Research Report nr D244
Helsinki 2013

Kaisa Manninen, Matti Sonck, Kristian Spilling

ENVIRONMENTAL IMPACT ASSESSMENT OF ALGAE CULTIVATION UNDER FINNISH CONDITIONS

CLEEN LTD
ETELÄRANTA 10
P.O. BOX 10
FI-00130 HELSINKI
FINLAND
www.cleen.fi

ISBN XXX-XX-XXXX-X
ISSN XXXX-XXXX

Cleen Ltd.
Research Report nr XX

Kaisa Manninen, Matti Sonck, Kristian Spilling

ENVIRONMENTAL IMPACT ASSESSMENT OF ALGAE CULTIVATION UNDER FINNISH CONDITIONS

ccsp
Carbon Capture and Storage Program

Cleen Ltd
Helsinki 2013

Report Title: Environmental Impact Assessment of Algae Cultivation Under Finnish Conditions

Key words: microalgae, life cycle assessment

Abstract

Microalgae are seen as promising biofuel source. Because of the climatic characteristics of the northern countries, algae cultivation is, however challenging in these regions. Also the final cost, energy consumption and technical solutions of the production and refining process are identified as problems. These problems have been widely studied and a solution where industrial symbiosis, where waste water and flue gas are utilized in the cultivation process, is suggested. Life cycle assessment (LCA) is used a methodology to evaluate the environmental impacts and critical life cycle phases of two algae cultivation reactors (closed photobioreactor and open pond systems) and the harvesting phase of algae biomass. Existing literature data was used in calculating the environmental impacts of two different algae cultivation systems, closed photobioreactor and open pond. Results bring out that attention should be paid on e.g. the technical solutions of different algae production units.

Helsinki, November 2013

Table of contents

1 Introduction

1.1 Background

The study has been carried out in the Work Package 2 of the Carbon Capture and Storage Programme (CCSP), which is the research program of CLEEN Ltd (Cluster for Energy and Environment), funded by the Finnish Technology Agency (TEKES) and the participating partners. The aim of the Subtask 2.4.1 Algae based solutions is to identify conditions for feasible and sustainable algae solutions. Mass cultivation of microalgae, e.g. for biofuel purposes, requires a supply of additional CO_2, to prevent carbon limitation of cell growth. Taking the advantage of high photosynthetic potential of microalgae, algal mass cultures may be used to trap CO_2 emissions from power plants and industry. The algae biomass can then be processed and utilized in energy production in power and heat plants or as biofuel.

Currently, the microalgae are cultivated worldwide amounts to ~5,000 tons of dry weight with an approximate value of € 1,250 million. The price of most microalgae based compounds and products are relatively high and the production volumes still small. Thus, there has not been pressure to minimize the algae cultivation costs, which are still much too high for production of low-value bulk products like biofuels. However, scenarios of decreasing production costs in the near future – through technological development, selection of microalgae strains and molecular engineering, manufacture of co-products, up-scaling of production facilities and provision of other services like nutrient removal – suggest that in 10–15 years the price of algae-based biofuels may become competitive with fossil fuels. (SUBMARINER 2012)

Researches of microalgae cultivation on outdoor has mostly been conducted in regions with relatively mild climates, because they give optimal light and temperature environment leading to high growth rates. These regions provide also relatively long cultivation period in a year because there is neither winter nor cold seasons. (Hulatt and Thomas 2011a) Therefore the climatic characteristics are challenging, when algae cultivated in northern countries (SUBMARINER 2012). However, various species of microalgae have potential for biofuel feedstock production and are capable of growing under a wide range of temperatures (U.S. DOE 2010).

1.2 Goal of the study

Algae biomass is an interesting renewable energy source. There are, however a lot of barriers in order to increase the algae production to commercial scale. The final cost, energy consumption and technical solutions of the production and refining process are the main problems. These problems have been widely studied and a solution where industrial symbiosis, where waste water and flue gas are utilized in the cultivation process, is suggested.

Life Cycle Assessment (LCA) is a useful method to assess the environmental impacts and recognize the problematic life cycle phases of different systems and products. In this study, LCA was used to compare two different algae cultivation systems in order to find out the most critical life-cycle phases and impact categories. The environmental impact assessment was carried out using SimaPro LCA software, which can calculate the results for several environmental impact categories. We have focused on the energy and mass balances, and the study was based on lab scale, experimental data complemented with data reported in the literature. The studied systems are tubular photobioreactor (System 1) and raceway paddlewheel open pond (System 2). The use of waste water as a nutrient source and flue gases as a CO_2 source was examined as a one option to reduce environmental impacts.

2 Materials and methods

2.1 Background information

2.1.1 Algal strains

The properties of algae strains differ and the choice of the strain depends on the desired product and technology to be used for fuel production. One of the biggest challenges for strain selection is the difficulty of translating desirable strain properties from the laboratory to the field. A desirable strain would have robust growth in open ponds under natural weather and cultivation conditions, and would retain attributes that are selected and measured in the controlled conditions of the laboratory. However, the ability to grow well and compete when exposed to environmental conditions is difficult to predict. (National Academy of Sciences 2012) For large-scale cultivation of microalgae, local species should be prioritized. These species are already adapted to climatic conditions and the risk of spreading alien, invasive species decreases. (SUBMARINER 2012)

The goal algal biomass production is to maximize the quantity of a final product per unit time, area, and water volume, and furthermore to maximize the product output per unit input of energy, nutrients, and other resources. The productivity can be measured through biomass and lipid accumulation per unit time. Other criteria, which are important for selecting algal strains for commercial biofuel production, include all variables that alter cost in the supply chain, which is important for economic viability. Ideally, the criteria for strain selection are measurable. The selection criteria are e.g. (National Academy of Sciences 2012)

- photosynthetic efficiency
- quantity of final products (total amount of biomass, its composition, and the products to be refined, extracted, or excreted from the biomass)
- nutrient and other resource requirements
- robustness (overall stability of the crop)
- harvestability (harvesting cost and energy consumption)
- processability and extractability (factors that influence the ease of extracting algal oil or processing algal biomass to fuels)

- added value of co-products
- local origin of strains (using locally selected strains could ease management and improve sustainability)
- non-toxic.

2.1.2 Cultivation facilities

Several algae cultivation technologies exist, which can roughly be divided in open pond and closed photo bioreactor systems. In order to find the sustainable and a viable commercial algae cultivation system (scalable productivity, maximization of system robustness, and minimization of costs), different aspects have to be addressed. They are e.g. the various material and energy inputs needed for the cultivation systems (pumping, harvesting etc.), the embodied energy required for construction, the embodied energy in fertilizer. (National Academy of Sciences 2012; Chiaramonti et al. 2013; Slade and Bauen 2013)

The majority of the large-scale, microalgal production systems in commercial operation today are open-pond systems, mainly due to economic factors and ease of scale up. The two most common types of open-pond systems are circular ponds and raceway ponds. Circular ponds are round ponds, with depths of 30-70 centimeters. Raceway ponds can constructed either as single units or a group of continuous units that are joined together with the typically depths of 15-40 centimeters. Conrete and plastic are usully used as construction material for pond, and paddle wheels, propellers, or air-lift pumps are used to agitate and circulate the mixture to prevent sedimentation. (National Academy of Sciences 2012; Slade and Bauen 2013)

In PBRs the culture medium is enclosed in a transparent array of tubes or plates. The two most common types of microalgal photobioreactors are tubular and the flat-plate systems, made of transparent containers, vessels or tubes, with an optimal thickness of about 2-4 centimeters. PBR systems allow for better control of the algae culture environment but tend to be more expensive than raceway ponds. (National Academy of Sciences 2012; Slade and Bauen 2013)

Straight horizontal, straight vertical, helical, to triangular configurations are the typical geometric configurations of tubular photobioreactors. Potential disadvantages of tubular photobioreactors are algae wall adhesion, biofouling, large pressure drop, and gradients in pH, dissolved oxygen, or CO_2 can occur along the tube length. These disadvantages might be resolved by innovative engineering designs. Flat-plate (or flat-panel) photobioreactors are transparent rectangular containers (usually vertical or inclined) with a light path of 1-30 centimeters. Flat-plate photobioreactors mix substrate by vigorous air sparging from the bottom. (National Academy of Sciences 2012)

2.1.3 Nutrients and CO_2

Nitrogen and phosphorus are the most important nutrients for algae not readily available (Kumar et al. 2010). Carbon, another key component of algal biomass is rarely a limiting factor in natural environments, but can limit growth in dense algal cultures. Microalgae cells contain roughly 50 % carbon (C), 4–8 % nitrogen (N) and 0.5–1 % phosphorus (P) per dry weight. In large-scale cultivation, these elements must be supplied at low cost; the use of pure, purchased CO_2 or artificial fertilizers are not economically and environmentally feasible (Clarens et al. 2010). A proposed solution to decrease the cost and environmental problems, is to use CO_2 from flue gas and nutrients from waste water (Kadam 2001; Christenson and Sims 2011). Fast-growing microalgal species prefer ammonium rather than nitrate as a primary nitrogen source and phosphorus should be supplied as phosphate because not all phosphorus compounds are bioavailable (Kumar et al. 2010). The nutrient concentration in wastewater will vary depending on the source, but both municipal and agricultural wastewater have been shown to be suitable for algal cultivation (Craggs et al. 1997; Mulbry et al. 2008). Flue gas from industry and power plants have also been successfully been used in algal cultivation, but the sulphur content, or other toxic compounds, might need to be reduced before introducing it into the algal cultivation (Chiu et al. 2011; Van Den Hende et al. 2012) .

2.1.4 Temperature and lighting

Temperature and availability of sunlight, both seasonally and annually, are key environmental parameters that will directly affect productivity. These factors are mainly dependent on the geographical factors such as latitude and elevation, which have major influence on the hours and intensity of available sunlight per day and the daily and seasonal temperature variations. (U.S. DOE 2010).

Light provides the energy for running photosynthesis and is driving the biomass production. The net reaction is the uptake of water and CO_2 and production of O_2 and sugars. At low light the production increases linearly with increasing light intensity and this is when photosynthesis works at maximum efficiency. At some point, as light increases, the production levels off and may eventually decrease due to light stress. This reduces the efficiency and an increasing part of the light energy is dissipated as heat. The exact relationship between light and production is dependent on the algal species and the acclimation state of the photosynthetic pigments that is responsible for harvesting light. A considerable fraction of the light energy is typically lost as heat when these pigments are exposed to full sunlight. This poses a challenge for algal cultivation. In order to obtain the maximum efficiency, light should be diluted in the sense that each photosynthetic reaction center only gets a fraction of the full sunlight. This could be obtained by the construction of the cultivation unit or by increasing turbulence. Turbulence in a dense culture ensures that cells are exposed to light at the surface only for brief periods at the surface, before circulating down into dark or dim conditions. This proves time for the cells to process the light energy and reduces loss to heat.

Optimal temperatures for microalgae cultivation vary greatly between different microalgal species, ranging from cold-water adapted species (0-5 °C) to species naturally occurring in hot springs (~40°C). There have been relatively few studies of algal growth at extreme temperatures, but at least cold water species seem to have similar growth rates and lipid concentration as species adapted to warmer waters (Schwenk et al. 2013). Optimal growth temperatures for some of the most studied species have been reported to be 15–26 °C (Kumar et al. 2010). Generally, growth rates will increase with increasing temperature within the temperature window of a given species, but growth will stop and cells start to die once temperature increases above a species-specific threshold.

2.1.5 Harvesting and dewatering

In principle, microalgae concentration in cultivation systems is very high, up to 1–10 g DW L^{-1}. However, to obtain such densities fertilizers and CO_2 must be added to the culture media. From the harvesting point of view, this density is still very low (>99 % water) and several harvesting technologies are currently being tested and further developed.

The choice of harvesting method will depend on the type of species involved (i.e. size, density, etc.), the quantity that needs to be processed and the desired final product. Generally, there are two main steps (AquaFuels 2009):

- Bulk harvesting – separate the biomass from the broth to achieve a slurry with 2-7% solid content (involving a concentration factor of 100-800) (e.g. flocculation, gravity sedimentation).
- Thickening – concentrate the slurry (i.e. centrifugation, filtration, ultrasonic aggregation). This is generally the more energy intensive step.

Flocculation is an effective method to aggregate the cells and increase the effective ‘particle’ size, which facilitates the downstream processing. It is important to choose flocculants that are non-toxic, effective in low concentrations and will not increase the amount of downstream processing. (AquaFuels 2009)

Filtration is a relatively slow process, but may be a feasible option for low value products where a higher level of moisture is acceptable. Conventional filtration can be used for larger algal species, while membrane or ultra-filtration may be necessary for smaller species. For low volumes of broth, filtration may be the more economically sound option. (AquaFuels 2009)

Gravity sedimentation can be used for larger species, but centrifugation is usually the preferred method of recovery. It is a more energy intensive method, but is also faster and can handle larger volumes. It also requires more maintenance and has higher costs, but can increase the slurry concentration by up to 150 times and be up to 95% efficient. (AquaFuels 2009)

Algae vary significantly in their response to certain flocculants. Some algae will aggregate and settle with an increase in pH, which can be controlled through changes in aeration with CO_2 or through the addition of lime. Aluminum sulfate and chitosan have also been shown to be effective flocculants. Previous LCA studies have assumed aluminum sulfate as the flocculant but other potential flocculants have not been valuated. For example, chitosan is a promising emerging coagulant that is manufactured from crustacean fishery waste, making it a renewable resource. The effectiveness of a particular flocculant and its dosage will vary tremendously from one algal species to another. (Brentner et al. 2011)

Drying is required to achieve high biomass concentrations. Because drying generally requires heat, methane drum dryers and other oven-type dryers have been used. However, the costs climb steeply with incremental temperature and/or time increases. Air-drying is possible in low-humidity climates, but will require extra space and considerable time. Solutions involving either solar or wind energy are also possible. (U.S. DOE 2010)

2.2 Literature data

Many LCA studies of the algae based biofuel production exist, but the comparison is difficult because of the different assumptions and system boundaries. Based on the research studies, the most critical phases of the algae cultivation and downstream processing can, however be identified. These are related to e.g. the estimations of the productivity and energy consumption. Table 1 presents the literature data variation of some parameters related to the algae cultivation phase. The energy consumption is highly dependent on the process configurations, such as the cultivation reactor type (open or PBR) and its properties (horizontal, vertical, velocity of the liquid, the need of liquid circulation etc.) Therefore it is important to use system specific data whenever possible.

Table 1. The literature data variation of some parameters related to algae cultivation phase.

Input parameters	**Tubular PBR**	**Raceway-paddlewheel**	**Reference**
Energy consumption, pumping	2500 W/m3, 562 W/m3	0,2 ;0,25; 0,24 W/m2	(Jorquera et al. 2010; Hulatt and Thomas 2011b)
Energy consumption, paddlewheel		0,2 kWh/kg; 3,73 W/m3	(Jorquera et al. 2010; Collet et al. 2011)
Used materials	plexiglas, polymethyl-methacrylate, glass, PMMA, HDPE	channels/blocks concrete/ compacted earth and lined with white plastic/PVC	
Energy lighting	10-50 W/m2		(Stewart and Hessami 2005; Kumar et al. 2010; Kothari et al. 2012)
Area needed	0,06 m2/kg	0,08 m2/kg	(Chisti 2007)
Areal productivity	72 g/m2,d; 35 g/m2,d; 11,31 g/m2,d	35; 25;	(Molina et al. 2001; Chisti 2007; Jorquera et al. 2010; Collet et al. 2011)

Volumetric productivity	1,535 kg/m3,d; 0,56 kg/m3,d: 1,5 kg/m3,d; 1,26 kg/m3,d'	0,117 kg/m3,d; 0,035 kg/m3,d	(Molina et al. 2001; Chisti 2007; Jorquera et al. 2010; Kumar et al. 2010)
Biomass concentration in broth	4 kg/m3; 1,02 kg/m3	0,14 kg/m3; 0,5 kg/m3; 0,35 kg/m3; 1,67 kg/m3; 2,45 kg/m3	(Chisti 2007; Jorquera et al. 2010; Stephenson et al. 2010; Collet et al. 2011; Hulatt and Thomas 2011b)
CO2_absorbtion	85%; 80%	90 %	(Collet et al. 2011)
CO2 consumption	1,83 kg/kg; 1,8 kg/kg	1,83 kg/kg; 1,172 kg/kg	(Chisti 2007; Collet et al. 2011)
P consumption		2,69 g/kg	(Collet et al. 2011)
N consumption		8,85 g/kg	(Collet et al. 2011)
O2-production	0,003 mol/m3,s		(Molina et al. 2001)

2.3 Life cycle assessment

The study is based on the life-cycle assessment (LCA) methodology, which is standardized by ISO 14040 and ISO 14044:2006. LCA addresses the environmental aspects and potential environmental impacts throughout a product’s life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal. LCA can be divided in four phases:

1) Goal and scope definition, which defines e.g the system under study, the functional unit, the product specifications of the systems and the system boundaries.
2) Life cycle inventory (LCI), which calculates all the inputs into the system and the outputs from the system. The LCI takes into account all the processes in the life cycle that produce inputs. The allocation of flows and releases are also included in the LCI.
3) Impact assessment (LCIA), in which the most significant environmental aspects are evaluated with the results of the LCI. The inventory results are associated with specific environmental impact categories and category indicators. The purpose is to understand these impacts.
4) Interpretation of the results. In this phase, the results of the LCI and LCIA are considered together. The results should be consistent with the defined goal and scope. Based on these results, conclusions can be reached, limitations explained and recommendations provided.

The life cycle assessment was done by using the SimaPro LCA computing program. Impact assessment consists of characterization and normalization phases. Characterization means, that LCI results are converted to common units and after that aggregated within the same impact category. It is carried out by using the ReCiPe impact assessment method. The ReCiPe method of impact assessment provides characterization factors for 18 impact categories. The explanation of the six most important recognized in this study are presented in Table 2with explanations. The outcome of the calculation is a numerical indicator result.

Table 2. Impact categories according to the ReCiPe impact assessment method.

ReCiPe impact categories	Indicator	Description
Climate change	CO_2-eq.	impact of specific air emissions on the radiative forcing of the atmosphere
Photochemical oxidant formation	kg NMVOC	Photochemical oxidation is secondary air pollution, also known as summer smog. It is the formed in the troposphere caused mainly by the reaction of sunlight with emissions from fossil fuel combustion creating other chemicals
Particulate matter formation	PM10-eq.	human health impacts of fine particulate matter (equivalent to 10 µm in diameter or less) in upper airways and lungs when inhaled
Terrestrial acidification	SO_2-eq.	impacts of specific air emissions on the acidity of soils (e.g. SO_2, NO_x)
Freshwater eutrophication	P-eq	nutrient enrichment of freshwaters causing increase in biomass production which results in depressed oxygen levels -> shift in species composition (e.g. P and N emissions)
Fossil depletion	oil-eq.	depletion of fossil fuels, such as oil

Normalization is an optional element of LCIA. It is the calculation of the magnitude of the category indicator results relative to some reference information. The aim of the normalization is to understand better the relative magnitude for each indicator results of the product system under study. Normalization transforms an indicator result by dividing it by a selected reference value. In this study, the normalization factors of ReCiPe midpoint for Europe are used.

3 System descriptions and LCI

Based on the reviewed research studies and experimental laboratory tests, two different algae cultivation systems were selected for the LCA. The reference systems represent the hypothetical cultivation plants in Suomenoja, Espoo Finland. The main purpose of the algae cultivation is to utilize the CO_2 from the near district heating power plant and also the nutrients from the waste water treatment plant. The general system boundaries of the studied systems are presented in Figure 1.

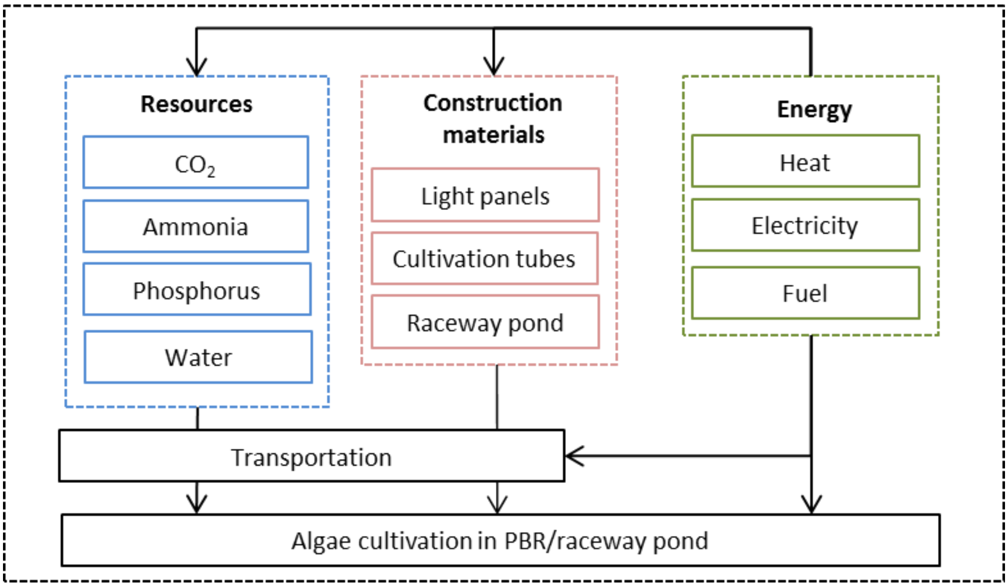

Figure 1. System boundaries

Data of the calculation is based on the literature and the experimental tests. The specific data for the high technology algae cultivation is difficult to find, because there are not much research done for the large scale systems. Therefore the data is based on the best available knowledge complemented with the experts' opinions.

The size of the System 1 is based on the available space in Suomenoja. The functional unit is defined based on the production capacity of the System 1. The design of the System 2 is defined to achieve the same production capacity. Only the cultivation part and the harvesting technologies are examined, i.e. excluding what the final end product is. Therefore the species of the algal strain is not defined. The transportation emissions are usually considered to cause only small part of the total LCA emissions and they are also excluded from this study due to lack of knowledge of the transportation distances.

3.1 Suomenoja waste water treatment plant

The Suomenoja wastewater treatment plant, which is the second largest of its kind in Finland, treats the wastewater of over 310 000 people from Espoo, Kauniainen, western Vantaa and Kirkkonummi. About 35 million m^3 of wastewater is treated each year, and the plant's average daily flow-through is roughly 100 000 m^3. Industrial wastewater accounts for about 8 per cent of the total volume of incoming wastewater. (HSY 2013)

The amount of the nutrients in the untreated wastewater is based on the measurements of the Finnish Environment Insitute (SYKE). The inflow of the waste water contains 3000 µM NH_4, 90 µM NO_3, 150 µM PO_4 and 260 µM DSi. Thus the N and P available for algae are 0,043 g/l and 0,005 g/l respectively with the N/P ratio of 9.3 (weight ratio). A ratio of 6.8–10 is considered optimal (Olgun 2012).

3.2 Suomenoja CHP power plant

The Suomenoja power plant produces heat for the inhabitants of Espoo, Kauniainen, and Kirkkonummi and electricity for the national grid. The power plant currently produces approximately 1 800 GWh of electricity and 2 200 GWh of district heat per year. The new combined heat and power plant consists of a gas turbine that uses natural gas as fuel, a steam boiler that recovers the heat from the gas turbine exhaust gases, and a steam turbine. The efficiency of the combined heat and power plant can be up to 90%. The production capacity of the Suomenoja power plant: electric power 359 MW, and district heat power 554 MW. The annual emissions of the power plant are CO_2: 1 010 000 t, SO_2: 1 170 t and NOx: 1350 t in 2011. (Fortum, 2013; M. Sonck,10.4.2013).

The consumption of energy required for injecting the CO_2 into the cultivation system may be expressed either as units of gas introduced, or when integrated into aeration system for mixing the cultivations, as units of cultivation medium. Also, the energy consumption is greatly dependent on the type of cultivation system. In the study of Kadam (2001), a blower was used to deliver CO_2 to ponds in a direct injection process. According the study, it is very energy intensive to compress CO_2 to high enough pressures in order to transport it for a long distance. Therefore the reactor and power plant are recommended to be located near. The energy consumption of direct CO_2 injection in the study was 22.2 kWh/t,CO_2 and it included only the energy consumed for CO_2 injection.

In the study of (Brentner et al. 2011), the electricity consumption of CO_2 was included in the electricity consumption of paddlewheel (3.75 W/m^3) for open pond system) and in the electricity consumption of aeration (6760 W/m^3) for PBR Because of different assumption in the literature e.g. (Kumar et al. 2010; Brentner et al. 2011) the rates of energy consumption are limitedly comparable.

3.3 Algae production

The available nutrients in waste water affect the amount algal biomass that is possible to produce. Based on the average composition of algae, 60 g nitrogen and 7.5 g phosphorus per kg of biomass, the maximum biomass production in Suomenoja can be calculated to be 62-70 ton DW per day (Table 3). As can be seen from the table, the nitrogen/phosphorus ratio is favorable in the sense, that neither of the nutrients becomes a considerable limiting factor in relation to each other.

Table 3. Potential of algae production in Suomenoja.

	Nutrient concentration [g/l]	**Potential algae production [t,DW/d]**	**Production area required [ha] at different productivity**					
Productivity [g/m2,d]			**50**	**40**	**30**	**20**	**10**	**5**
N	0,042	70	140	175	233	350	700	1400
P	0,005	62	124	155	207	310	620	1240

3.3.1 System 1 - Tubular photobioreactor

The technology of system 1 represents an advanced closed photobioreactor (PBR) system (Figure 2). Algae are grown in long-lasting plastic tubes, which are placed horizontally inside an existing building. Flue gas from the power plant and the algae culture are mixed into the waste water in the degassing tank and after that the water is pumped to the top of the cultivation system by using centrifugal pumps. The water flows through the cultivation system by gravity. The cultivation plant of System 1 is constructed in a building with the dimensions: 50 m x 50 m x 30 m. The stacks of tubes are set horizontally at intervals of 0.2 m. The outer diameter of the tube is 0.06 m and inner diameter 0.058 m, which leads to a total volume of ~16500 m^3. The light is provided with light panels, which are placed between the tubes. The total surface area of the cultivation plant is 375 000 m^2 when it is simply calculated based on the dimensions. Based on the production area required (Table 3) the areal productivity of approximately 29 g m^{-2} d^{-1} can be achieved. Based on this production rate, the theoretical yearly production of the System 1 is ~4000 t (daily production 11 t) with a volumetric productivity of 0.66 kg m^{-3} d^{-1}.

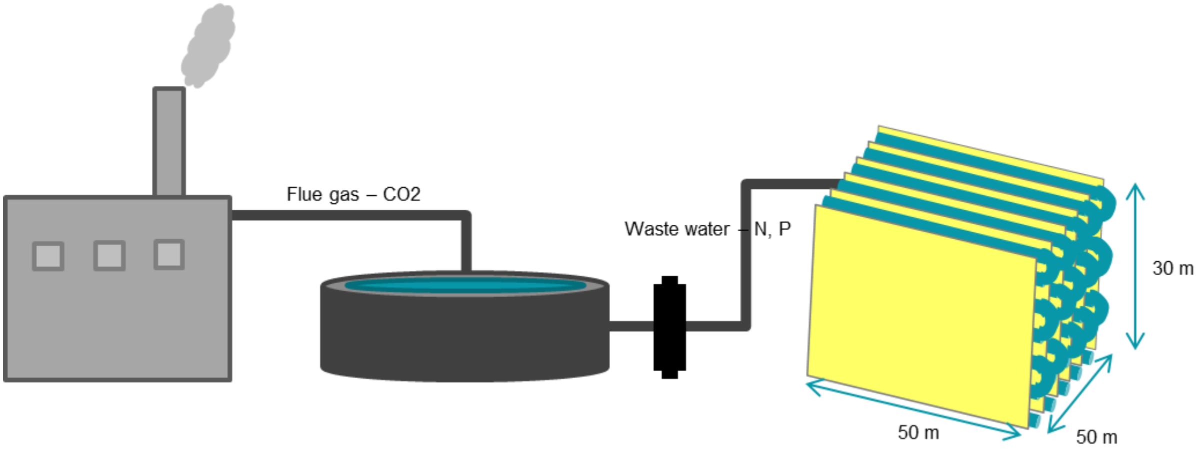

Figure 2. System 1.

3.3.2 System 2 - Raceway paddlewheel open pond

Algae are grown in open, raceway ponds (Figure 3). Flue gas from the power plant and the algae culture is mixed into the waste water in the degassing tank and after that the water is pumped into the ponds. The water is circulated with paddlewheels. The dimensions of the open pond are: 50 m x 10 m and 0.3 m deep. The areal requirements have been set to reach the same yearly production as system 1. According to the literature, a realistic production rate of an open pond system is 20 g m^{-2} d^{-1}. In order to achieve the same production as system 1, an area of 544 929 m^2 is needed. That would require 1090 open pond units with the total volume of 163 479 m^3.

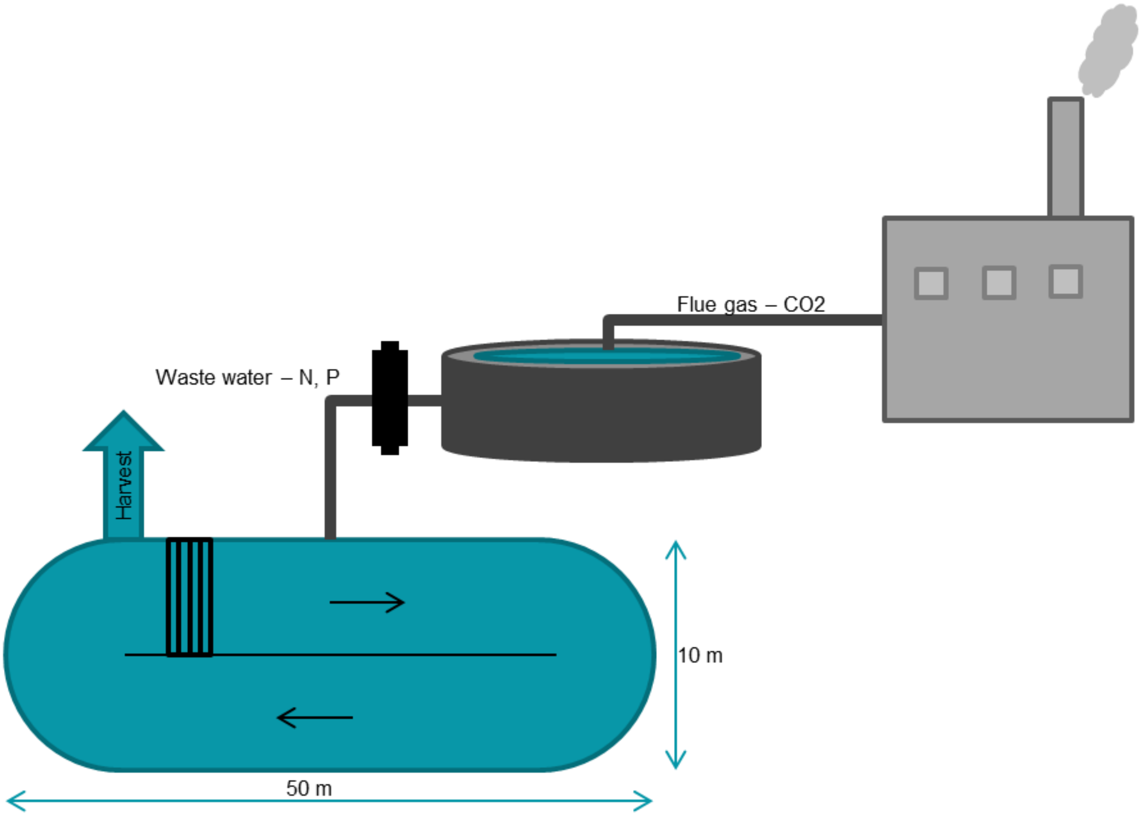

Figure 3. System 2

3.4 Harvesting techniques

Existing studies have pointed out that the dewatering of microalgae is one of the main bottlenecks in algal culturing. According to Xu et al. (2011) what is needed to improve the overall energy balance of algal cultivation is to reduce the energy consumption of the dewatering step. This can be achieved by two different strategies: one is to improve the dewatering efficiency by using new, low energy consuming drying techniques (dry route) and the second one is to avoid the drying phase of the process by applying oil extraction in the water phase (wet route).

Development of harvesting technologies is being carried out, and for example the objective of a group of European small and medium enterprises, SMEs (Salsnes, Asio and Inwatec) is to develop a universal algae harvesting technology by building on their experiences gained from removing particles from wastewater. Salsnes Water to Algae Treatment (SWAT) technology will use a flocculator followed by a Salsnes Filter to harvest algae (Figure 4). The goal of the SWAT technology is 95% algae recovery, 40% lower costs than the best state of the art technologies (Centrifuge and Dissolved Air Flotation) and energy consumption <0.08 kWh/m^3 of algae. The test results showed that the optimum flocculant and optimum dose is very dependent on the type of algae. Very good flocculation could be achieved with all the tested algae species, but for some species it may not be achieved at an economically acceptable chemical dose. (Operation SWAT).

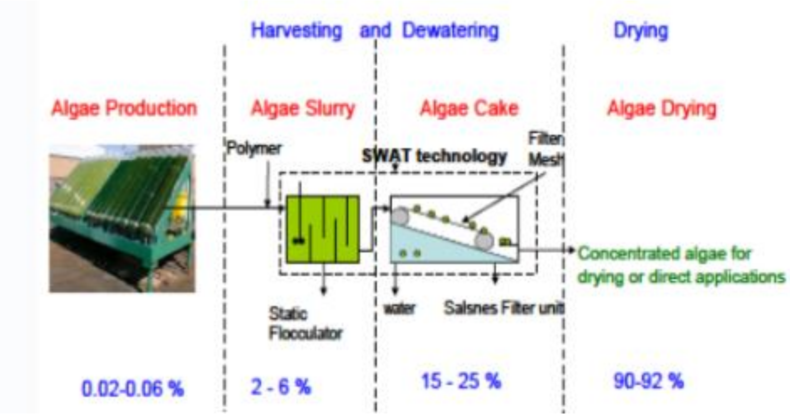

Figure 4. SWAT harvesting technology (Operation SWAT)

Different flocculants that have been used in the dewatering phase are e.g. lime, aluminum and chitosan. When comparing chitosan with other flocculants, it can be refered to as a renewable resource. The amount of chitosan needed for the process is 43% and 10% of the amount of aluminum and lime, respectively. (Brentner et al. 2011)

The energy consumption of two promising harvesting technologies and dry weight of the algae biomass is presented in Table 4.

Table 4. Two promising harvesting technologies.

Harvesting step	Electricity consumption		Dry weight % in the beginning of the harvesting step
The technique of Xu et al. 2011			
Preconcentration - Lime flocculation:			**0,05 %**
Pump	0,045	kWh/kg,dw	
Lime	0,018	kWh/kg,dw	
Step 1			**2 %**
Centrifuge	0,026	kWh/kg,dw	
Step 2			**16 %**
Filtration	0,06	kWh/kg,dw	
Drying			**30-50 %**
Thermal (Delta dryer)	0,46	kWh/kg,dw	**Final dry weight 85 %**
SWAT technique			
Flocculation			**0,02-0,06 %**
Static flocculation			
Filtering			**2-6%**
Salsnes Filter unit			**Final dry weight 15-25 %**
Total	0,08	kWh/m3	

3.5 Summary of the LCI data

Table 5 presents the LCI data used in the calculations for System 1 and 2. The numbers are valid only for the systems described in the section 3.3.1 and 3.3.2. The assumptions are changed in the scenarios presented in section 4.3.

Table 5. LCI data used in the calculations.

Input parameters	System 1	System 2	Unit
Area needed	2 500	544 929	m^2
Total volume of the cultivation reactor	16 513	163 479	m^3
Areal productivity	29	20	$g/m^2,d$
Volumetric productivity	0,66	0,07	kg/m3,d
Used materials	Tubes: polymethyl-methacrylate, Lights: LED technology	Channels: concrete	
Energy consumption, pumping	876	-	MWh/a
Energy consumption, paddlewheel	-	2 053	MWh/a
Energy lighting	72 927	-	MWh/a
Cultivation time	24	24	h
Biomass production	3 978	3 978	t/a
CO2_absorbtion	85	85	%
CO2 consumption	1,83	1,83	kg/kg
P consumption	7,5	7,5	g/kg
N consumption	60,0	60,0	g/kg

3.5.1 LCI data sources

Electricity profile used in the calculations

The emissions factors of the electricity production depend on the energy source and production technology. The Finnish average grid electricity was chosen because it is not yet known what electricity production technology will be used. Different emission factors for the Finnish average emissions exist. The average emission factors of the years 2006-2008, calculated by the Finnish Environment Institute (SYKE) are presented in Table 6. (Finnish Environment Institute 2011). The chosen emissions have an impact on the most important impact categories from a Finnish point of view. The emission factors include the direct emissions and the emissions from the raw material acquisition. Electricity import and export is taken into account.

Table 6. The emissions factors of Finnish average electricity (SYKE).

Emission	CO2	CH4	N2O	SO2	NOx	CO	PM<2,5	2,5< PM >10	PM>10
kg/MWh	287	0,9	0,01	0,76	0,5	0,11	0,01	0,05	0,02

Another option is to use the Finnish average electricity profile from the Ecoinvent database v2.2. The factors include the direct emissions, and also the emissions from the infrastructure of the electricity network and distribution of electricity. It includes more than 500 airborne emissions and in total almost 1300 emission components. The electricity production profiles of the technologies are presented in Table 7 and Table 8.

Table 7. Electricity profile of Ecoinvent

Electricity profile	Fossil	Nuclear power	Hydro power	New renewable	Imports
Ecoinvent	27.5 %	27 %	18 %	11.5 %	16.1 %

Table 8. Electricity profile of SYKE

Electricity profile	Hydro power	Wind power	Nuclear power	Hard coal	Oil	Natural gas	Peat	Wood fuels	Other fuels	Imports
SYKE	8.5 %	0.1 %	40.5 %	15.0 %	0.5 %	8.5 %	6.8 %	8.6 %	2.4 %	9.2 %

Material construction

Emissions data for the material construction of reactors (polymethyl methacrylate and concrete) and LED lights was taken from the Ecoinvent database v2.2 (Table 9).

Table 9. Ecoinvent unit processes used in the calculation (Ecoinvent 2010)

Unit process	Name	Description
LED lights	Light emitting diode, LED, at plant	This dataset covers raw material input and production efforts for the production of currently used light emitting diodes (LED) for hole-through mounting technology.
Polymethyl methacrylate	Polymethyl methacrylate, sheet, at plant	Aggregated data for all processes from raw material extraction until delivery at plant
Concrete	Concrete, normal, at plant	Includes the whole manufacturing processes to produce ready-mixed concrete, internal processes (transport, etc.) and infrastructure. No administration is included. Special outputs: wastewater, average data of 11 German concrete plants

LED light technology

LED lighting technology was chosen for the light source, because it is the most promising technology in terms of energy consumption (Welz et al. 2011). The assumption used was that the whole surface of system 1 is illuminated. Existing LCA studies of the LED technology were not suitable for the calculations, because the data on energy consumption and LCA data on production of LED lamps was not available. The need for lighting and the energy consumption is based on data from LED Finland (LED Finland):

The power consumption of one LED-light unit is 120 W.
Light intensity (assumption) 200 µmol/m2,s
1 W/m2 = 4,5 µmol/m2,s

The need of light:
*200 µmol/m2,s * (1/4,5)= 44,4 W/m2*

The area that can be illuminated:
120 w/44,4 W/m2 =2,7 m2

The total illuminated surface area is 375 000 m2.

The LED lamps needed for the total area:
375000 m2/2,7 m2=138 900 units.

Total energy consumption per day (12 h lighting time per day)
12 h 138 900 *120 W =200 MWh/day*

Energy consumption of the systems

According to the existing studies, the energy consumption of the algae cultivation and harvesting are critical points for the overall energy balance of the system. The estimation of the energy consumption of the systems is difficult due to the fact, that the systems are non-existent plants and the energy consumption is highly dependent on the technical solutions. The data for the technical solution of system 1 was not available in the literature, and the simple calculation was done by using the equation for the hydraulic pump power (http://www.engineeringtoolbox.com/pumps-power-d_505.html)

$$P_h = q \rho g h / (3.6 \, 10^6)$$

where
P_h = *power (kW)*
q = *flow capacity* (m^3/h)
ρ = *density of fluid* (kg/m^3)
g = *gravity* ($9.81 \; m/s^2$)
h = *differential head (m)*

$$P_s = P_h / \eta$$

where
P_s = *shaft power (kW)*
η = *pump efficiency*

The following assumptions are used:

q = 688 flow capacity (m3/h)

ρ = 1000 density of fluid (kg/m3)

g = 9,81 gravity (m/s2)

h = 30 differential head (m)

η = 0,6 pump efficiency

This calculation takes only into account the power needed to pump liquid to the upper part of the cultivation units, and a realistic capacity of the pump and energy losses was excluded. Existing literature studies shows higher energy consumption for the tubular photobioreactors, but it is assumed, that the liquid flows through the system 1 by gravity and circulating is not needed.

The energy consumption data for the paddlewheel circulation, used in system 2, is studied in many research studies. The energy consumption of 0.25 W/m^2 in raceway pond found in the review of Chiaramonti et al. (2013) is used.

4 Results

4.1 Limiting factors in biomass production

The functional unit of the calculations is based on the yearly biomass production in system 1. The production amount is defined according to the available nutrients in the waste water of Suomenoja and the volume of the PBR. In system 2, the waste water volume needed to produce same amount of algae as in system 1 is 1.6 –fold than the daily waste water inflow. When the total annual waste water inflow of 35 000 000 m^3 in Suomenoja is taken into account, the yearly biomass production of 2446 t in system 2 can be achieved compared with the production of 24090 t in system 1.

4.2 Life cycle impact assessment (LCIA)

The normalized results and the comparison between the studied systems are presented in the following chapters. Some of the impact categories are excluded because of the high uncertainties and unreliability. The quantitative results are presented for the most important impact categories: climate change (CC), photochemical oxidant formation (POF), particulate matter formation (PMF), terrestrial acidification (TA), freshwater eutrophication (FE) and fossil depletion (FD). The interpretation of the results on other impact categories, is also discussed.

The results are calculated using the Finnish average grid electricity as an energy source (SYKE). Because this electricity profile include only limited amount of emissions, the electricity production does not have an effect on every impact category. The dewatering system used in the calculation is the harvesting technique presented by Xu et al. (2011), where the 85% dry weight can be achieved.

4.2.1 System 1

The LCIA results for system 1 are presented in Figure 5. TA and CC impacts seem to have the biggest relative effects followed by the PMF and POF. The effects are mainly caused by the electricity consumption. Therefore there is a need for further research in particular related to lighting, pumping and dewatering.

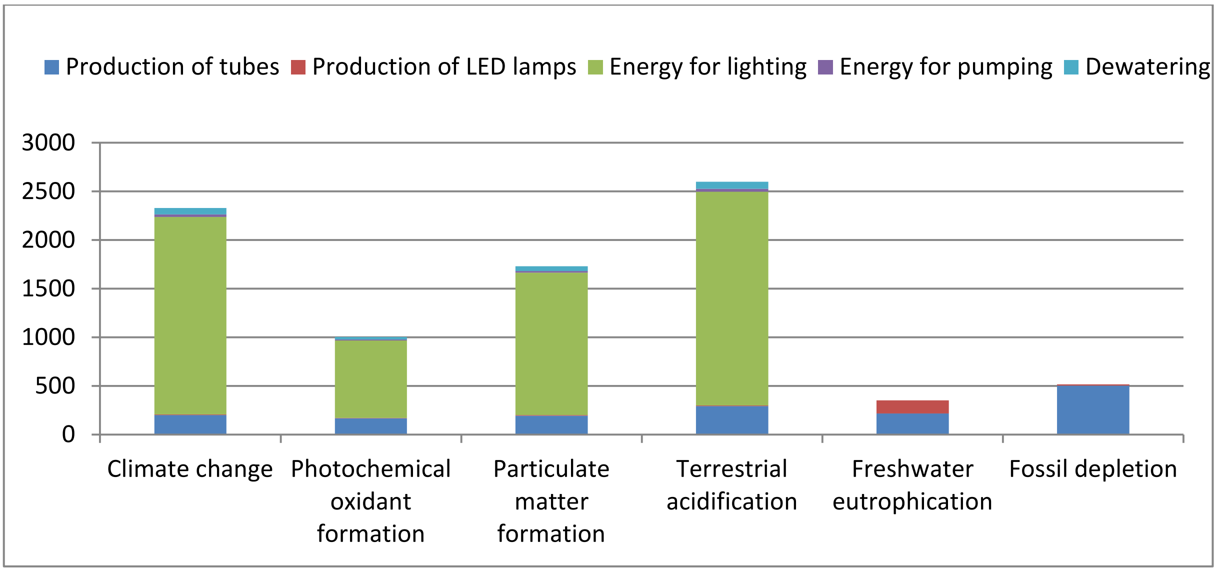

Figure 5. Normalized results for System 1.

The energy consumption is based on rough estimations and especially the energy consumption of pumping is highly uncertain as explained in section 3.5.1.

4.2.2 System 2

The LCIA results for system 2 are presented in Figure 6. CC and TA impacts seem to have the biggest relative effects followed by the PMF. The energy consumption of dewatering and paddlewheels cause the main impacts. Concrete production has a relative large impact on the FE.

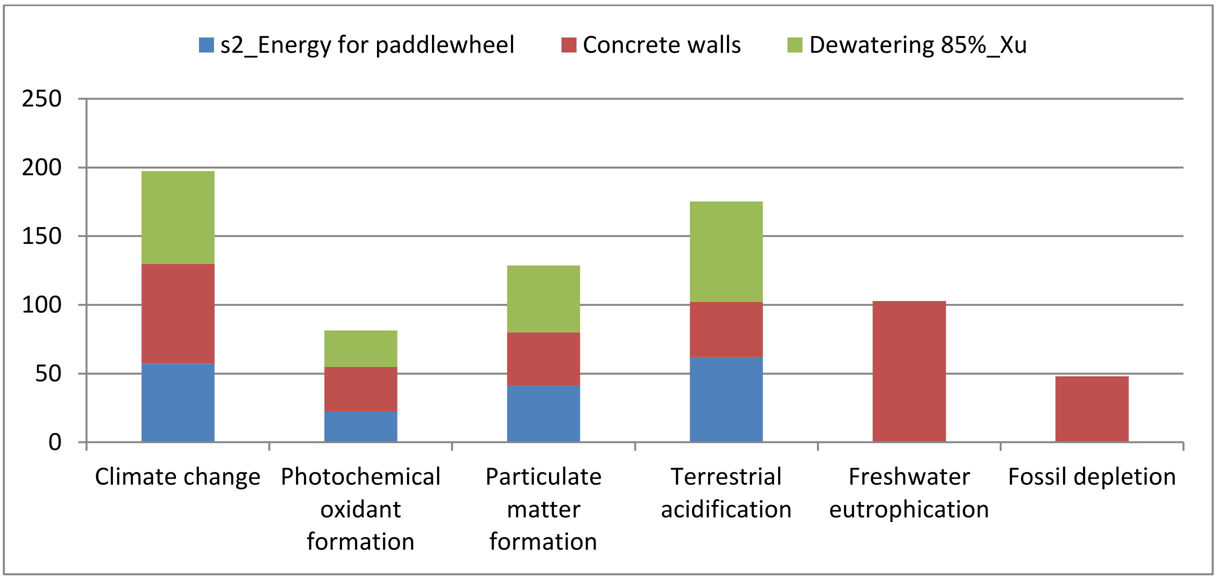

Figure 6. Normalized results for System 2.

4.3 Scenarios

Different scenarios were examined in order to identify and find the effect of changes in separate variables for System 1. Table 10 presents the variables changed in different scenarios compared to the base case.

Table 10. Description of scenarios.

Section/Case	Energy source	Lighting area	Tube material	Harvesting technique	CO2 pumping
4.2.1 – Base case	SYKE's electricity profile	Entire surface	polymethyl methacrylate	(Xu et al. 2011)	not included
4.3.1	Ecoinvent electricity profile, coal, hydro	Entire surface	polymethyl methacrylate	(Xu et al. 2011)	not included
4.3.2	SYKE's electricity profile	Entire surface /outer surface	polymethyl methacrylate	(Xu et al. 2011)	not included
4.3.3	SYKE's electricity profile	not included	glass/polymethyl methacrylate	(Xu et al. 2011)	not included
4.3.4	Ecoinvent electricity	not included	not included	(Xu et al. 2011)	not included
4.3.5	SYKE's electricity profile	Entire surface	polymethyl methacrylate	(Xu et al. 2011)	(Kumar et al. 2010; Brentner et al. 2011)

4.3.1 Case – Energy source

The LCIA in section 4.2 was done using Finnish average electricity as the energy source. However, local energy production systems could have a decreasing or increasing effect on the emissions. Figure 7 shows the variation in the results when the electricity is produced by coal or hydro, or by using the Ecoinvent or SYKE's electricity profile. When using hydroelectricity, the relative impacts related to facilities (LED lamp production and tube production) increase, because the electricity profile used in the cultivation plant does not have an effect on them. It can be also seen, that the Ecoinvent electricity profile includes emissions, which have effects on freshwater eutrophication. This impact category cannot be seen when using SYKE's electricity profile.

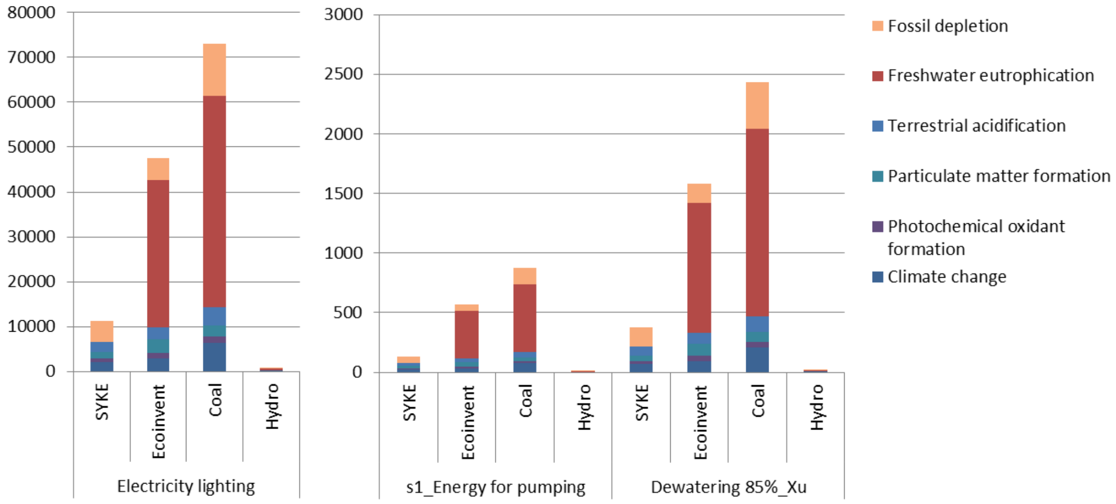

Figure 7. Environmental impacts variation when using different electricity production profile.

4.3.2 Case - Lighting area

In this case, the artificial light is provided only for the outer surface of the PBR of system 1. The energy consumption of the lighting is 2.3% of the total energy needed if the entire surface is illuminated. When the energy consumption decrease the environmental impacts related to production of tube stand out (Figure 8).

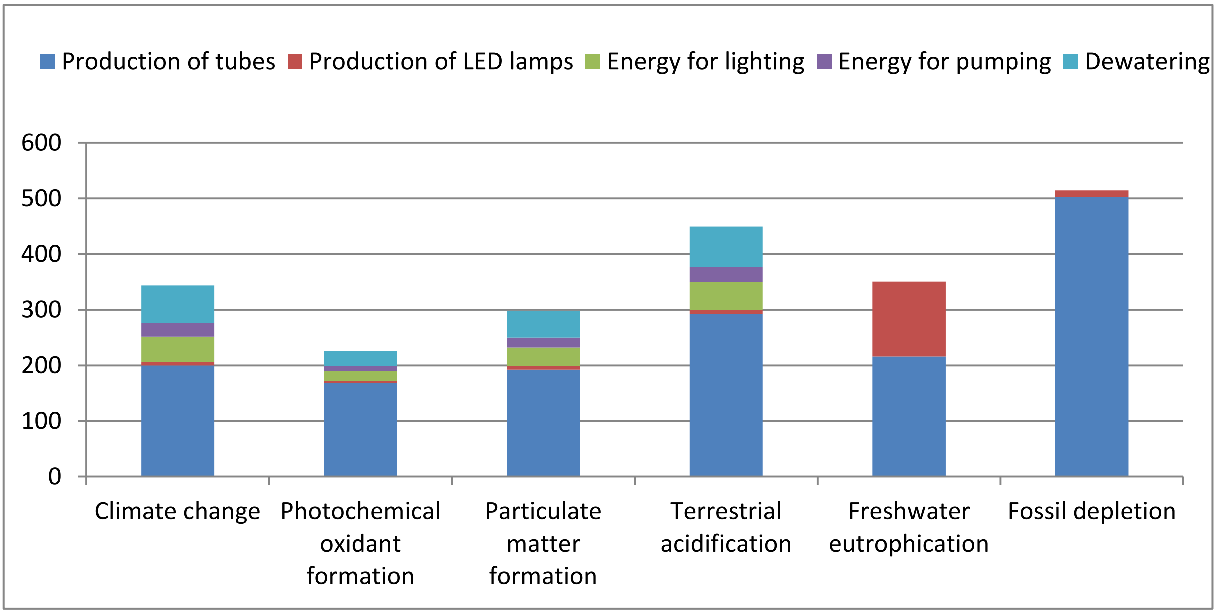

Figure 8. The environmental impacts for the System 1, when only the outer surface is illuminated with artificial lights.

4.3.3 Case – Tube material

The comparison of tube material between polymethyl methacrylate and glass show, that the environmental impacts in other categories than freshwater eutrophication are smaller, when using glass tubes. The impacts of FE of glass tubes are approximately 30 % compared with impact of polymethyl methacrylate tubes (Figure 9). This comparison, however assume that lifespan and thickness of tubes are same regardless of the material. The density of the materials is taken into account in order to calculate the amount of material needed.

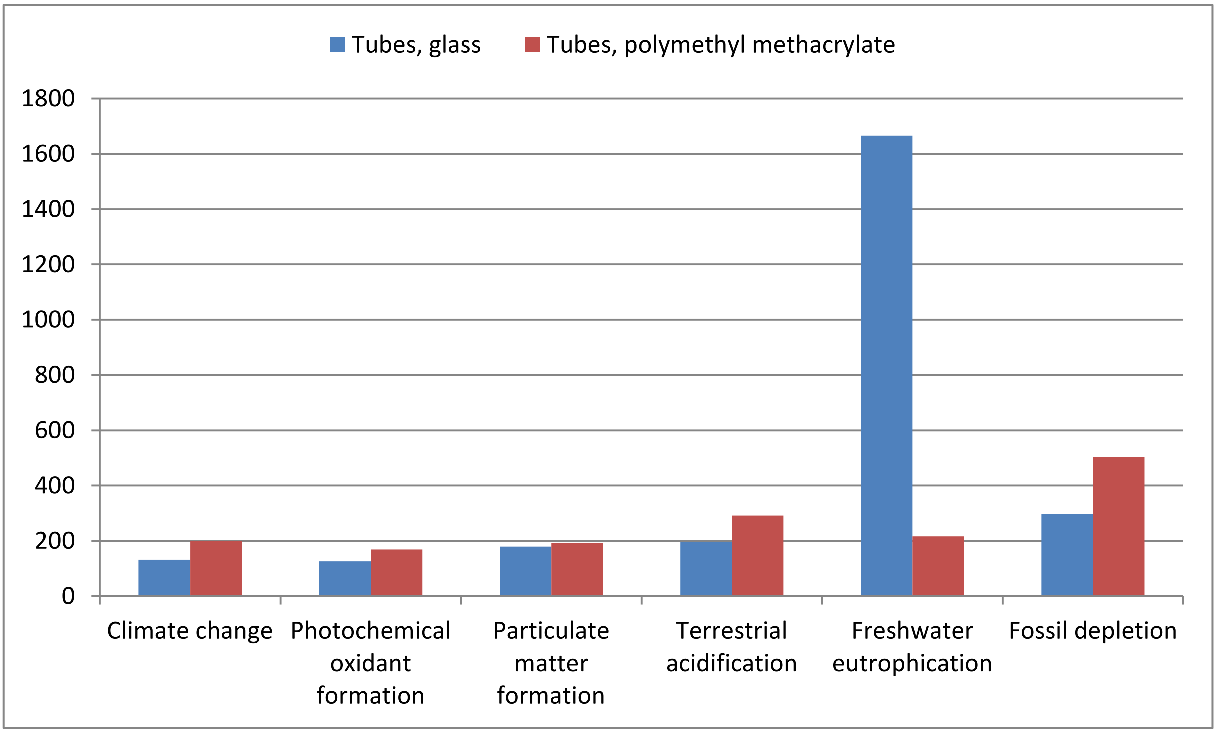

Figure 9. The comparison of environmental impacts for the System 1, when glass and polymethyl methacrylate are used as tube material.

The study of Burgess and Fernández-Velasco (2007) compared the energy content, lifespan and density data for three tube materials (Table 11). The conclusion of the study was that LDPE is the preferred material.

The other aspect affecting the final decision of the material depends on e.g. the technical solution of the PBR, ease of the maintenance and costs.

Table 11. Comparison of different tube materials (Burgess and Fernández-Velasco 2007).

Material	Material energy content [MJ/kg]	Material lifespan [y]	Material density [kg/m3]	Proposed wall thickness [mm]	Energy content [MJ/m2]	Lifespan weighted energy content [MJ/m2,y]
Glass	25	20	2470	1,6	310	15,5
LDPE (Low Density Polyethylene Film)	78	3	920	0,18	40,5	13,5
Acrylic	131	20	1180	3	1456	72,8

4.3.4 Case – Harvesting technique

The harvesting tehcniques of SWAT and Xu et al. (2011) are compared in Figure 10. Only the energy consumed in this phase is compared and other life cycle phases are excluded. These techniques represent the examples of the best available harvesting techniques available at the moment. The Ecoinvent electricity profile was used and this is the reason the freshwater eutrophication impact category is relativly high. The difference of harvesting techniques is due to the lower energy consumption in SWAT. However, it should be taken into account that both techniques represent the best available future technology, and the energy consumption can still vary. In our algae cultivation system, the water content of the dewatered liquid is high compared with the system presented by SWAT and Xu et al. (2011), which can further increase electricity consumption.

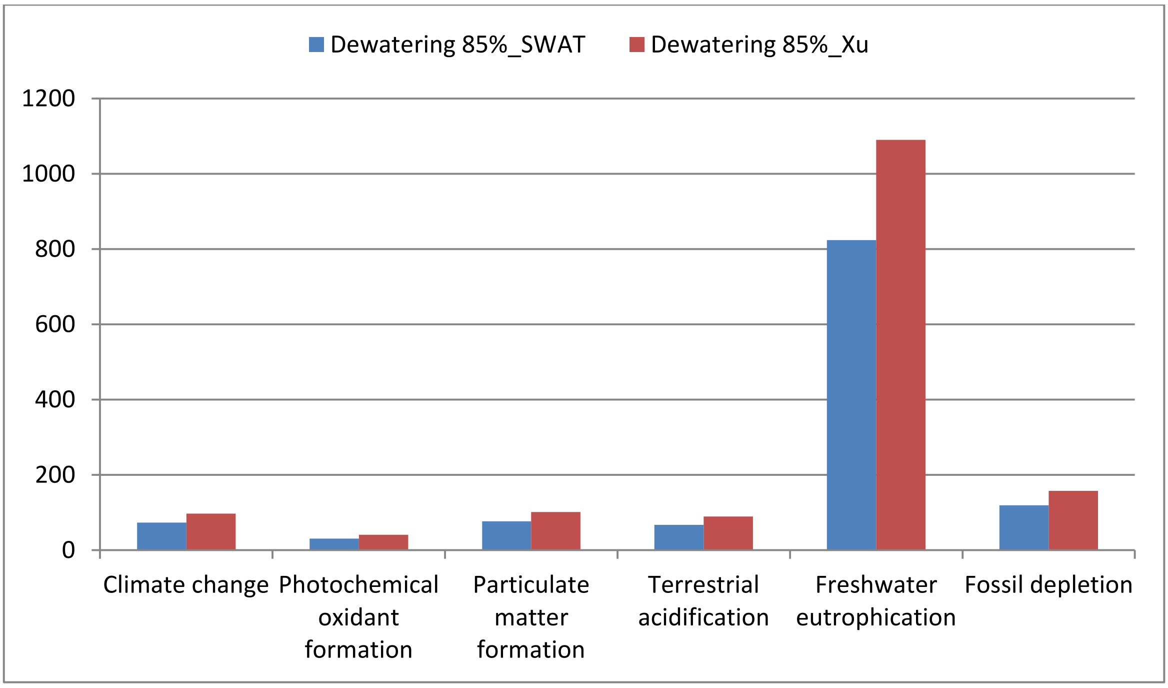

Figure 10. The comparison of harvesting techniques of SWAT and Xu et al. (2011) by using the electricity profile of Ecoinvent.

4.3.5 Case – CO_2 pumping

The energy consumption of CO_2 pumping into the cultivation reactor is not taken into account in the results presented in section 4.2. Two different energy consumption numbers found from literature were used in the case study (section 3.2). The results show very high variability in the energy consumption (Figure 11), and further research would be needed to get better estimates. When using the numbers from Brentner et al. (2011), the energy consumption of CO_2 dominate the results, whereas energy consumption of Kumar et al. (2010) is only a small part of the total consumption. However, as it was mentioned in the section 3.2, these numbers cannot be compared because the energy consumption of Kumar et al. (2010) include only the energy consumed for CO_2 injection. In the study of Brentner et al. (2011), CO_2 is assumed to be introduced by a gas sparger and circulated by a paddlewheel in the open pond system, whereas the PBRs are assumed to rely on aeration.

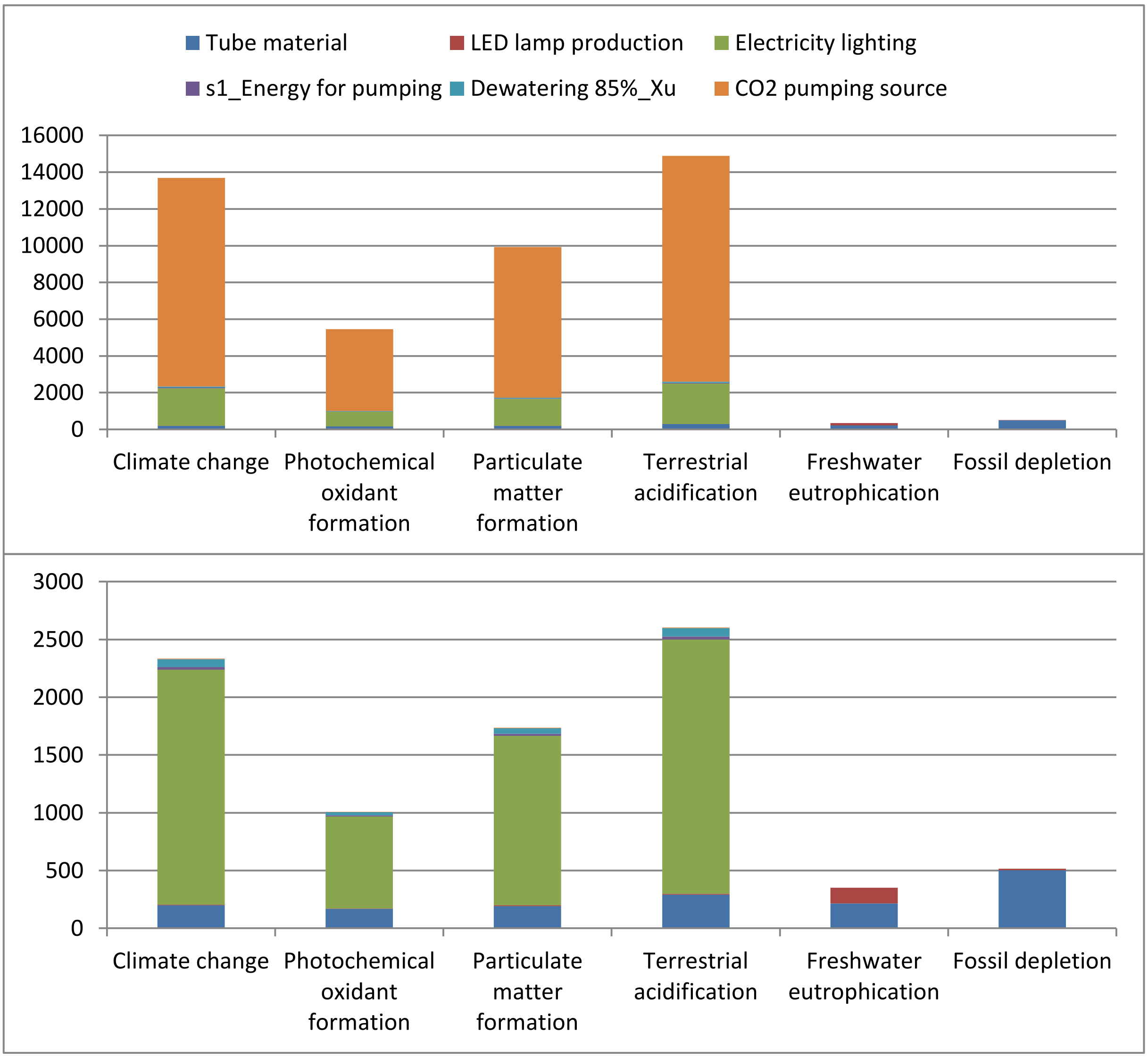

Figure 11. The energy consumption comparison, when the CO_2 pumping is taken into account. In the upper figure, the energy consumption of the study of Brentner et al. (2011) is used (3.75 . The lower figure presents the energy consumption of Kumar et al. (2010).

4.3.6 Environmental impacts of other categories

The human toxicity potential reflects the potential harm of a unit of chemical released into the environment. It is based on both the inherent toxicity of a compound and its potential dosed. Total emissions can be evaluated in terms of benzene equivalence (carcinogens) and toluene equivalents (noncarcinogens). The potential dose is calculated using a generic fate and exposure model. (Hertwich et al. 2001)

Freshwater and marine ecotoxicity emissions are mainly caused by the tube and electricity production. Compared with the other impact categories, they stand out, but in general, ecotoxicity emissions include high uncertainties, and the estimation of the impacts is unreliable.

Natural land transformation is also one of the impact categories, which arise when changing the electricity profile e.g. from SYKE's profile to Ecoinvent profile. The profile takes for example into account the extraction of raw materials that are used to produce the electricity. The high bar of natural land transformation is therefore explained by the high energy consumption of the system.

4.4 Utilized resources and avoided emissions

When the yearly biomass production is examined, the consumption of CO_2 and inorganic nutrients (N and P) can be estimated. The consumption of nutrients and CO_2 depends on the algal composition and we used average numbers (see section 2.1.3).

Nutrient need of algae:

C: 500 kg/ton
P: 7,5 kg/ton
N: 60 kg/ton

The algae production is based on the nutrient concentration of the waste water. The consumption of nutrients can be increased by extending the cultivation area or by concentrating the waste water. In our calculations we were assuming a limited space for System 1 and thus there are also limited amount of nutrients available.

The CO_2 consumption was calculated based on the amount of biomass produced. Different studies show that microalgae do not capture all the CO_2 that is injected into the culture. For example Collet et al. (2011) estimated 90% capturing, while Doucha and Lívanský (2006) estimated the number to be 70%. The non-absorbed CO_2 has to be taken into account in the emission calculation.

An annual production of 3978 t algae consumes:

- CO_2: 7293 t/a (0,7% of the total CO_2 emissions from Suomenoja)
- N: 239 t/a (16%)
- P: 30 t/a (18%)

4.4.1 Nutrient recycling

Large quantities of nutrients would be needed during the algae cultivation. Using waste water as the nutrient source decrease the need for purchased nutrients, but this can also be obtained if the residual algal biomass or the water from the harvesting phase would be recycled back to the cultivation phase. (Rösch et al. 2012)

Rösch et al. (2012) presents the nitrogen and phosphorus losses and recycling rates for worst, base and best case scenarios of biodiesel production with microalgae, using three different downstream processes for the residual biomass (anaerobic digestion, hydrothermal gasification and use as animal feed). The results for the base case of biodiesel production and anaerobic digestion are presented in Table 12.

Table 12. The nitrogen and phosphorus losses and recycling rates for biodiesel production with microalgae and anaerobic digestion of the residual algal biomass (Rösch et al. 2012).

	Loss of N	Loss of P
Cultivation - Outgassing of NH3	5%	-
Biodiesel production – Co-extraction of proteins and phospholipids	1%	-
Biodiesel production – Co-extraction of phospholipids	-	1%
Anaerobic digestion - unconverted biomass	18.8%	19.8%
Anaerobic digestion - Outgassing of NH3	12%	-
Anaerobic digestion – Storing and processing	1.9%	-
Recycling	61.3%	79.2%

As an example, cases of nutrient recycling with two different recycling rates are calculated (Table 13).

1) The examination was done without biodiesel production, and it is thus assumed that the recycling rates for N and P are higher than what is presented in Table 13. Recycling rates of 65% for N and 80% for P were used.

2) This case presents the best case of Rösch et al. (2012), with recycling rates for N and P of 90%.

Table 13. The nutrient recycling with different recycling rates.

	Nutrient amount [kg/a]	Recycling with the rate of 65%/80% [kg/a]	Recycling with the rate of 90% [kg/a]
N	4200	2730	3780
P	465	372	410

The study states that a critical point for using effluents from hydrothermal gasification could be that heavy metals can accumulate in the effluent of the gasification plant due to adsorption and absorption of the heavy metals by the microalgae. Thus, concentration may increase to levels exceeding the tolerance of the microalgae. Further studies are needed to investigate the long-term effect of applying the effluent in microalgae cultivation. The composition of the separated effluents, that contain the major part of phosphorus, as well as the suitability of the salts for the use in microalgae cultivation, has not been yet been analyzed. Also, the disposition of unconverted material has not been addressed so far. (Rösch et al. 2012)

4.5 Energy consumption and balance

Electricity consumption was assessed roughly for each scenario based on available literature values. It is noteworthy that the assessments do not include processing of algal biomass after the dewatering phase. The assessments reveal that if the entire surface in the System 1 was illuminated, the energy consumption would be a magnitude greater when compared with the System 2, as well as with the outer surface illumination scenario in the system 1. Also in terms of energy balance, illumination of the entire surface in System 1 results in negative energy balance when production of e.g. biodiesel is considered, already when the further processing of algal biomass after the dewatering phase is not taken into consideration. In other scenarios, the data indicates positive energy balance under the mentioned circumstances and restrictions.

5 Discussion

5.1 Environmental impacts

The results of the environmental impacts depends significantly on the system boundaries, the assumptions made (e.g. materials used, surface illuminated) and the processes used (e.g. electricity profile). Therefore, the accuracy of the results depends in how reliable the data from the studied system is. This has to be kept in mind with regard to the LCA results of this study. The lack of extensive, large-scale data, as well as the need to combine data from several studies with different process configuration, is a source of uncertainty.

Careful interpretation of the results is important in order to avoid misunderstandings and wrong conclusions, for example when local impacts are considered. Emissions related to e.g. tube production usually occur somewhere else than at the plant site. There are also impact groups (e.g. toxicity impacts), which are difficult to estimate and therefore include high uncertainties and these are often excluded from the results.

It is important to recognize the significant impacts related to the specific study, and the most critical phases in the algae energy production process. In our case, the energy production profile has substantial effects on many impact categories - of which freshwater eutrophication, terrestrial acidification and climate change are often the most important - and consequently on the total environmental impact of the cultivation system. Attention should be paid on the available or potential energy production options. The individual process steps and resources that appear to require most attention are energy consumption for pumping, lightning, and drying phases of the process.

5.2 Energy consumption

The LCIA results and data from the literature show that the energy consumption has a significant role in the total environmental impacts. There are still a lot of uncertainties, especially related to the energy consumption related to pumping and circulating the culture liquid in system 1. Kumar et al. (2010) argued that the high energy input in horizontal tubular PBR is necessary to reach the high linear liquid velocities (20–50 m/s) for achieving optimal productivity. Circulation in the tubes was not considered in our system, because it was assumed that the liquid would flow by gravitational force. The following questions related to pumping needs to be clarified:

- How much energy is consumed for pumping the liquid to the top of the reactor?
- Is there a need for circulating the liquid when it flows through the tubes?
- What are the energy consumption and the technology solution used for injecting the flue gas into the algae cultivation reactor?

Lighting is also one of the critical points. When algae are cultivated at high latitudes, where sufficient natural light is not available all-year-round, one option is to use artificial light. System 1 represents a very large, closed PBR system, where the entire surface is illuminated. Consequently, the energy consumption increased to very high levels. Illuminating the entire reactor of the suggested size and proportions is probably not sustainable with the current technology scope. High latitudes where stable light conditions are not provided may not be the ideal location for any algal cultivation plant, and would require solutions beyond the current technology scope. Also the costs of that wide-ranging lighting system are high.

The following questions related to lightning needs to be clarified:

- What is the need for lighting: translucent construction material for the building (greenhouse gas), different PBR architecture (larger illuminated area)
- The choice of lighting system and solutions for improving light economy at high latitudes (LED, halogen, integrated/movable system, conventional/advanced lighting system e.g. curtain, lenses)

Harvesting is also identified as a critical point for microalgal cultivation and low energy consuming and effective dewatering technologies are being developed. The following questions related to harvesting needs to be clarified:

- What is the end product: the need of dry matter content depends on the end product and the target of dry matter content affects the choice of harvesting technology?
- What are the properties of the algae species (e.g. auto-flocculating species)?
- What is the cultivation strategy, where algae produce the end product without the need of harvesting and dewatering?

5.3 Carbon and nutrient capture potential

Absorbing all the CO_2 from a large power plant require large areas; system 1: 0,34 $m^2/t,CO_2$ and system 2: 75 $m^2/t,CO_2$. It was demonstrated that capturing of approximately 1% of the total CO_2 emissions from a Suomenoja-size power plant would require at least dozens of hectares of cultivation surface. Since maximization of illuminated surface per consumed land area is limited by the high cost and environmental impacts of artificial illumination, as demonstrated in Case 1, available land area constitutes an important limiting factor concerning the CCS potential.

According to the AquaFuels (2009) the concentration of 1–10 g of dry weight per liter is very high, but from a harvesting point of view, this density is still very low (>99 % water). In our system, the concentration was even lower. Increasing the cultivation time could increase the final concentration to some extent; however, if the waste water is used, the amount of nutrient will set the limit for how much biomass can be cultivated. Adding fertilizers to increase the algal concentration is possible, but not a viable alternative because of the negative environmental (being very energy intensive to produce) and economic (adding additional costs) effects this has on the overall cultivation process. A better alternative would be developing a technology for recycling of the nutrients bound to the algal biomass. This would enable harvesting of the carbon as oil or starch whereas the main nutrients (nitrogen and phosphorus) would be recycled back to the cultivation system. Even if the concentration would increase, there would still be a lot of water to remove so a critical part would be to develop low cost, low energy solutions to harvesting the biomass.

6 Further research

Energy consumption was one of the most important resource questions, because it is highly dependent on e.g. the cultivation reactor type (open pond, photobioreactor), but also on the capacity of the plant. The site- and plant-specific data will be needed in order to get reliable and transparent results. Therefore, further research should focus on the technical solutions of different algae production units. That should include the proposed decisions for the pumping technique of e.g. water and CO_2.

Another issue is the energy consumption related to the harvesting and dewatering of the algae biomass. If the algae cultivation plant is located near or is integrated with the power plant, one research topic would be waste heat integration with the drying phase, which could decrease the energy consumption from that side. Another strategy could be to reduce energy consumption and costs by the selection of the algae to be cultivated. This could be done by several different approaches. Firstly, energy demand during harvesting and dewatering might be reduced by cultivating autoflocculating algae. Secondly, these process steps could possibly be bypassed by cultivating species that excrete the product directly, instead of requiring gathering and processing the algal biomass. Hence, the availability and stability of these species in large-scale cultivations also requires consideration.

Lighting of the algal biomass reactor seemed to be unsustainable from an environmental point of view in the base scenario of Case 1. Therefore more research is needed to examine the realistic need of lighting, as well as screening alternative, low-energy illumination strategies. It is highly dependent on the location and reactor type of the cultivation plant. If the cultivation plant is located in the latitudes, with long, dark and cold winter seasons, artificial lighting is probably required in order to enable production around the year. This can be improved up to certain extent by cultivating microalgae species adapted to low light conditions. However, there are clear limitations to how efficient photosynthesis can be, but there are algae that could supplement this with active uptake of organic carbon i.e. mixotrophy, and this could increase production if e.g. the wastewater contains suitable compounds. Generally, lower latitudes provide more constant temperature and light conditions, and realistic lightning solutions for northern conditions are limited, and the geographical location of the cultivation plant remains an essential step in feasibility assessments.

The overall environmental assessment will also require scenarios for the utilization of the algae biomass. Different end product production routes should be compared based on existing research studies. One of the main interests has been in the energy utilization, e.g. algae biodiesel, biogas, bioethanol and direct combustion. Also the utilization of the reject biomass from energy production e.g. as organic fertilizers may be considered. The replacement of fossil fuels by algal fuels would also decrease fossil CO_2 emissions. When defining system boundaries, it is important to include the examination of life cycle phases.

7 References

AquaFuels. 2009. Algae and aquatic biomass for a sustainable production of 2nd generation biofuels. http://www.aquafuels.eu/deliverables.html

Brentner, L. B., Eckelman, M. J. & Zimmerman, J. B. 2011. Combinatorial Life Cycle Assessment to Inform Process Design of Industrial Production of Algal Biodiesel. Environmental Science & Technology 45(16): 7060-7067.

Burgess, G. & Fernández-Velasco, J. G. 2007. Materials, operational energy inputs, and net energy ratio for photobiological hydrogen production. International Journal of Hydrogen Energy 32(9): 1225-1234.

Chiaramonti, D., Prussi, M., Casini, D., Tredici, M. R., Rodolfi, L., Bassi, N., Zittelli, G. C. & Bondioli, P. 2013. Review of energy balance in raceway ponds for microalgae cultivation: Re-thinking a traditional system is possible. Applied Energy 102(0): 101-111.

Chisti, Y. 2007. Biodiesel from microalgae. Biotechnology Advances 25(3): 294-306.

Chiu, S.-Y., Kao, C.-Y., Huang, T.-T., Lin, C.-J., Ong, S.-C., Chen, C.-D., Chang, J.-S. & Lin, C.-S. 2011. Microalgal biomass production and on-site bioremediation of carbon dioxide, nitrogen oxide and sulfur dioxide from flue gas using Chlorella sp. cultures. Bioresource Technology 102(19): 9135-9142.

Christenson, L. & Sims, R. 2011. Production and harvesting of microalgae for wastewater treatment, biofuels, and bioproducts. Biotechnology Advances 29(6): 686-702.

Clarens, A. F., Resurreccion, E. P., White, M. A. & Colosi, L. M. 2010. Environmental Life Cycle Comparison of Algae to Other Bioenergy Feedstocks. Environmental Science & Technology 44(5): 1813-1819.

Collet, P., Helias, A., Lardon, L., Ras, M., Goy, R.-A. & Steyer, J.-P. 2011. Life-cycle assessment of microalgae culture coupled to biogas production. Bioresource Technology 102(1): 207-214.

Craggs, R. J., McAuley, P. J. & Smith, V. J. 1997. Wastewater nutrient removal by marine microalgae grown on a corrugated raceway. Water Research 31(7): 1701-1707.

Doucha, J. & Lívanský, K. 2006. Productivity, CO2/O2 exchange and hydraulics in outdoor open high density microalgal (Chlorella sp.) photobioreactors operated in a Middle and Southern European climate. Journal of Applied Phycology 18(6): 811-826.

Ecoinvent. 2010. Ecoinvent data v2.2. http://www.ecoinvent.ch/

Finnish Environment Institute. 2011. Emissions of electricity purchasing in life cycle calculations. http://www.ymparisto.fi/default.asp?node=26328&lan=fi

Hertwich, E. G., Mateles, S. F., Pease, W. S. & McKone, T. E. 2001. Human toxicity potentials for life-cycle assessment and toxics release inventory risk screening. Environ Toxicol Chem 20(4): 928-39.

HSY. 2013. Suomenoja wastewater treatment plant. http://www.hsy.fi/en/waterservices/wastewater_treatment/Pages/suomenoja.aspx

Hulatt, C. J. & Thomas, D. N. 2011a. Energy efficiency of an outdoor microalgal photobioreactor sited at mid-temperate latitude. Bioresource Technology 102(12): 6687-6695.

Hulatt, C. J. & Thomas, D. N. 2011b. Productivity, carbon dioxide uptake and net energy return of microalgal bubble column photobioreactors. Bioresource Technology 102(10): 5775-5787.

Jorquera, O., Kiperstok, A., Sales, E. A., EmbiruÃ§u, M. & Ghirardi, M. L. 2010. Comparative energy life-cycle analyses of microalgal biomass production in open ponds and photobioreactors. Bioresource Technology 101(4): 1406-1413.

Kadam, K. 2001. Microalgae Production from Power Plant flue Gas: Environmental Implications on a Life Cycle Basis. NREL

Kothari, R., Pathak, V. V., Kumar, V. & Singh, D. P. 2012. Experimental study for growth potential of unicellular alga Chlorella pyrenoidosa on dairy waste water: An integrated approach for treatment and biofuel production. Bioresource Technology 116(0): 466-470.

Kumar, A., Ergas, S., Yuan, X., Sahu, A., Zhang, Q., Dewulf, J., Malcata, F. X. & van Langenhove, H. 2010. Enhanced CO2 fixation and biofuel production via microalgae: recent developments and future directions. Trends in Biotechnology 28(7): 371-380.

LED Finland. 120W LED Finland -valaisin. http://ledfinland.fi/120w-led-finland-valaisin-2/

Molina, E., Fernández, J., Acién, F. G. & Chisti, Y. 2001. Tubular photobioreactor design for algal cultures. Journal of Biotechnology 92(2): 113-131.

Mulbry, W., Kondrad, S. & Buyer, J. 2008. Treatment of dairy and swine manure effluents using freshwater algae: fatty acid content and composition of algal biomass at different manure loading rates. Journal of Applied Phycology 20(6): 1079-1085.

National Academy of Sciences. 2012. Sustainable Development of Algal Biofuels in the United States. The National Academies Press. 9780309260329. http://www.nap.edu/openbook.php?record_id=13437.

Operation SWAT. http://www.asio.cz/en/operation-swat-286840

Rösch, C., Skarka, J. & Wegerer, N. 2012. Materials flow modeling of nutrient recycling in biodiesel production from microalgae. Bioresource Technology 107(0): 191-199.

Schwenk, D., Seppälä, J., Spilling, K., Virkki, A., Tamminen, T., Oksman-Caldentey, K.-M. & Rischer, H. 2013. Lipid content in 19 brackish and marine microalgae: influence of growth phase, salinity and temperature. Aquatic Ecology: 1-10.

Slade, R. & Bauen, A. 2013. Micro-algae cultivation for biofuels: Cost, energy balance, environmental impacts and future prospects. Biomass and Bioenergy 53(0): 29-38.

Stephenson, A. L., Kazamia, E., Dennis, J. S., Howe, C. J., Scott, S. A. & Smith, A. G. 2010. Life-Cycle Assessment of Potential Algal Biodiesel Production in the United Kingdom: A Comparison of Raceways and Air-Lift Tubular Bioreactors. Energy & Fuels 24(7): 4062-4077.

Stewart, C. & Hessami, M.-A. 2005. A study of methods of carbon dioxide capture and sequestration—the sustainability of a photosynthetic bioreactor approach. Energy Conversion and Management 46(3): 403-420.

SUBMARINER. 2012. SUBMARINER Compendium. An Assessment of Innovative and Sustainable Uses of Baltic Marine Resources. Maritime Institute in Gdańsk. 978-83-62438-14-3.

U.S. DOE. 2010. National Algal Biofuels Technology Roadmap. U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Biomass Program. http://biomass.energy.gov.

Van Den Hende, S., Vervaeren, H. & Boon, N. 2012. Flue gas compounds and microalgae: (Bio-)chemical interactions leading to biotechnological opportunities. Biotechnology Advances 30(6): 1405-1424.

Welz, T., Hischier, R. & Hilty, L. M. 2011. Environmental impacts of lighting technologies — Life cycle assessment and sensitivity analysis. Environmental Impact Assessment Review 31(3): 334-343.

Xu, L., Brilman, D. W. F., Withag, J. A. M., Brem, G. & Kersten, S. 2011. Assessment of a dry and a wet route for the production of biofuels from microalgae: Energy balance analysis. Bioresource Technology 102(8): 5113-5122.