario, the total impact decreased to 1.7 kg 1,4-DB eq per MJ biogas burned. The cultivation phase dominated with 83 % in the human toxicity impact category. The resulting absolute value was higher than the one for the fossil reference (natural gas). In the zero electricity scenario, the concentration phase was contributing with 1 %, namely by the electricity demand for microfiltering the algae broth.

<u>Aggregated process contribution to human toxicity per scenario</u>

The human toxicity impact was displayed according to the shares of the clustered impacts: electricity, water, operating supplies and construction materials (see *Figure 13*).

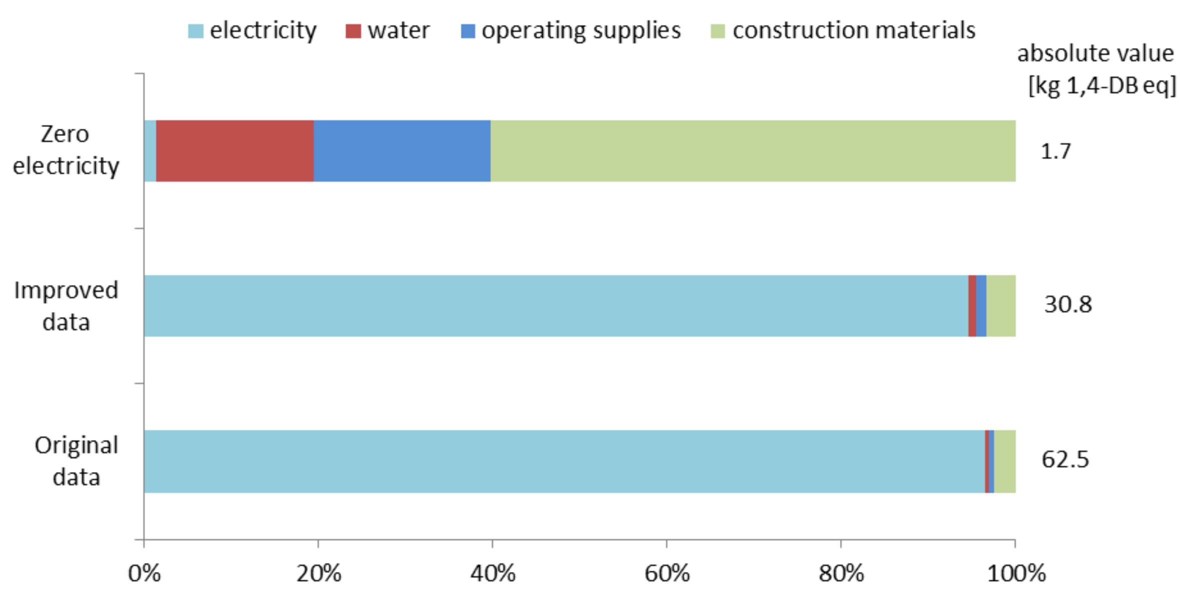


***Figure 13:*** *Aggregated contribution of processes to human toxicity for 1 MJ of burned algae-based biogas in different scenarios.*

Electricity could be identified as the main driver for the original data scenario (96 %) as well as for the improved data scenario (95 %). Depending on the electricity mix, in this case for Germany, the harming potential can be related to the treatment of the spoil. In fact, about 73 % of the electricity impact are related to the flow of manganese which results from the disposal of spoil.

In the zero electricity scenario, construction materials contribute to the highest share 60% of 1,4-DB eq followed by significant contributions of operating supplies 20 % and water 18 %.

Impact contribution to human toxicity during cultivation in the zero electricity scenario

Apart from the impact of electricity, it was investigated in detail which materials contribute to human toxicity in the cultivation phase. In Figure 14 the single material contributions are displayed, as the construction had an overall impact of 60 % during cultivation. Chromium steel represented the highest share in materials, 0.32 kg 1,4-DB eq (38 %) per MJ of algae based biogas burned. Another main contributor was glass, used for the reactor tubes with 0.19 kg 1,4-DB eq (22 %). With a total of 40 %, also the other process groups water and operating supplies contributed significantly. For water and operating supplies, the impact was related to manganese emission due to infrastructure production (e.g. building of a chemical plant) and upstream electricity inputs for various pre-processes.

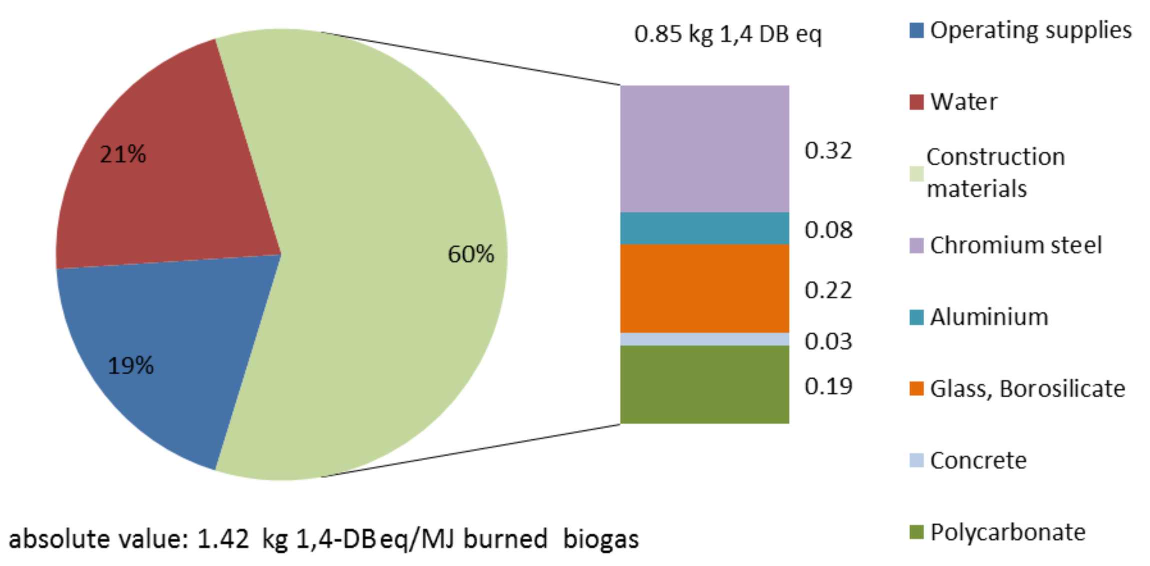


***Figure 14:*** *Contribution to human toxicity in the cultivation phase for the zero electricity scenario, three process groups are displayed: construction materials (in detail), operating supplies and water (clustered).*

### 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.

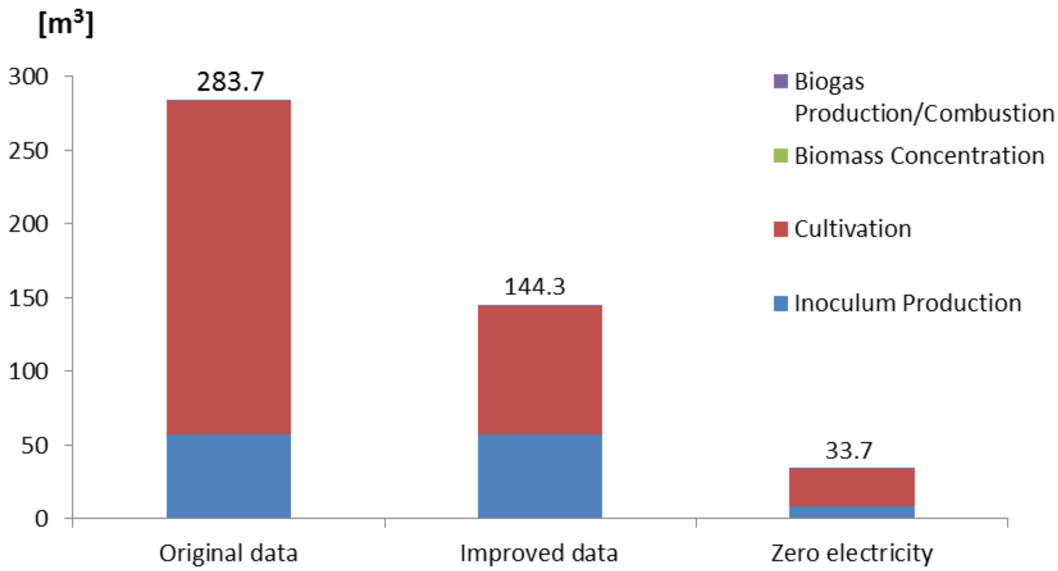


***Figure 15:*** *Contribution of life-cycle phases to water depletion for 1 MJ of burned algae-based biogas for different scenarios.*

Figure 15 shows the impact category water depletion. The shares of contribution are referring to all scenarios. Main contribution within the original data scenario (79 %) was related to the phase of cultivation. Almost all the rest (20 %) was related to the inoculum production phase. Compared to the life-cycle impact of natural gas, the absolute value (283.7 $m^3$ per MJ burned biogas) is higher.

In the improved data scenario, impacts of the cultivation phase decreased while, simultaneously, those related to the inoculation increased with respect to the original relations. The total impact was reduced by about 48%.

In the zero electricity scenario, the cultivation phase was dominating the results. Now, water depletion was driven by the materials and direct water inputs.

Aggregated process contribution to water depletion per scenario

Figure 16 shows the result of the impact water depletion per scenario. It was observed that the water depletion in the original data scenario and in the improved data scenario was not caused by direct water consumption for the inoculum (25 %) and cultivation process (75 %) but was again mainly driven by the demand for 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.

In the original data scenario 99 % of the absolute water depletion is related to the water used for electricity production. If this flow was cut off, the absolute value would have been 4.3 $m^3$ instead of 283.7$m^3$. In the improved data scenario 98 % of depleted water is due to the water used in the turbine for electricity production. In the zero electricity scenario the main direct contribution is due to the construction materials, but the flow of water used in turbines is representing a share of 95 %. This can be explained by the upstream (indirect) electricity input for the production of the construction materials that is driving the overall impact even in this scenario. Without taking this flow into account, we could derive an absolute water depletion value of 1.6 $m^3$.

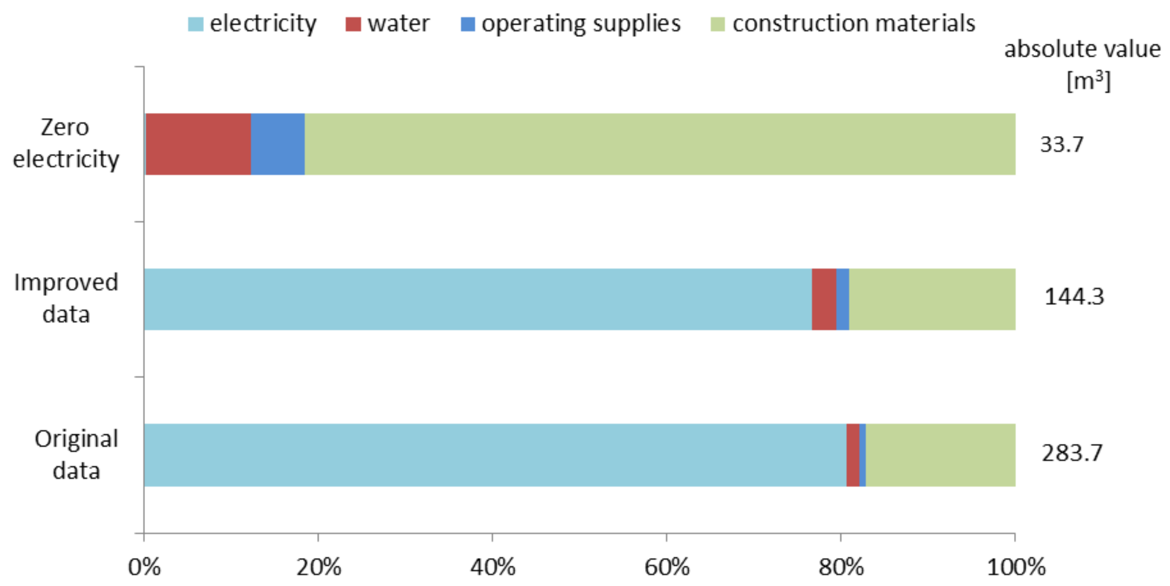


***Figure 16:*** *Aggregated contribution of processes to water depletion for 1 MJ of burned algae-based biogas in different scenarios.*

Impact contribution to water depletion during cultivation in the zero electricity scenario

Even without electricity inputs, 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 exceed the direct water contributions. Direct water input accounted for only 16 %. Within this group the cultivation medium had a minor contribution; cleaning and cooling water were dominating the water input group.

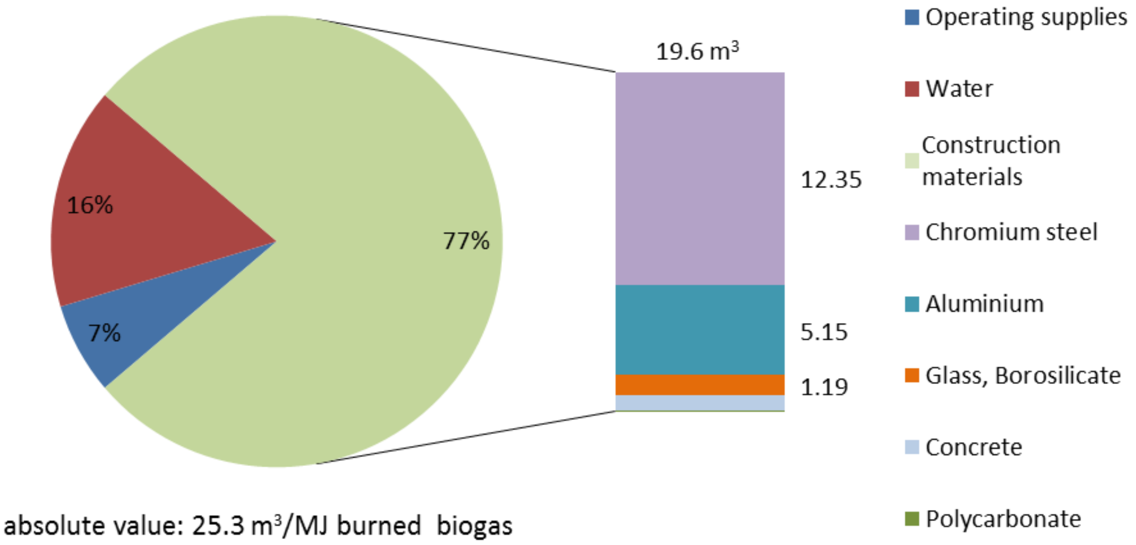


***Figure 17:*** *Contribution to water depletion in the cultivation phase for the zero electricity scenario, three process groups are displayed: construction materials (in detail), operating supplies and water (clustered).*

## 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 shows similar results and trends to those observed achieved with ReCiPe.

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 improved data scenario, it was shown that the overall CEENE impact decreased from 1588 $MJ_{ex}$ to 841 $MJ_{ex}$. A reduction in electricity and steel inputs during the cultivation phase by two thirds leads to a decrease in the overall impact by about 47 %. The fossil reference, the production and combustion of 1 MJ natural gas, shows a CEENE value of 1.04 $MJ_{ex}$. Consequently, the CEENE impact value referring to the original data exceeded the one for natural gas.

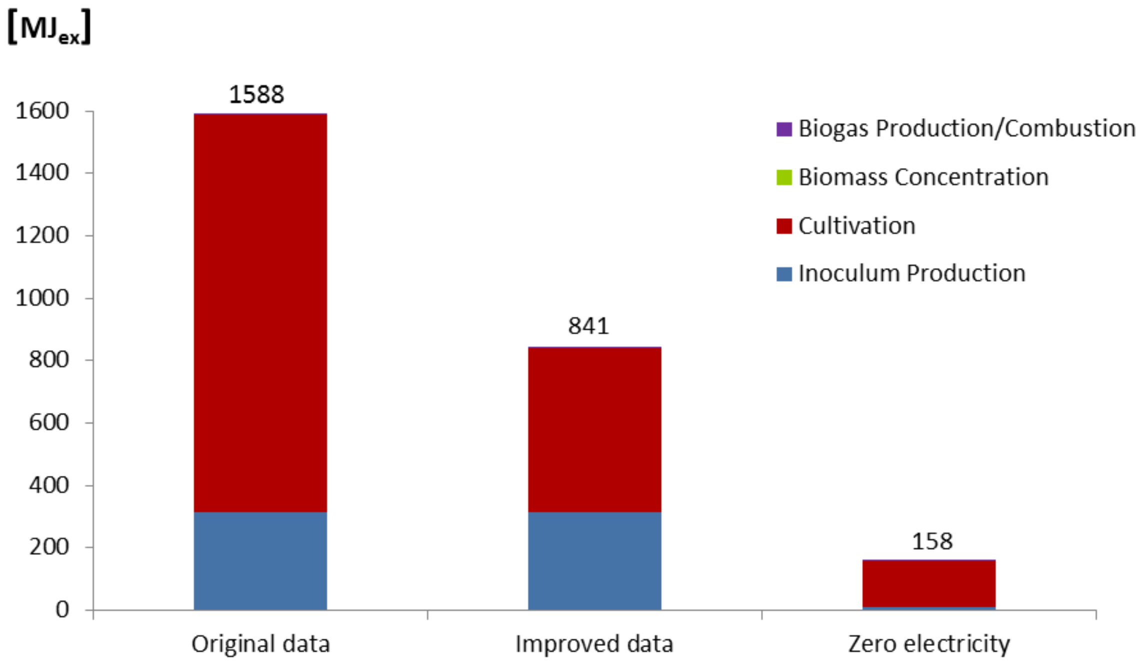


***Figure 18:*** *Contribution of life-cycle phases to the CEENE footprint for 1 MJ of burned algae-based biogas for different scenarios.*

Impact contribution of the resource categories to CEENE per scenario

The results of the three scenarios are presented in *Figure 19*. The highest share of the total CEENE impact for the original data scenario as well as for the improved data scenario is related to fossil fuel consumption, 76 % and 72 % respectively. Fossil fuels were followed by nuclear energy representing the main shares of the German electricity mix. Water resources are dominating the CEENE impact of the zero electricity scenario 51 %, resulting from indirect water inputs for the material processing as well as direct water inputs as culture medium, added by water for cleaning and cooling purposes. In this respect, the CEENE results differ substantially from the ReCiPe results for water depletion since water use in turbine for hydropower production was characterized with a factor of zero in this methodology. The marine resources categories did not show up in in the results and was consequently not displayed.

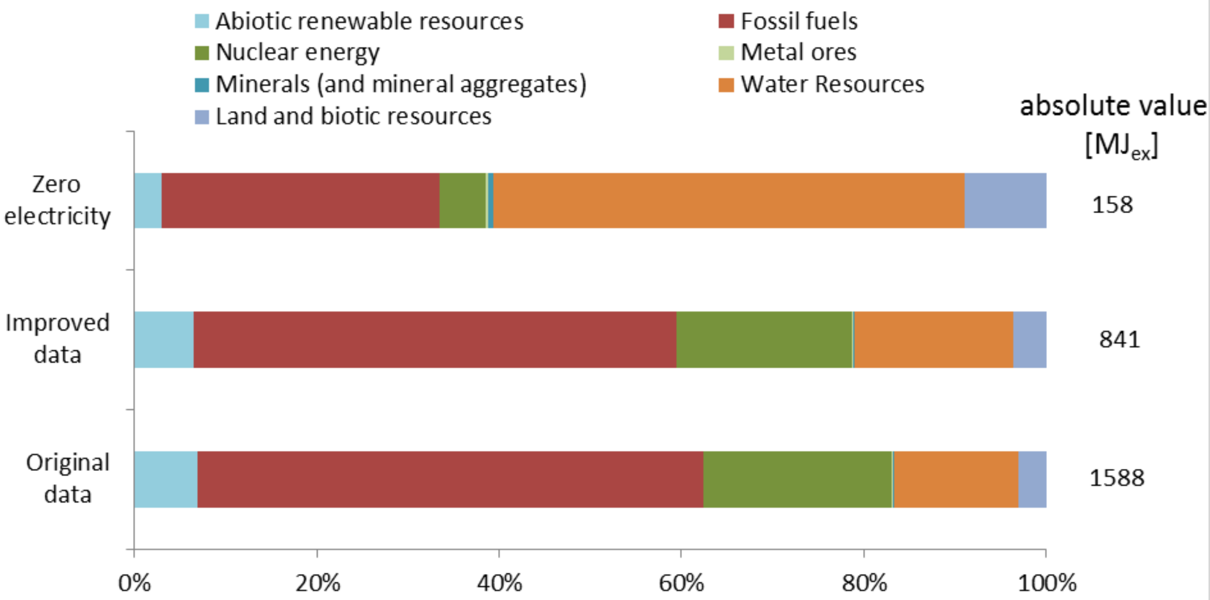


***Figure 19:*** *Impact contribution to CEENE for different resource categories for 1 MJ of burned algae-based biogas.*

# 6 Summary and Interpretation

The results of the LCIA with ReCiPe show that the environmental impacts of energetic use of microalgae cultivated in PBR were driven by the electricity consumption. The electricity demand for pumping and lighting during the algae cultivation phase represents the predominant contributor within the algae production of the considered lab scale system. This results are in accordance to those from the economic models developed in the EnAlgae context by Spruijt et al. (2015). They conclude that the "electricity requirement of algae production needs to decrease considerably in order to make bulk markets accessible for microalgae". By replacing the German electricity mix by renewable energies in the future these results may change.

At the time of evaluation, the biomass was produced in a batch cultivation system which was inoculated ten times per year. The share of electricity in the overall results even covered the contribution of other flows like construction materials. To be able to detect environmental impacts, apart from those related to electricity, the zero electricity scenario was analyzed and contributors within this production step were highlighted. Then, the impacts were related to the materials used, especially polycarbonate and chromium steel. 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 low impact in fossil depletion but high impact in mineral resource depletion, whereas for polycarbonate it is the other way round.

If operated continuously in a fed-batch or semi-continuous mode, and integrated in the bioremediation scheme of a RAS that supplies nutrients for the algae and in exchange receives nutrient-depleted water from the algae facility as proposed in the "Best Practice Output", improvements in environmental impacts are generated from minimizing water consumption and waste water production. 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 Less energy consuming production systems such as airlift systems and thin layer reactors should also be considered.

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. This view might change if credits e.g. for the bioremediation of process water from the RAS are included and high value products (*Nannochloropsis salina* has an average lipid content of almost 30% and produces the essential fatty acid eicosapenatenoic acid (EPA)) are extracted before the remaining biomass is used for biomethane production.

# 7 Conclusions

At htw saar, the microalgae production runs at experimental scale. The technical equipment and materials in use are not optimized towards an efficient energy use. The small scale prevented theoretical upscaling approaches, as the data baseline was not suitable to be abstracted.

The LCA results uncover the bottlenecks of algae production. Under the current technological restrictions (process set up and scale), it seems hardly possible to overcome the unfavorable energy inputs for the operation of tubular photobioreactors in a greenhouse. Future research should focus not only on process optimization but also on possibilities to combine the process with renewable sources of electricity. This suggestion is independent of the final product. Energy in terms of biomethane from algae produced in the described system does not fulfill sustainability criteria.

The results emphasize the necessity to develop upstream integrated systems such as that described in the Best Practice of pilot 5, of novel, energy efficient harvesting systems and downstream processing. The energy demand also indicates a necessity for extracting high value products before the remaining biomass is used for biomethane or other energy use, i.e. in a biorefinery approach.

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## 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 three scenarios in *Table S 1*- S 3.

***Table S 1:*** *ReCiPe midpoints, absolute values and shares according to life-cycle phases (original data scenario) per MJ algae-based biogas.*

| ReCiPe Impact category (midpoints) | | Inoculum Production | % | Cultivation | % | Biomass Concentration | % | Biogas Production | % | Sum |
|---|---|---|---|---|---|---|---|---|---|---|
| Climate change (CC) | kg CO2 eq | 1.58E+01 | 20.78 | 6.02E+01 | 79.18 | 2.41E-02 | 0.03 | 7.62E-03 | 0.01 | 7.61E+01 |
| Ozone depletion (OD) | kg CFC-11 eq | 6.77E-07 | 18.89 | 2.90E-06 | 81.07 | 1.02E-09 | 0.03 | 2.73E-10 | 0.01 | 3.58E-06 |
| Terrestrial acidification (TA) | kg SO2 eq | 2.33E-02 | 19.75 | 9.47E-02 | 80.18 | 3.36E-05 | 0.03 | 4.11E-05 | 0.03 | 1.18E-01 |
| Freshwater eutrophication (FE) | kg P eq | 1.97E-02 | 21.37 | 7.24E-02 | 78.59 | 3.04E-05 | 0.03 | 7.16E-06 | 0.01 | 9.21E-02 |
| Marine eutrophication (ME) | kg N eq | 4.70E-03 | 21.12 | 1.76E-02 | 78.84 | 7.22E-06 | 0.03 | 2.39E-06 | 0.01 | 2.23E-02 |
| Human toxicity (HT) | kg 1,4-DB eq | 1.33E+01 | 21.22 | 4.92E+01 | 78.74 | 2.03E-02 | 0.03 | 4.98E-03 | 0.01 | 6.25E+01 |
| Photochemical oxidant formation (POF) | kg NMVOC | 1.83E-02 | 19.58 | 7.50E-02 | 80.36 | 2.67E-05 | 0.03 | 2.98E-05 | 0.03 | 9.33E-02 |
| Particulate matter formation (PMF) | kg PM10 eq | 9.24E-03 | 18.96 | 3.95E-02 | 80.99 | 1.25E-05 | 0.03 | 1.32E-05 | 0.03 | 4.87E-02 |
| Terrestrial ecotoxicity (TET) | kg 1,4-DB eq | 8.47E-04 | 20.17 | 3.35E-03 | 79.80 | 1.24E-06 | 0.03 | 3.78E-07 | 0.01 | 4.20E-03 |
| Freshwater ecotoxicity (FET) | kg 1,4-DB eq | 1.22E-01 | 21.05 | 4.58E-01 | 78.91 | 1.86E-04 | 0.03 | 4.71E-05 | 0.01 | 5.81E-01 |
| Marine ecotoxicity (MET) | kg 1,4-DB eq | 1.23E-01 | 21.07 | 4.59E-01 | 78.89 | 1.85E-04 | 0.03 | 4.90E-05 | 0.01 | 5.82E-01 |
| Ionising radiation (IR) | kg U235 eq | 7.04E+00 | 21.25 | 2.61E+01 | 78.71 | 1.08E-02 | 0.03 | 2.63E-03 | 0.01 | 3.31E+01 |
| Agricultural land occupation (ALO) | m2a | 2.44E-01 | 20.17 | 9.65E-01 | 79.79 | 3.64E-04 | 0.03 | 1.02E-04 | 0.01 | 1.21E+00 |
| Urban land occupation (ULO) | m2a | 8.97E-02 | 13.04 | 5.98E-01 | 86.95 | 8.10E-05 | 0.01 | 2.92E-05 | 0.00 | 6.88E-01 |
| Natural land transformation (NLT) | m2 | 1.06E-03 | 19.56 | 4.34E-03 | 80.40 | 1.56E-06 | 0.03 | 4.91E-07 | 0.01 | 5.40E-03 |
| Water depletion (WD) | m3 | 5.77E+01 | 20.34 | 2.26E+02 | 79.62 | 7.79E-02 | 0.03 | 3.07E-02 | 0.01 | 2.84E+02 |
| Mineral resource depletion (MRD) | kg Fe eq | 1.20E+00 | 16.21 | 6.18E+00 | 83.76 | 9.72E-04 | 0.01 | 1.42E-03 | 0.02 | 7.37E+00 |
| Fossil fuel depletion (FD) | kg oil eq | 4.04E+00 | 20.74 | 1.54E+01 | 79.22 | 6.15E-03 | 0.03 | 1.59E-03 | 0.01 | 1.95E+01 |

***Table S 2:*** *ReCiPe midpoints, absolute values and shares according to life-cycle phases (improved data scenario) per MJ algae-based biogas.*

| ReCiPe Impact category (midpoints) | | Inoculum Production | % | Cultivation | % | Biomass Concentration | % | Biogas Production | % | Sum |
|---|---|---|---|---|---|---|---|---|---|---|
| Climate change (CC) | kg CO2 eq | 1.58E+01 | 41.20 | 2.25E+01 | 58.72 | 2.41E-02 | 0.06 | 7.62E-03 | 0.02 | 3.84E+01 |
| Ozone depletion (OD) | kg CFC-11 eq | 6.77E-07 | 34.15 | 1.30E-06 | 65.78 | 1.02E-09 | 0.05 | 2.73E-10 | 0.01 | 1.98E-06 |
| Terrestrial acidification (TA) | kg SO2 eq | 2.33E-02 | 37.13 | 3.94E-02 | 62.75 | 3.36E-05 | 0.05 | 4.11E-05 | 0.07 | 6.28E-02 |
| Freshwater eutrophication (FE) | kg P eq | 1.97E-02 | 43.65 | 2.54E-02 | 56.26 | 3.04E-05 | 0.07 | 7.16E-06 | 0.02 | 4.51E-02 |
| Marine eutrophication (ME) | kg N eq | 4.70E-03 | 42.58 | 6.33E-03 | 57.33 | 7.22E-06 | 0.07 | 2.39E-06 | 0.02 | 1.10E-02 |
| Human toxicity (HT) | kg 1,4-DB eq | 1.33E+01 | 43.01 | 1.75E+01 | 56.91 | 2.03E-02 | 0.07 | 4.98E-03 | 0.02 | 3.08E+01 |
| Photochemical oxidant formation (POF) | kg NMVOC | 1.83E-02 | 36.74 | 3.14E-02 | 63.15 | 2.67E-05 | 0.05 | 2.98E-05 | 0.06 | 4.97E-02 |
| Particulate matter formation (PMF) | kg PM10 eq | 9.24E-03 | 35.76 | 1.66E-02 | 64.14 | 1.25E-05 | 0.05 | 1.32E-05 | 0.05 | 2.58E-02 |
| Terrestrial ecotoxicity (TET) | kg 1,4-DB eq | 8.47E-04 | 39.08 | 1.32E-03 | 60.85 | 1.24E-06 | 0.06 | 3.78E-07 | 0.02 | 2.17E-03 |
| Freshwater ecotoxicity (FET) | kg 1,4-DB eq | 1.22E-01 | 42.40 | 1.66E-01 | 57.52 | 1.86E-04 | 0.06 | 4.71E-05 | 0.02 | 2.88E-01 |
| Marine ecotoxicity (MET) | kg 1,4-DB eq | 1.23E-01 | 42.67 | 1.64E-01 | 57.24 | 1.85E-04 | 0.06 | 4.90E-05 | 0.02 | 2.87E-01 |
| Ionising radiation (IR) | kg U235 eq | 7.04E+00 | 43.02 | 9.31E+00 | 56.89 | 1.08E-02 | 0.07 | 2.63E-03 | 0.02 | 1.64E+01 |
| Agricultural land occupation (ALO) | m2a | 2.44E-01 | 38.62 | 3.87E-01 | 61.30 | 3.64E-04 | 0.06 | 1.02E-04 | 0.02 | 6.32E-01 |
| Urban land occupation (ULO) | m2a | 8.97E-02 | 16.25 | 4.62E-01 | 83.73 | 8.10E-05 | 0.01 | 2.92E-05 | 0.01 | 5.52E-01 |
| Natural land transformation (NLT) | m2 | 1.06E-03 | 35.98 | 1.88E-03 | 63.95 | 1.56E-06 | 0.05 | 4.91E-07 | 0.02 | 2.93E-03 |
| Water depletion (WD) | m3 | 5.77E+01 | 40.00 | 8.65E+01 | 59.93 | 7.79E-02 | 0.05 | 3.07E-02 | 0.02 | 1.44E+02 |
| Mineral resource depletion (MRD) | kg Fe eq | 1.20E+00 | 34.10 | 2.31E+00 | 65.83 | 9.72E-04 | 0.03 | 1.42E-03 | 0.04 | 3.50E+00 |
| Fossil fuel depletion (FD) | kg oil eq | 4.04E+00 | 41.01 | 5.81E+00 | 58.91 | 6.15E-03 | 0.06 | 1.59E-03 | 0.02 | 9.86E+00 |

***Table S 3:*** *ReCiPe midpoints, absolute values and shares according to life-cycle phases (zero electricity scenario) per MJ algae-based biogas.*

| ReCiPe Impact category (midpoints) | | Inoculum Production | % | Cultivation | % | Biomass Concentration | % | Biogas Production | % | Sum |
|---|---|---|---|---|---|---|---|---|---|---|
| Climate change (CC) | kg CO2 eq | 4.10E-01 | 10.58 | 3.43E+00 | 88.60 | 2.41E-02 | 0.62 | 7.62E-03 | 0.20 | 3.88E+00 |
| Ozone depletion (OD) | kg CFC-11 eq | 2.65E-08 | 5.06 | 4.97E-07 | 94.70 | 1.02E-09 | 0.19 | 2.73E-10 | 0.05 | 5.25E-07 |
| Terrestrial acidification (TA) | kg SO2 eq | 1.91E-03 | 12.88 | 1.29E-02 | 86.62 | 3.36E-05 | 0.23 | 4.11E-05 | 0.28 | 1.49E-02 |
| Freshwater eutrophication (FE) | kg P eq | 2.14E-04 | 14.49 | 1.23E-03 | 82.97 | 3.04E-05 | 2.06 | 7.16E-06 | 0.48 | 1.48E-03 |
| Marine eutrophication (ME) | kg N eq | 8.76E-05 | 12.41 | 6.09E-04 | 86.23 | 7.22E-06 | 1.02 | 2.39E-06 | 0.34 | 7.06E-04 |
| Human toxicity (HT) | kg 1,4-DB eq | 2.58E-01 | 15.15 | 1.42E+00 | 83.36 | 2.03E-02 | 1.19 | 4.98E-03 | 0.29 | 1.70E+00 |
| Photochemical oxidant formation (POF) | kg NMVOC | 1.25E-03 | 10.77 | 1.03E-02 | 88.74 | 2.67E-05 | 0.23 | 2.98E-05 | 0.26 | 1.16E-02 |
| Particulate matter formation (PMF) | kg PM10 eq | 1.37E-03 | 16.68 | 6.81E-03 | 83.01 | 1.25E-05 | 0.15 | 1.32E-05 | 0.16 | 8.21E-03 |
| Terrestrial ecotoxicity (TET) | kg 1,4-DB eq | 5.67E-05 | 14.28 | 3.39E-04 | 85.31 | 1.24E-06 | 0.31 | 3.78E-07 | 0.10 | 3.97E-04 |
| Freshwater ecotoxicity (FET) | kg 1,4-DB eq | 3.48E-03 | 15.63 | 1.86E-02 | 83.33 | 1.86E-04 | 0.83 | 4.71E-05 | 0.21 | 2.23E-02 |
| Marine ecotoxicity (MET) | kg 1,4-DB eq | 4.62E-03 | 20.09 | 1.82E-02 | 78.89 | 1.85E-04 | 0.80 | 4.90E-05 | 0.21 | 2.30E-02 |
| Ionising radiation (IR) | kg U235 eq | 1.07E-01 | 12.88 | 7.12E-01 | 85.51 | 1.08E-02 | 1.30 | 2.63E-03 | 0.32 | 8.33E-01 |
| Agricultural land occupation (ALO) | m2a | 1.15E-02 | 10.39 | 9.90E-02 | 89.19 | 3.64E-04 | 0.33 | 1.02E-04 | 0.09 | 1.11E-01 |
| Urban land occupation (ULO) | m2a | 3.82E-02 | 8.75 | 3.98E-01 | 91.23 | 8.10E-05 | 0.02 | 2.92E-05 | 0.01 | 4.37E-01 |
| Natural land transformation (NLT) | m2 | 6.13E-05 | 8.67 | 6.43E-04 | 91.04 | 1.56E-06 | 0.22 | 4.91E-07 | 0.07 | 7.07E-04 |
| Water depletion (WD) | m3 | 8.35E+00 | 24.77 | 2.53E+01 | 74.91 | 7.79E-02 | 0.23 | 3.07E-02 | 0.09 | 3.37E+01 |
| Mineral resource depletion (MRD) | kg Fe eq | 6.39E-01 | 28.29 | 1.62E+00 | 71.61 | 9.72E-04 | 0.04 | 1.42E-03 | 0.06 | 2.26E+00 |
| Fossil fuel depletion (FD) | kg oil eq | 1.15E-01 | 10.85 | 9.35E-01 | 88.42 | 6.15E-03 | 0.58 | 1.59E-03 | 0.15 | 1.06E+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.*

| ReCiPe Impact category (midpoints) | | Value |
|---|---|---|
| Climate change (CC) | kg CO2 eq | 6.10E-02 |
| Ozone depletion (OD) | kg CFC-11 eq | 2.10E-11 |
| Terrestrial acidification (TA) | kg SO2 eq | 8.47E-05 |
| Freshwater eutrophication (FE) | kg P eq | 2.98E-07 |
| Marine eutrophication (ME) | kg N eq | 8.22E-07 |
| Human toxicity (HT) | kg 1,4-DB eq | 2.95E-04 |
| Photochemical oxidant formation (POF) | kg NMVOC | 8.37E-05 |
| Particulate matter formation (PMF) | kg PM10 eq | 1.95E-05 |
| Terrestrial ecotoxicity (TET) | kg 1,4-DB eq | 9.18E-07 |
| Freshwater ecotoxicity (FET) | kg 1,4-DB eq | 2.02E-06 |
| Marine ecotoxicity (MET) | kg 1,4-DB eq | 2.09E-06 |
| Ionising radiation (IR) | kg U235 eq | 1.11E-04 |
| Agricultural land occupation (ALO) | m2a | 5.35E-06 |
| Urban land occupation (ULO) | m2a | 1.01E-05 |
| Natural land transformation (NLT) | m2 | 4.86E-06 |
| Water depletion (WD) | m3 | 9.69E-04 |
| Mineral resource depletion (MRD) | kg Fe eq | 6.28E-05 |
| Fossil fuel depletion (FD) | kg oil eq | 2.23E-02 |

For detailed investigation, only five categories have been selected (see below). The ReCiPe endpoints have been calculated to get an impression of the contribution on midpoint level to the overall environmental sustainability (on the original data scenario baseline). 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. 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 biogas combustion | Inoculum Production | % | Cultivation | % | Biomass Concentration | % | Biogas Production/Combustion | % | aggregated Endpoint |
|---|---|---|---|---|---|---|---|---|---|---|
| Photochemical oxidant formation | kg NMVOC | 7.12E-10 | 19.58 | 2.92E-09 | 80.36 | 1.04E-12 | 0.03 | 1.16E-12 | 0.03 | |
| Ozone depletion | kg CFC-11 eq | 7.24E-09 | 20.14 | 2.87E-08 | 79.82 | 1.05E-11 | 0.03 | 3.39E-12 | 0.01 | |
| Ionising radiation | kg U235 eq | 1.16E-07 | 21.25 | 4.28E-07 | 78.71 | 1.78E-10 | 0.03 | 4.32E-11 | 0.01 | **1.63E-04** |
| Particulate matter formation | kg PM10 eq | 2.40E-06 | 18.96 | 1.03E-05 | 80.99 | 3.24E-09 | 0.03 | 3.42E-09 | 0.03 | |
| Human toxicity | kg 1,4-DB eq | 9.28E-06 | 21.22 | 3.44E-05 | 78.74 | 1.42E-08 | 0.03 | 3.49E-09 | 0.01 | |
| Climate change | kg CO2 eq | 2.21E-05 | 20.78 | 8.43E-05 | 79.18 | 3.37E-08 | 0.03 | 1.07E-08 | 0.01 | |
| **Ecosystems [species*yr]** | **per 1 MJ biogas combustion** | **Inoculum Production** | **%** | **Cultivation** | **%** | **Biomass Concentration** | **%** | **Biogas Production/Combustion** | **%** | **aggregated Endpoint** |
| Marine ecotoxicity | kg 1,4-DB eq | 2.16E-11 | 21.07 | 8.08E-11 | 78.89 | 3.25E-14 | 0.03 | 8.64E-15 | 0.01 | |
| Freshwater ecotoxicity | kg 1,4-DB eq | 1.05E-10 | 21.05 | 3.95E-10 | 78.91 | 1.60E-13 | 0.03 | 4.06E-14 | 0.01 | |
| Terrestrial ecotoxicity | kg 1,4-DB eq | 1.27E-10 | 20.17 | 5.04E-10 | 79.80 | 1.87E-13 | 0.03 | 5.69E-14 | 0.01 | |
| Terrestrial acidification | kg SO2 eq | 1.35E-10 | 19.75 | 5.49E-10 | 80.18 | 1.95E-13 | 0.03 | 2.39E-13 | 0.03 | |
| Freshwater eutrophication | kg P eq | 8.74E-10 | 21.37 | 3.21E-09 | 78.59 | 1.35E-12 | 0.03 | 3.18E-13 | 0.01 | **6.78E-07** |
| Urban land occupation | m2a | 1.86E-09 | 13.04 | 1.24E-08 | 86.95 | 1.68E-12 | 0.01 | 6.06E-13 | 0.00 | |
| Agricultural land occupation | m2a | 2.93E-09 | 20.17 | 1.16E-08 | 79.79 | 4.36E-12 | 0.03 | 1.22E-12 | 0.01 | |
| Natural land transformation | m2 | 7.95E-09 | 19.93 | 3.19E-08 | 80.03 | 1.17E-11 | 0.03 | 3.64E-12 | 0.01 | |
| Climate change | kg CO2 eq | 1.25E-07 | 20.78 | 4.78E-07 | 79.18 | 1.91E-10 | 0.03 | 6.04E-11 | 0.01 | |
| **Resources [$]** | **per 1 MJ biogas combustion** | **Inoculum Production** | **%** | **Cultivation** | **%** | **Biomass Concentration** | **%** | **Biogas Production/Combustion** | **%** | **aggregated Endpoint** |
| Metal depletion | kg Fe eq | 8.54E-02 | 16.21 | 4.42E-01 | 83.76 | 6.95E-05 | 0.01 | 1.01E-04 | 0.02 | **3.75E+00** |
| Fossil depletion | kg oil eq | 6.69E-01 | 20.74 | 2.56E+00 | 79.22 | 1.02E-03 | 0.03 | 2.63E-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.

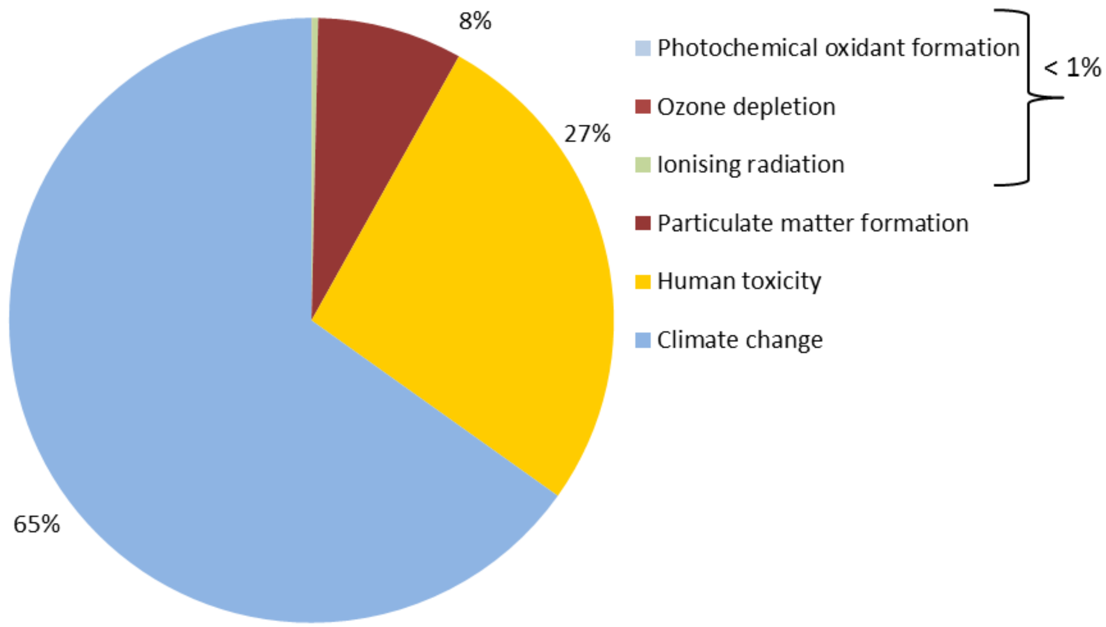



***Figure S 1:*** *Weighted contribution of midpoint categories on the endpoint level "damage to human health" per MJ algae-based biogas.*

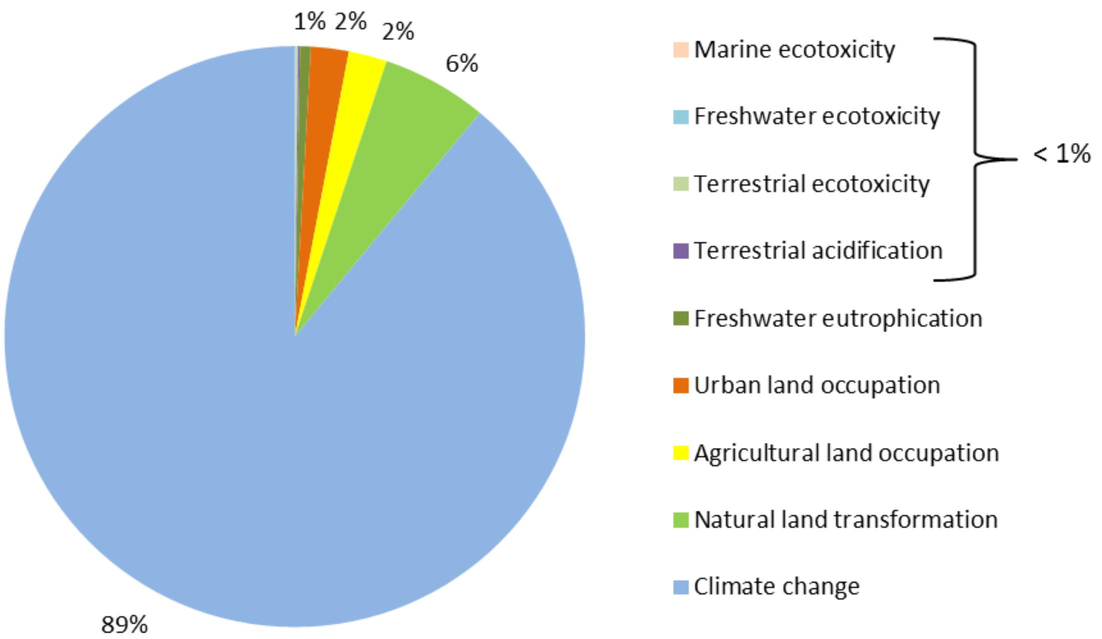



***Figure S 2:*** *Weighted contribution of midpoint categories on the endpoint level "damage to ecosystem diversity" per MJ algae-based biogas.*

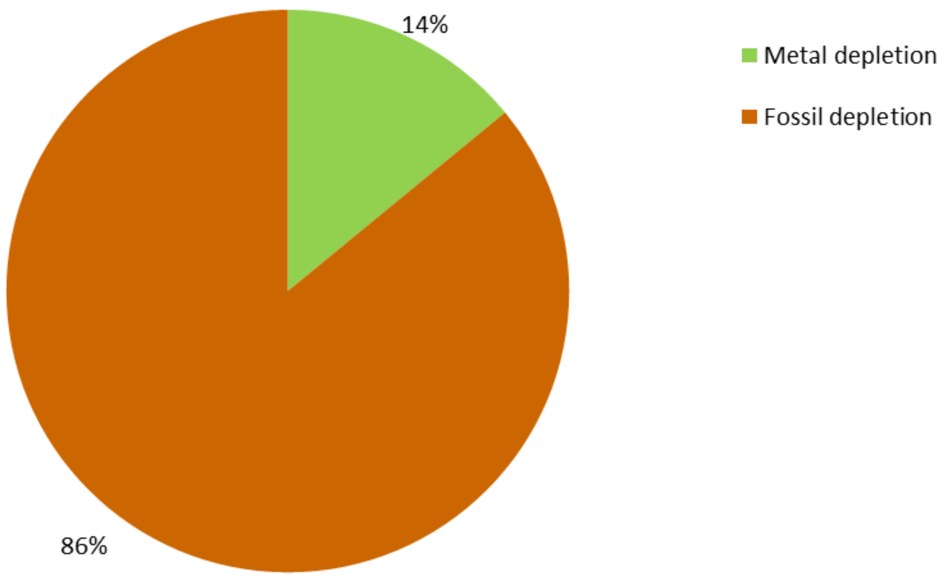
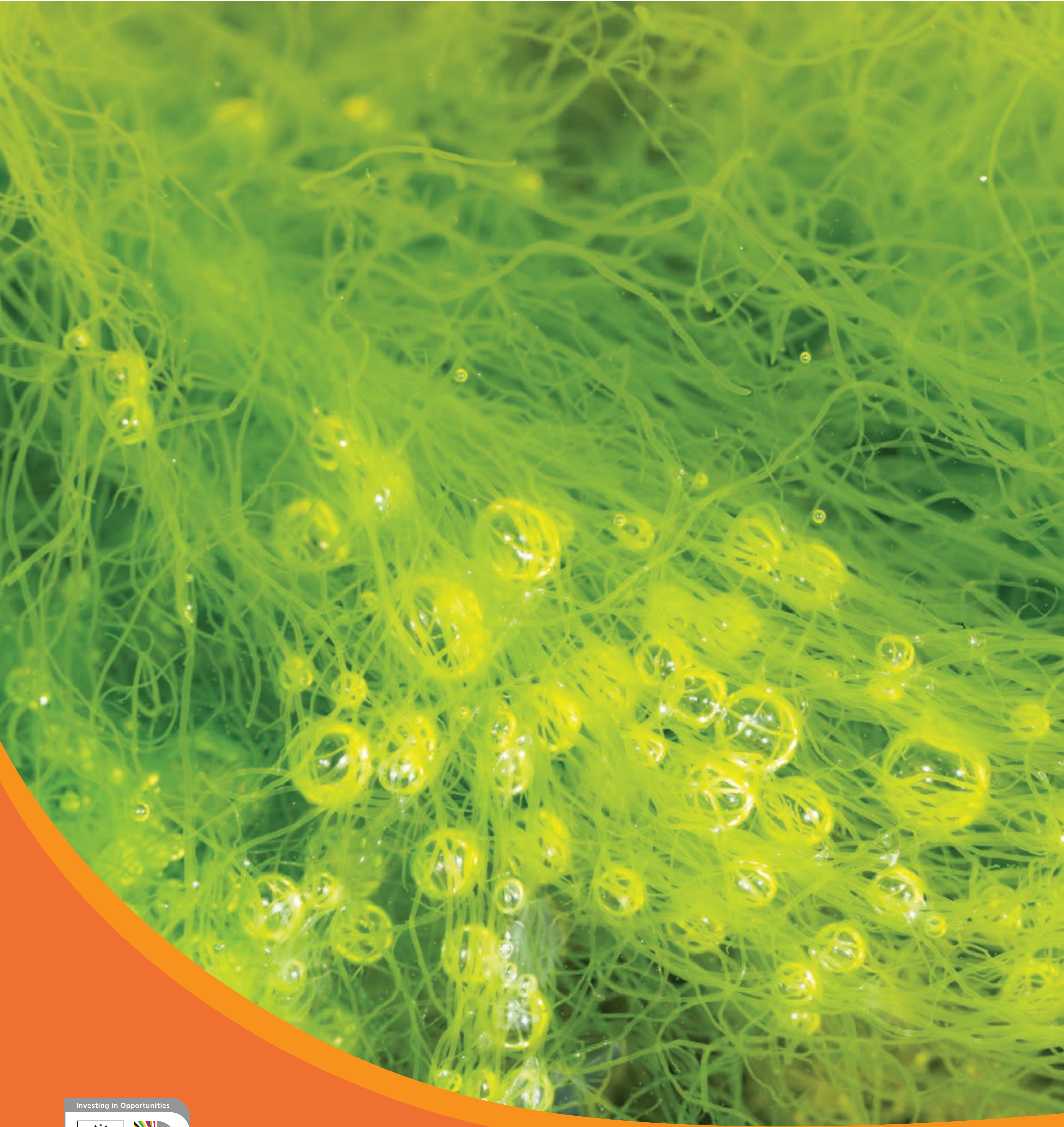



***Figure S 3:*** *Weighted contribution of midpoint categories on the endpoint level "damage to resource availability" per MJ algae-based biogas.*



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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