Annex 8 – Template for report-based deliverables

ALL-GAS

INDUSTRIAL SCALE DEMONSTRATION OF SUSTAINABLE ALGAE CULTURES FOR BIOFUEL PRODUCTION

Deliverable Title	D13.2 – Report on the preliminary evaluation
Deliverable Lead:	Fraunhofer UMSICHT
Related Work package:	WP 13 - Sustainability Analysis
Author(s):	Daniel Maga
Due submission date:	30/06/2014
Actual submission date:	30/05/2015
Project Number	268208
Call and Contract:	ENERGY.2010.3.4-1
Instrument:	Collaborative Project
Start date of Project:	01/05/2011
Duration:	60 months

Project funded by the European Commission within the Seventh Framework Programme		
Dissemination Level		
PU	Public	X
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

This project is supported by funding from the DG ENER under the 7th Research Framework Programme of the European Union

HISTORY CHART

Issue	Date	Changed page(s)	Cause of change	Implemented by
1.0	30-11-2012	All sections		

EXECUTIVE SUMMARY

To establish the Life Cycle Assessment (LCA) of a 10 ha algae production, extensive work has been carried out in order to collect primary data from the All-Gas pilot plant and to complement it with additional primary and secondary data if necessary.

In addition, the goal and scope definition was harmonized within the Algae cluster and a common paper “Unified approach to Life Cycle Assessment between three unique algae biofuel facilities“ was written (Bradley et al. 2015).

The following preliminary evaluation of the All-Gas plant considers the common goal and scope definition and focuses on energy, water, and land use.

When analysing electricity demands, thermal energy demand and embedded energy, a clear positive EROI was found for the All-Gas approach compared to conventional waste water treatment (WWT). The LCA results show that greenhousegas emissions can also be reduced by at least 30 %, even if unfavourable assumptions on N_2O emissions by land application of digestate is included.

On the other hand, about 10 times more land is needed for the All-Gas approach compared to conventional WWT. This leads to higher evaporation which can reach 10 % of inflow in summer months and signifies a blue water consumption in case of water reuse.

Keywords:

LCA, Life cycle inventory, Energy balance

Table of Contents

1 Introduction

Currently humanity is reliant on fossil oil for fuel and high value products. For reasons of climate change and finite supply, this situation must change. Numerous processes have been developed for producing fuel from organic materials such as bioethanol produced from sugar cane. However, there are serious concerns over greenhouse gas, land, and water impacts of these fuels, most clearly expressed in the food vs. fuel debate. This preliminary evaluation should support the evaluation of the All-Gas approach with regard to these aspects.

2 System description

As shown in Figure 2-1 the system boundaries of the All-Gas approach compromise several unit processes (UP).

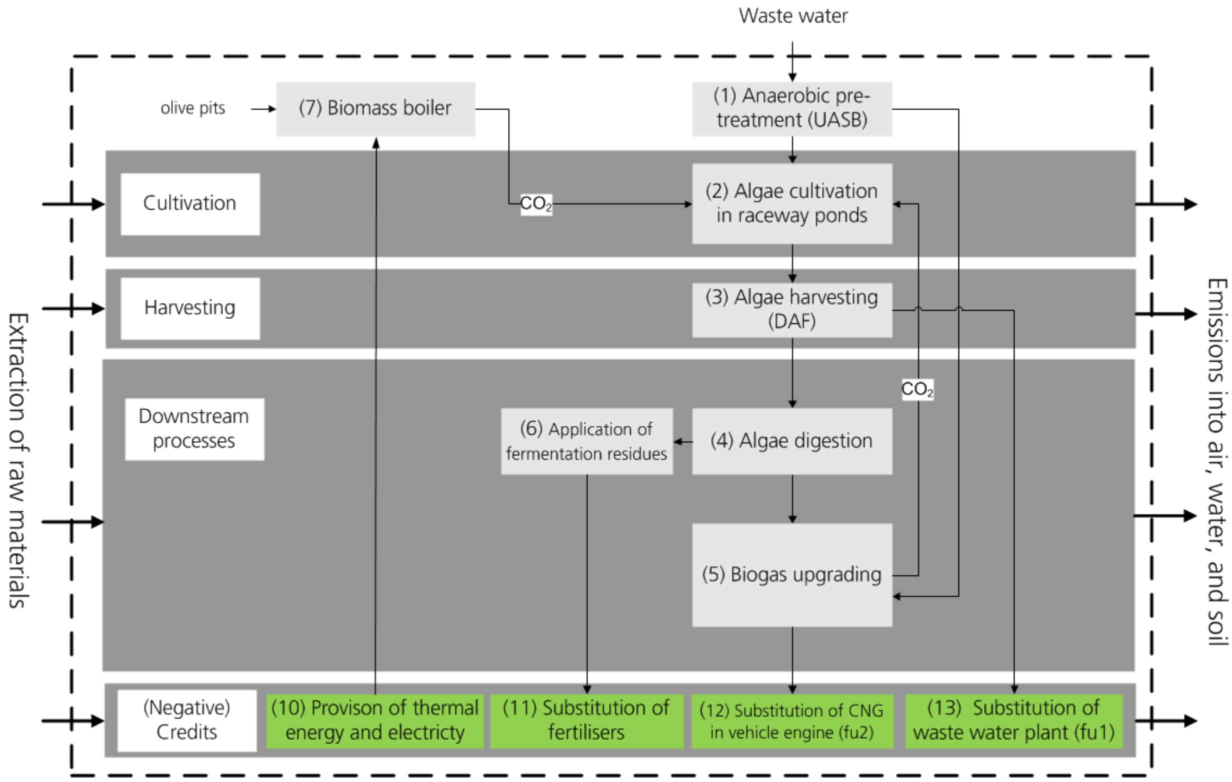

Figure 2-1: System boundaries of the All-Gas approach

The LCA study follows the idea of life cycle thinking choosing a "cradle-to-grave" approach. The investigated system encompass the following UPs: (1) anaerobic waste water pre-treatment, (2) cultivation of microalgae in primary treated waste water, (3) harvesting of algae, (4) biogas production from algal biomass, (5) biogas upgrading and provision at a service station, (6) application of fermentation residues on the field, and (7) CO_2 and energy generation in a biomass boiler. In addition, it includes (10) the provision/substitution of thermal energy and electricity, (11) the substitution of fertiliser, (12) the substitution of compressed natural gas (CNG) in a vehicle engine, and (13) the substitution of conventional waste water treatment.

The algae biorefinery system starts with the removal of oil, grease, and sand from municipal waste water followed by an anaerobic pre-treatment. Therefore, optimised upflow anaerobic sludge blanket (UASB) digesters are used that produce biogas with a methane content of around 80 % methane and reduce the total and soluble COD in the waste water by 60 % and

45 % respectively. Nitrogen and phosphorus concentrations, however, remain unchanged during the anaerobic treatment of the waste water, although the ammonia concentration could generally be increased. Some biogas remains dissolved and is stripped from the treated waste water and the H_2S content in the entire biogas is reduced by > 90 % using a biofilter.

The pre-treated waste water is pumped to high rate algae ponds (HRAPs) with a total area of 10 ha with dimensions of 250x18x0.3 m (LxWxH) each. The pond water velocity is kept at 0.3 $m*s^{-1}$ by low energy flow buster with a submergible impeller 12 hours a day and with the half of energy demand in the night. The slightly increased velocity is applied to prevent sediment accumulation. In order to trigger algae growth, carbon dioxide is injected that is provided externally through a piping system coming from biogas upgrading and from flue gas produced in a biomass boiler which is fed with olive pits.

In annual average, CO_2 is provided 12 hours per day. The overall CO_2 uptake is measured to be higher than 90 % (Aqualia 2014). Apart from the external supply of carbon dioxide, CO_2 produced by bacteria and waste water alkalinity is taken into account. This internal CO_2 production accounts for around two thirds of the total CO_2 demand that was determined to be 1.67 kg CO_2*kg algae DM^{-1} based on stoichiometric calculations considering a C content in algae biomass of 45%).

After algae cultivation with an average hydraulic retention time (HRT) of six days, taking into account the conservative design value for winter conditions, algae is harvested via a coagulation-flocculation system. In summer time up to 10,000 m^3*d^{-1} of waste water can be treated resulting into a HRT of 3 days. Algae biomass is recovered using a dissolved air flotation (DAF) unit with a recovery yield of 95 % and a solid content of 4 % after harvesting. The DAF effluent contains less than 10 and 1 $mg*L^{-1}$ total nitrogen and phosphorus respectively and thus fulfils the requirements of the legislation (threshold 10 - 15 and 2 $mg*L^{-1}$ N and P respectively according to EU UWWT Directive).

In this model the harvested algal biomass is anaerobically treated in a mesophilic digester at 35 °C. The required thermal energy to maintain this temperature is provided by a nearby boiler burning olive pits or other agricultural residues (green waste) and if necessary is complemented by thermal energy produced by an external power plant operated with natural gas. In reality no additional external energy will be used but a part of the produced biogas such as the one recovered by stripping will be used as additional fuel or digestion will alternatively be operated at a lower temperature. In the anaerobic digester, low biogas yields were achieved of around 0.11 L CH_4*g VS^{-1} added (Aqualia 2014) probably due to the unavailability of the biomass substrate to anaerobic bacteria because of the thick cellular membrane of algae or bacteria. This value depends on the algae species and their growth conditions and at laboratory scale more than the double of biogas yield was achieved..

In order to increase biogas yields, digestion can be performed at thermophilic conditions resulting in yields of up to 0.16 L CH_4*g VS^{-1} added. Alternatively, algae could be pre-treated in order to accelerate hydrolysis, which is the first step of anaerobic digestion, and enhances biogas production by breaking cell membranes and liberating intracellular material to be easily degraded by anaerobic bacteria. However, in this case it is necessary to first harvest and concentrate the algae prior to pre-treatment to about 15 to 20 %, as practised in large WWT Plants (Cambi process). Pre-concentration and thermal hydrolysis are energy-demanding steps and therefore this option has been excluded.

The fermentation residues resulting from the digestion plant contain around 2.8 % solids and 1.28 $g*L^{-1}$ ammonium. As a first assumption, these fermentation residues are dewatered and disposed by an external service provider. In the case of smaller WWT plants in the south of

Spain, residues are often land applied, and the nitrogen and phosphorus rich biosolids have high fertilizer value.

Biogas from the UASB reactors and the digestion plant is upgraded to biomethane. As the choice of one of the project partners, HyGear, VSA (Vacuum Swing Adsorption) process is used for the separation of CO_2 and CH_4. The VSA contains 6 absorbers filled with carbon molecular sieves (CMS). For this preliminary LCA a PSA system is assumed due to availability of data. The CO_2 enriched stream can be injected into the HRAPs and the upgraded biogas is intended to be used as automotive fuel with the filling station within the All-Gas plant. Therefore, the biomethane is pressurised from 5 bars (after PSA) to 200 bars minimal required for vehicle use.

The main assumptions used in the LCA model are presented in Table 2-1.

Table 2-1: Assumptions used for the LCA model, base line scenario

Description	Value	Unit	Notes
Methane yield from UASB digesters	0.15	m^3 CH_4* kg COD^{-1}	Optimised UASB design without heating
Average net productivity of algal biomass	18	g VSS * m^{-2}*d^{-1}	Before harvesting also including bacteria, assumed achievable on an annual basis
Nitrogen content in algae biomass	8	wt.%	Polyculture of microalgae cultivated in pre-treated waste water
Carbon content in algae biomass	45	wt.%	Average value
Lipid content in algae biomass	5	wt.%	5 % lipids, 50 % protein, 13 % carbohydrates
Low heating value of methane	50	MJ*kg^{-1}	35.9 MJ*m^{-3} at an assumed density of 0.718 kg*m^{-3} at standard temperature and pressure
Pump efficiency	70	%	Commercial pumps values
Average hydraulic retention time in ponds	6	Days	Varies from 3 to 6 days depending on season and weather
Linear water velocity in pond channels	0.3	m*s^{-1}	0.3 m*s^{-1}, 12 h daytime, low mixing in the night
Mixing energy required	360	kWh*d^{-1} *10 ha^{-1}	12 h mixing*d^{-1}, 0.2 W*m^{-2} (10 ha) + 12 h mixing*d^{-1} at 0.1 W*m^{-2}
Harvesting efficiency in DAF	95	%	40 g*L^{-1} (4 %) biomass in concentrate, flocculants are used
Hours per day of flue gas sparging	12	h*d^{-1}	Annual average; sufficient CO_2 dissolved in ponds mornings and

Description	Value	Unit	Notes
			evenings
Average energy requirement for flue gas distribution	0,0027	$kWh*kg^{-1}$	According to the GREET model (U.S. Department of Energy 2013), only for pumping, 1.2 m sump depth
Concentration of CO_2 in flue gas	11.5	vol%	Calculated for the biomass boiler operated with olive pits
Overall use efficiency of CO_2	90	%	Experimental data shows that new injection system with 1 m depth and small bubbles can reach a CO_2 transfer efficiency in HRAPs of about 95 %
Anaerobic digester HRT	21.6	days	Digester with 1 200 m³ and heated to 35 °C
Methane yield from anaerobic digestion	0.11	$L\ CH_4*g\ VS^{-1}$	Experimental data from pilot-scale digesters; corresponds to 21 % biodegradability
Fugitive methane emissions from AD plant	2.2	wt.%	Methane slip from AD plant (Cuhls et al. 2014)

3 Life cycle inventory

3.1 Energy balance

The energy analysis includes direct energy flows such as the electricity and fuel consumption of the algae biorefinery as well as the amount of biomethane produced. The main direct energy flows are presented in Figure 3-1. A detailed overview of electricity consumptions of each unit process (UP) is given in Table 3-1. All values presented in Figure 3-1 and Table 3-1 refer to the operating of the algae biorefinery for one day, based on the average assumption of ca. 5000 m^3*d^{-1} treated in a 10 ha surface. These are the conservative design values which are valid for winter conditions in Andalusia, more than double of waste water could be treated in summertime.

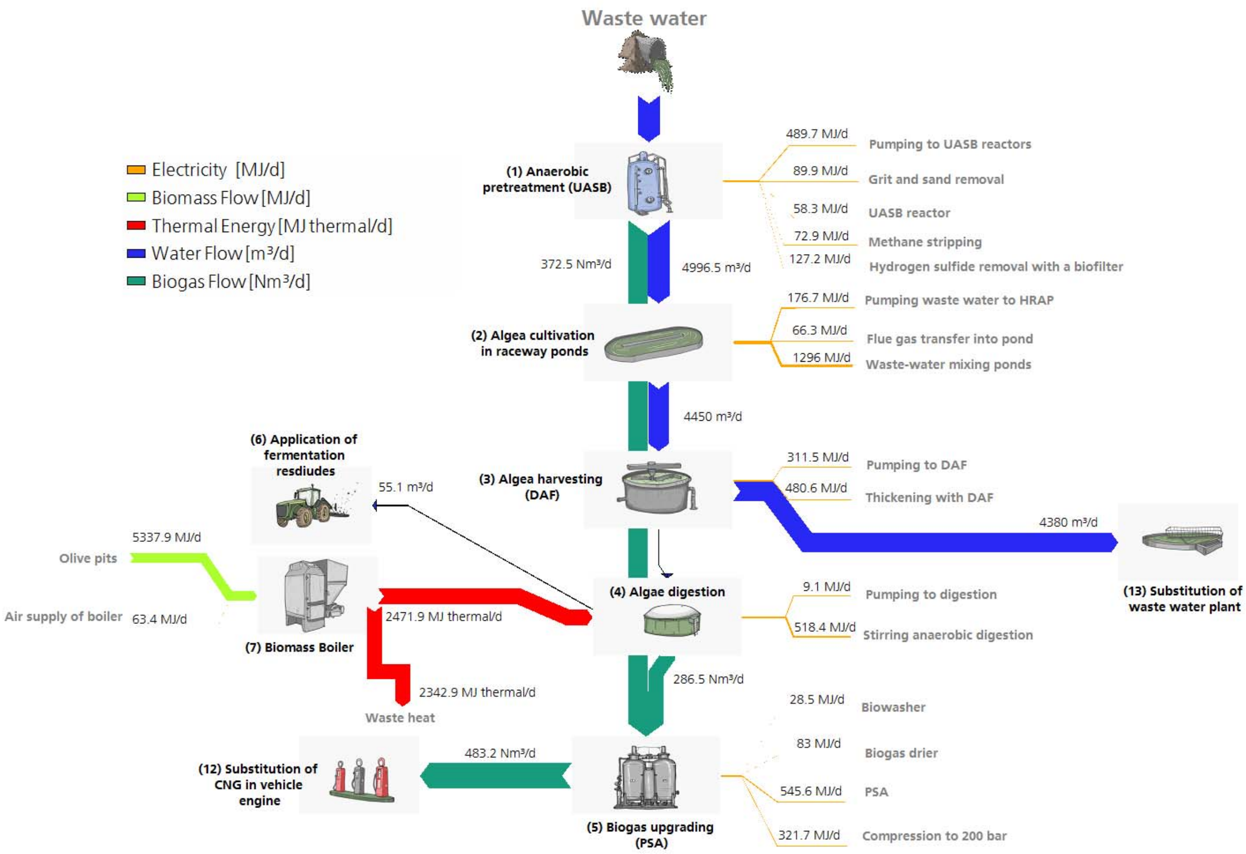

Figure 3-1: Direct energy flows of the algae biorefinery per day of operation, base line scenario, own illustration (©Fraunhofer UMSICHT)

Table 3-1 presents the primary energy demand, which is equal to the cumulative primary energy demand (CED), of the electricity consumption for the EU-28 electricity grid mix in 2011, Spanish electricity grid mix in 2011, and the future European electricity grid mix estimated for 2020 as described in (Bradley et al. 2015).

Table 3-1: Electricity consumption and related cumulative primary energy demand (CED) of the algae biorefinery in MJ per day, UP: unit process

UP	Process	Electricity consump-tion [MJ]	Total CED: EU grid mix [MJ]	Total CED: ES: grid mix [MJ]	Total CED: EU grid mix 2020 [MJ]
1	Primary treatment of waste water	90	255	265	256
1	Pumping waste water to UASB	490	1 386	1 442	1 394
1	Methane stripping	73	206	215	208
1	UASB reactor	58	165	172	166
1	H_2S removal with a biofilter	127	360	375	362
1	Pumping waste water to HRAP	177	500	520	503

UP	Process	Electricity consump-tion [MJ]	Total CED: EU grid mix [MJ]	Total CED: ES: grid mix [MJ]	Total CED: EU grid mix 2020 [MJ]
2	Flue gas transfer into pond	66	188	195	189
2	Water mixing	1 296	3 669	3 817	3 689
3	Pumping water to DAF	312	882	917	887
3	Thickening with DAF	481	1 360	1 415	1 368
4	Pumping to digestion	9	26	27	26
4	Stirring anaerobic digestion	518	1 467	1 527	1 476
5	Biowasher	28	81	84	81
5	Biogas drier	83	235	245	236
5	PSA	546	1 544	1 607	1 553
5	Compression to 200 bar	322	911	947	916
7	Air supply of boiler	63	180	187	181
	Total thermal energy	2 472	no value	no value	no value
	Total electricity	4 739	13 414	13 956	13 490

Apart from electricity the daily thermal energy demand for the biogas plant, assuming mesophilic conditions at 35 °C, is calculated to be in the annual average 2 472 MJ end energy.

The distribution of the primary energy demand caused by electricity consumption by process area is given in Figure 3-2. The dewatering and disposal of fermentation residues has not been included into the balance yet. This will be done after clarifying all process data.

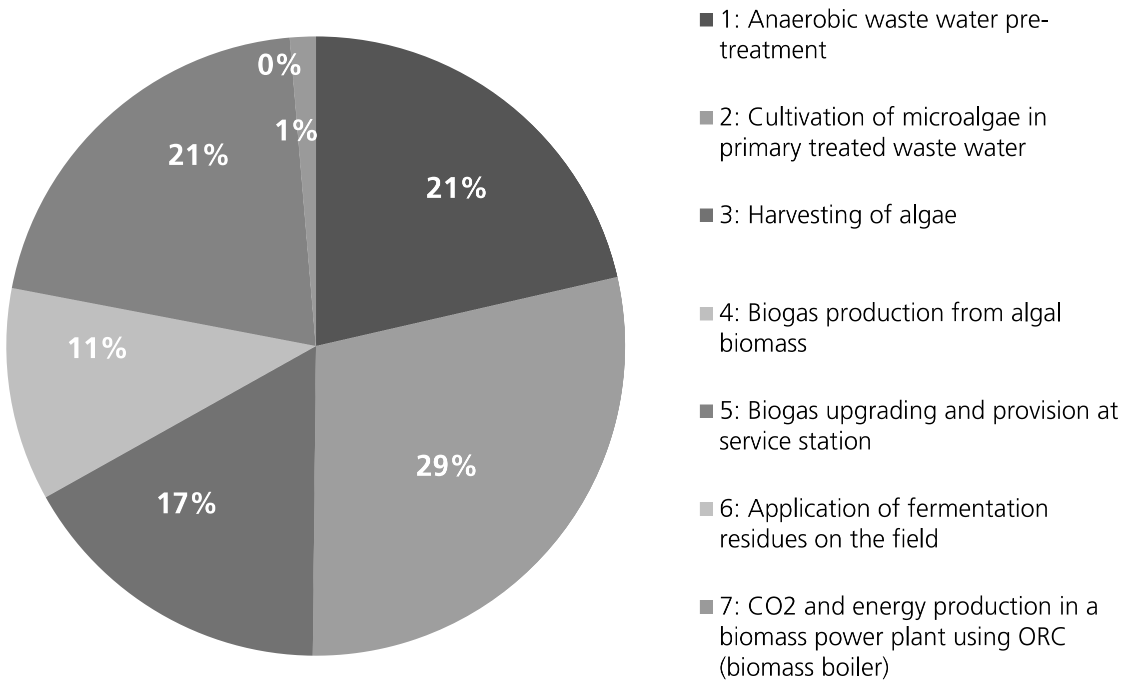

Figure 3-2: Primary energy distribution of electricity consumption by process area

Besides, indirect energy flows are taken into account which result from material inputs that contain embedded energy. One example is the embedded energy in activated carbon used for the fine desulphurisation step applied in the biogas upgrading process. Also considering the primary energy demand of indirect energy flows, approx. 30 000 MJ CED are needed per day, whereas approx. 50 % are caused by electricity consumption.

Based on the direct and indirect energy flows given in **Fehler! Verweisquelle konnte nicht gefunden werden.** the second-order energy return on investment, as defined by Mulder and Hagens and applied for algae biofuels by Beal et al., can be calculated (Mulder, Hagens 2008; Beal et al. 2011). For calculating the EROI of biomethane produced in the algae biorefinery equation (3-1) is applied.

$$EROI_{BM} = \frac{EC_{BM} + EC_{CP}}{E_{BM}} = \frac{LHV_{BM} * \rho_{BM} + EC_{CP}}{E_{BM}} [-] \qquad (3\text{-}1)$$

EC_{BM} is the energy content of biomethane, EC_{CP} is the primary energy of the co-products fertiliser and water purification, and E_{BM} is the direct and indirect energy required to produce biomethane. Also, in equation (3-1) LHV is the lower heating value of biomethane (49.8 $MJ*kg^{-1}$), and ρ_{BM} is the biomethane density (0.72 $kg*m^{-3}$ at 0 °C and 1 013 bars). With regard to the All-Gas approach an EROI of approx. 2 is calculated which means that the system has a positive energy balance. Solar energy that is converted into algal biomass or bacteria is neglected within this calculation.

Depending on the following parameters the EROI can vary a bit:

- disposal of fermentation residues
- algae productivity
- digestion efficiency

- Energy input in pond and digester mixing

Concerning these factors, the present results here included correspond to the most conservative values obtained experimentally which will probably be improved in a nearby future after a proper validation of experimental results from the scale-up. This will lead to a more favourable scenario with an even higher EROI.

3.2 Water balance

According to the goal and scope definition (Bradley et al. 2015) only blue water (ground water + lake water + river water + fossil ground water) is considered, excluding rainwater. Precipitation water is not considered since it does not refer to blue water, even though some of it would be captured for irrigation/reuse. In addition, rainwater would contribute to less than 2 % compared to the evaporation losses.

Blue water consumption considers freshwater lost to the watershed due to water vapour to air, evapotranspiration, water incorporated into products, and water release to sea. Therefore, it can be calculated as input of ground water, lake water, river water, and fossil ground water minus total blue water release from technosphere into rivers or lakes (water outputs).

Approximately 5 000 m^3 of waste water are treated per day in 10 ha open ponds. Considering the local saturation vapour pressure and the average temperature in Chiclana de la Frontera during the period 1960-1990 (IPCC 2014), the average evaporation over the 10 ha water surface is calculated to be 550 m^3 per day. Experimental data with the meteorological station in the All-Gas project shows slightly higher annual average values of approximately 590 m^3 per day. The data used for these calculations is shown in Figure 3-3. Precipitation water is not considered since it does not refer to blue water.

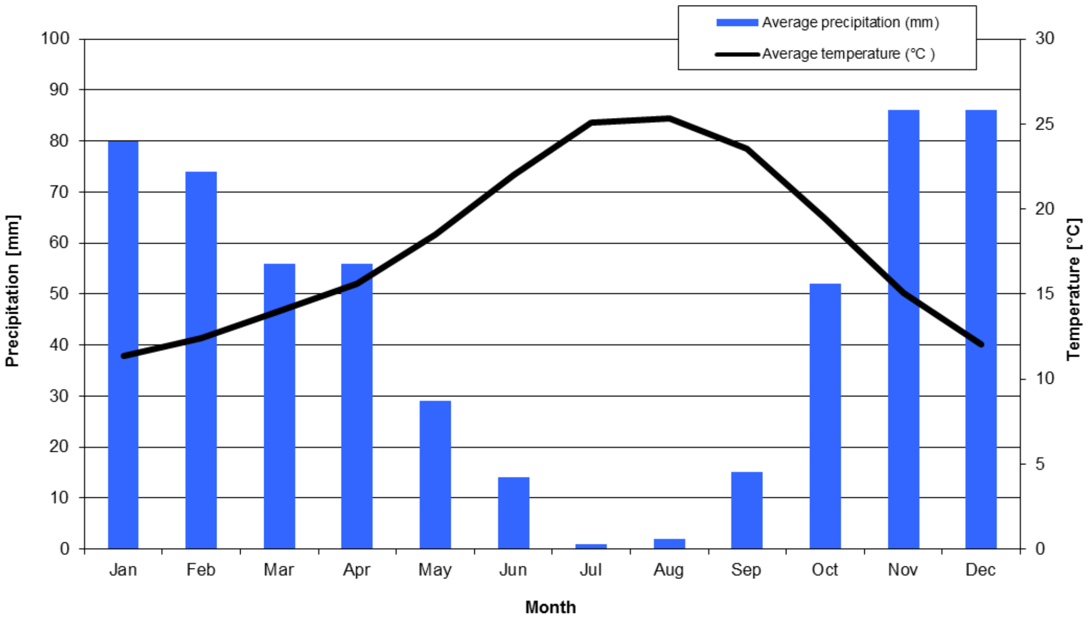

Figure 3-3: Climate chart Chiclana de la Frontera, figures refer to the time frame 1960-1990 and were taken from the IPCC data distribution centre (IPCC 2014)

Apart from water blue water consumption due to evaporation of water in ponds, the disposal of UASB sludge as well as disposal of fermentation residues contributes to blue water consumption. Since the amount of blue water consumption depends on the way of disposal, these values represent only a first estimation. An overview of the blue water flows of the All-Gas approach is given in Figure 3-4.

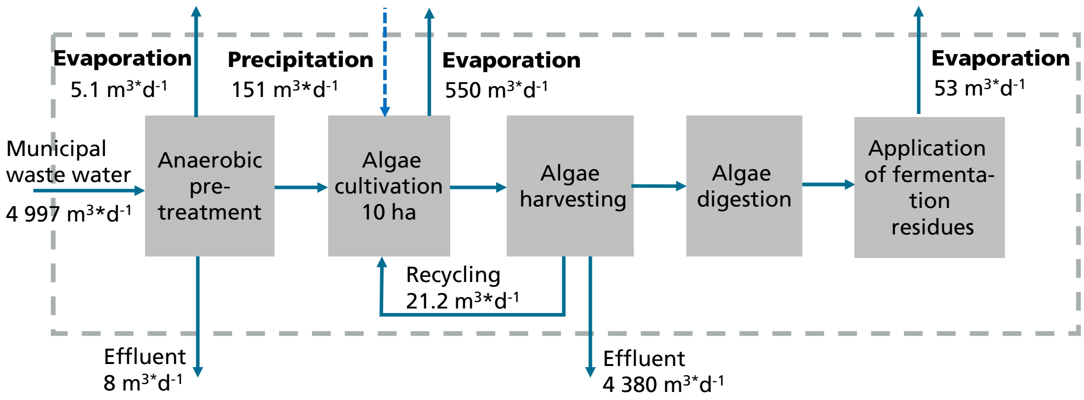

Figure 3-4: Blue water balance of the algae biorefinery; values refer to one day of operation, dotted arrow indicates green water which is not considered

Apart from the blue water consumption that is directly linked to the algae biorefinery, blue water consumption also arises in the upstream chains. Blue water consumption occurs in the production of the installations e.g. in production of concrete bricks or polypropylene liner for the ponds or in the production of operating materials such as diesel, flocculation agents or activated carbon. However, in total these upstream chains account for less than one m^3 of blue water consumption per day.

Higher amounts of blue water consumption would go along with the provision of olive pits (73.4 m^3*d^{-1}) and the need of electricity which accounts for 5.4 m^3*d^{-1} (European electricity mix of 2011 is assumed). Irrigation water for olive pits is calculated using monetary allocation between olive oil and olive pits. Per ha olive plantations, around 4 000 m^3 irrigation water is needed annually in Andalusia resulting in an annual average yield of ca. 3 000 kg olives DM per hectare (Molero Cortés 2006).

It has to be emphasized that the combustion of olive pits (or similar green waste) was proposed to overcome the restriction of the EU, which prohibited that fossil exhaust gases would be used to grow algal biomass.

3.3 Land use

Land use and land use changes of first generation biofuels are a large concern. The production of algae promises two big benefits: firstly marginal land can be used to avoid land use change (transformation) and secondly less land is required compared to other biofuels due to higher biomass yields per ha (Sengupta et al. 2015).

As in the case of the All-Gas approach non-arable land is used which means that negative land transformation does not occur.

Since the All-Gas plant is constructed within Chiclana de la Frontera, land use can be calculated as the midpoint indicator »urban land occupation«.

The main space demanding part is the cultivation of algae in high raceway algae ponds (HRAP) which needs approximately 13 ha when considering a water surface of 10 ha.

In relation to one m^3 of waste water treated, this means an annual occupation of 0.074 m^2. This value is ca. 10 times higher compared to conventional waste water treatment as shown in Figure 3-5.

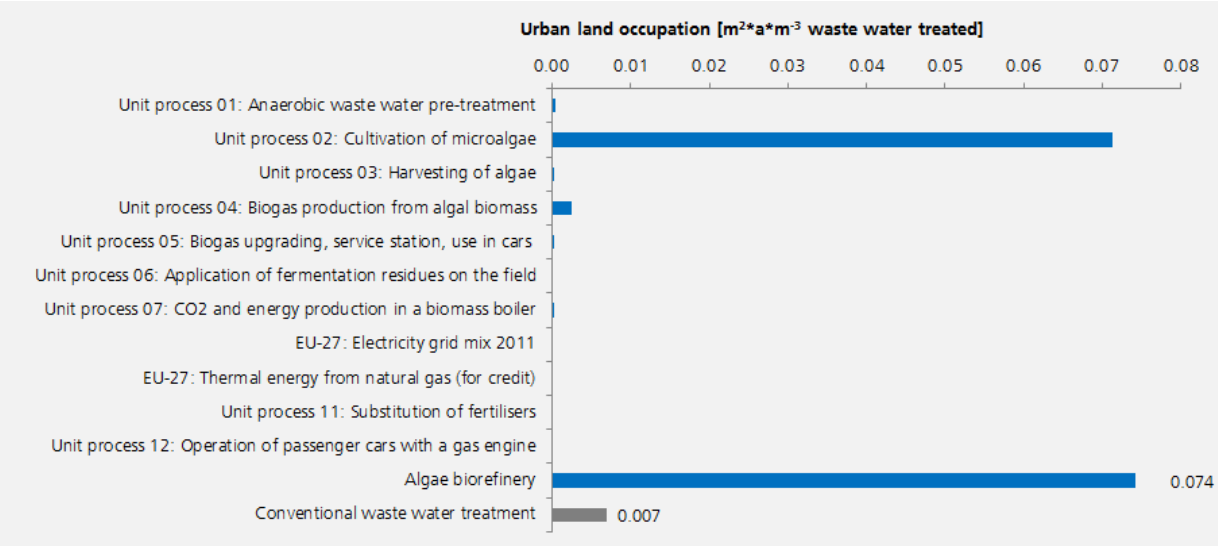

Figure 3-5: Urban land occupation of the All-Gas approach compared to conventional waste water treatment

3.4 Summary life cycle inventory

The foreground data used in the LCA model is shown below.

UP1: Anaerobic waste water pre-treatment & methane stripping	INPUTS					OUTPUTS				
	MATERIALS	VALUE	UNIT	VALUE	UNIT	MATERIALS	VALUE	UNIT	VALUE	UNIT
	WASTE WATER	4 996 530	$kg*d^{-1}$			3) UASB EFFLUENT	4 983 264	$kg*d^{-1}$		
	1) PRIMARY TREATMENT OF WASTE WATER			24.98	$kWh*d^{-1}$	3) BIOGAS	372.45	Nm^3*d^{-1}	2969.8	$kWh*d^{-1}$
	2) ELECTRICITY FOR PUMPING WW TO UASB			136.02	$kWh*d^{-1}$	3) ANAEROBIC SLUDGE	13 266	$kg*d^{-1}$	545.4	$kWh*d^{-1}$
	3) ELECTRICITY FOR METHANE STRIPPING			20.26	$kWh*d^{-1}$	METHANE SLIP	2.98	kg*d-1		
	3) ELECTRICITY FOR UASB REACTOR			16.20	$kWh*d^{-1}$	SOLID WASTE TO LANDFILL	74.00	kg*d-1		
	3) HEAT FOR UASB REACTOR			0	$kWh*d^{-1}$					
	3) ELECTRICITY FOR PUMPING WW TO METHANE STRIPPING			not needed due to inclination	$kWh*d^{-1}$					
	4) ELECTRICITY FOR H2S REMOVAL WITH BIOFILTER			35.33	$kWh*d^{-1}$					
	5) ELECTRICITY FOR ODOR CONTROL			excluded	$kWh*d^{-1}$					
	6) ELECTRICITY FOR PUMPING WW TO PONDS			49.09	$kWh*d^{-1}$					

UP2: Cultivation of microalgae in primary treated waste water	INPUTS					OUTPUTS				
	MATERIALS	VALUE	UNIT	VALUE	UNIT	MATERIALS	VALUE	UNIT	VALUE	UNIT
	1) INPUT WATER FROM UASB & RECYCLING	5 000 000	$kg*d^{-1}$			ALGAE AND BACTERIA	2337.66	$kg*d^{-1}$		
	1) FLUE GAS	2 312	$kg*d^{-1}$			EVAPORATED WATER	550 000	$kg*d^{-1}$		
	1) ELECTRICITY TO TRANSFER FLUE GAS INTO POND			18.43	$kWh*d^{-1}$	POND EFFLUENT	4 450 000.00	$kg*d^{-1}$		
	2) LINERS MADE OF PP FOR PONDS	19.11	$kg*d^{-1}$			CO_2 (BIOTIC) INTO THE AIR	80.20	$kg*d^{-1}$		
	2) CONCRETE HOLLOW BLOCK FOR PONDS	93.59	$kg*d^{-1}$							
	2) ELECTRICITY FOR WATER MIXING			360.00	$kWh*d^{-1}$					
	2) CO_2 FROM BIOGAS	166.89	Nm^3*d^{-1}							

UP3: Harvesting of algae	INPUTS					OUTPUTS				
	MATERIALS	VALUE	UNIT	VALUE	UNIT	MATERIALS	VALUE	UNIT	VALUE	UNIT
	ALGAE AND BACTERIA	2 337.66	$kg*d^{-1}$			RECYCLED WATER	16 735.60	$kg*d^{-1}$		
	POND EFFLUENT	4 450 000.00	$kg*d^{-1}$			WET BIOMASS @ 4 %	55 519.48	$kg*d^{-1}$	12 139	$kWh*d^{-1}$
	ELECTRICITY FOR PUMPING WATER TO DAF			86.53	$kWh*d^{-1}$	EFFLUENT DAF	4 379 965.70	$kg*d^{-1}$		
	ELECTRICITY FOR THICKENING WITH DAF			133.5	$kWh*d^{-1}$					
	COAGULANTS	89.00	$kg*d^{-1}$							
	POLYMERS	13.35	$kg*d^{-1}$							

	INPUTS					OUTPUTS				
	MATERIALS	VALUE	UNIT	VALUE	UNIT	MATERIALS	VALUE	UNIT	VALUE	UNIT
UP4: Biogas production from algal biomass	WET BIOMASS at 4 % SOLIDS CONTENT	55 519	kg*d^{-1}			BIOGAS	286.47	Nm^3*d^{-1}	1855.9145	kWh*d^{-1}
	REQUIRED THERMAL ENERGY AD			687	kWh*d^{-1}	NO_2 EMISSIONS INTO THE AIR	0.08	kg*d^{-1}		
	WASTE HEAT FROM PSA LEAN GAS			57.2	kWh*d^{-1}	AMMONIA EMISSIONS INTO THE AIR	4.33	kg*d^{-1}		
	ELECTRICITY FOR MIXING AD			144.0	kWh*d^{-1}	NMVOC INTO THE AIR	1.28	kg*d^{-1}		
	BIOGAS PLANT (INFRASTRUCTURE)	0.000137	pieces*d^{-1}			EFFLUENT AD	55 053	kg*d^{-1}		
	ELECTRICITY FOR PUMPING TO DIGESTION			2.52	kWh*d^{-1}	ANAEROBIC SLUDGE (RESIDUES DM)	1897.06	kg*d^{-1}		
						WASTE HEAT	93.78	kWh		

	INPUTS					OUTPUTS				
	MATERIALS	VALUE	UNIT	VALUE	UNIT	MATERIALS	VALUE	UNIT	VALUE	UNIT
UP5: Biogas upgrading and provision at a service station	TOTAL BIOGAS INPUT	659	Nm^3*d^{-1}			BIOMETHANE (97 % PURITY)	483.2	Nm^3*d^{-1}	4 816	kWh*d^{-1}
	ELECTRICTY FOR BIOWASHER			7.9	kWh*d^{-1}	CARBON DIOXIDE	166.89	Nm^3*d^{-1}		
	WATER FOR BIOWASHER	27	kg*d^{-1}			USED ACTIVATED CARBON	0.33	kg*d^{-1}		
	NaOH FOR BIOWASHER	1	kg*d^{-1}			METHANE EM. FROM PSA TO AIR	0.65	kg*d^{-1}		
	ELECTRICTY FOR DRIER			23.1	kWh*d^{-1}	METHANE EM. FROM STATION TO AIR	0.065	kg*d^{-1}		
	ELECTRICITY FOR PSA			152	kWh*d^{-1}	WASTE HEAT FOR BIOGAS PLANT			57.156042	kWh$_{th}$*d^{-1}
	ACTIVATED CARBON	0.33	kg*d^{-1}							
	LUBRICANTS PSA	0.03	kg*d^{-1}							
	ELECTRICTY FOR COMPRESSION			89	kWh*d^{-1}					

	INPUTS					OUTPUTS				
	MATERIALS	VALUE	UNIT	VALUE	UNIT	MATERIALS	VALUE	UNIT	VALUE	UNIT
UP6: Application of fermentation residues	FERMENTATION RESIDUES	55 053	kg*d^{-1}			NH_3 EMISSIONS TO AIR	21	kg*d^{-1}		
	DIESEL FOR TRANSPORT	30	kg*d^{-1}			N_2O EMISSIONS TO AIR	4.76	kg*d^{-1}		
	DIESEL FOR APPLICATION	21	kg*d^{-1}			CH_4 EMISSIONS TO AIR	2	kg*d^{-1}		
						EVAPOTRANSPIRATION	53 313	kg*d^{-1}		
						CO_2 BIOTIC TO AIR	3 262	kg*d^{-1}		
						CARBON FIXED IN SOIL	99	kg*d^{-1}		

	INPUTS					OUTPUTS				
	MATERIALS	VALUE	UNIT	VALUE	UNIT	MATERIALS	VALUE	UNIT	VALUE	UNIT
UP7: CO_2 and energy generation in a biomass boiler	OLIVINE KERNELS (DM)	277	kg*d^{-1}	1482.8	kWh*d^{-1}	ELECTRICITY			0	kWh*d^{-1}
	AIR	1 743	kg*d^{-1}			EXCESS HEAT			1 337	kWh$_{th}$*d^{-1}
	ELECTRICITY FOR AIR SUPPLY			17.62	kWh*d^{-1}	ASH	3	kg*d^{-1}		
						FLUE GAS	2 213	kg*d^{-1}		
						CO_2 IN FLUE GAS	472	kg*d^{-1}		
						SO_2 IN FLUE GAS	0.22	kg*d^{-1}		
						CO IN FLUE GAS	0.00	kg*d^{-1}		
						NO_2 IN FLUE GAS	8.74	kg*d^{-1}		

4 Conclusion

The first evaluation shows the energy demands of the All-Gas approach at demonstration scale as well as the blue water consumption and land demand.

All electricity demands, thermal energy demand and embedded energy were calculated for the All-Gas approach. First results show a clear positive EROI of around 2. In contrast, conventional waste water treatment consumes energy making its replacement by the All-Gas approach attractive.

Although blue water consumption of the All-Gas approach, due to evaporation on the large ponds in summer, is approx. 20 times higher compared to conventional waste water treatment it needs to be evaluated site specific if this has negative impacts or not. Today the majority of treated waste water in Chiclana de la Frontera is fed into the receiving water which ends in the sea after several hundreds of meters. This means the fresh water is lost in any way making it difficult to decide whether the water footprint of the All-Gas plant really is higher compared to conventional waste water treatment.

With regard to land use approximately 10 times more land is needed compared to conventional waste water treatment. On the other hand, the value of the land used is very low and it is questionable whether the land can be used for other beneficial applications or not.

It should be mentioned that the values presented are conservative assumptions for the annual average. Higher yields and a better environmental performance are achievable in the summer time which has not been completely investigated yet.

In addition, the All-Gas demonstration plant is still under development allowing for further improvements. For example, the impacts of a new water mixing system are currently investigated as well as possible fermentation residues management options.

4.1 Outlook greenhouse gas emissions

A first cradle-to-grave LCA model has already been designed which allows calculating the carbon footprint (CF) of purifying 1 m3 of waste water or 1 MJ biofuel incinerated in a car engine which were defined as functional units.

The CF of one m^3 of waste water treated is shown in Figure 4-1, and the CF of one MJ biomethane incinerated in a car engine is presented in Figure 4-2.

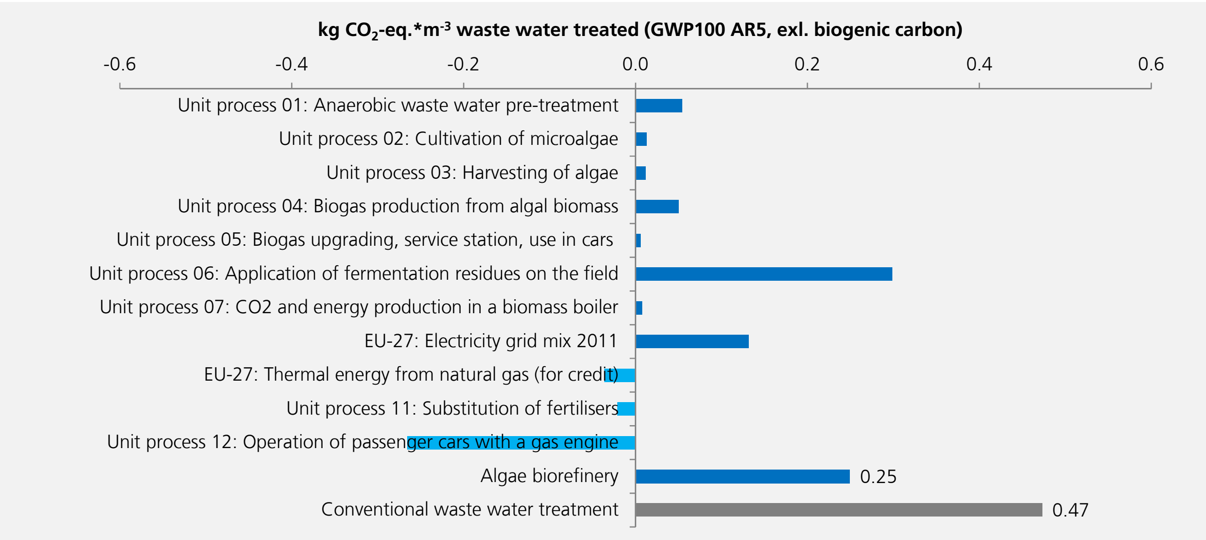

Figure 4-1: Global warming potential per m^3 of waste water treated (GWP100 AR5 excl. biogenic carbon)

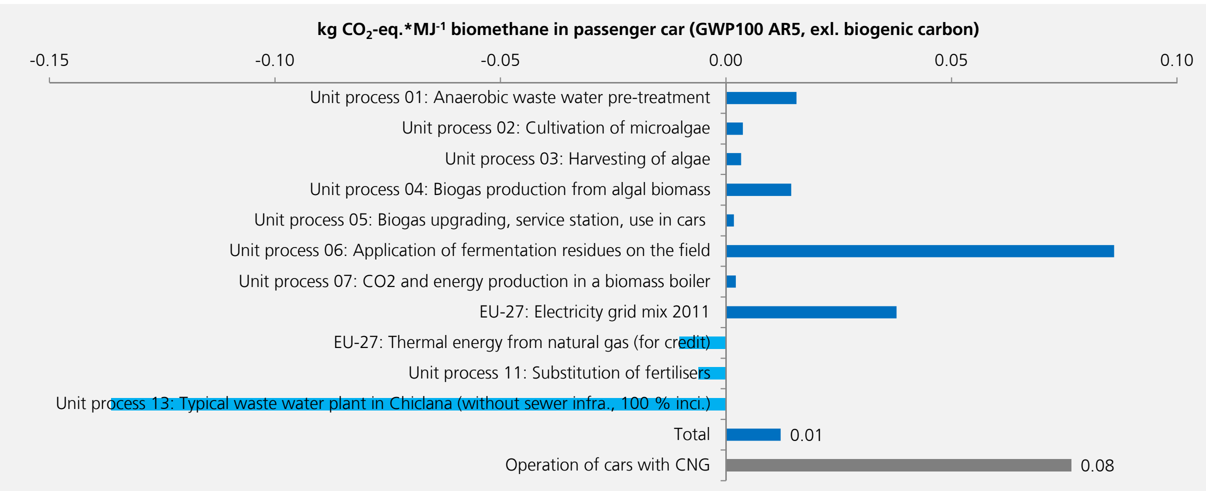

Figure 4-2: Global warming potential per MJ of biomethane incinerated in a car engine (GWP100 AR5 excl. biogenic carbon)

The calculated CF of 1 MJ biomethane used in a car engine is about one quarter of the reference value for fossil fuels which is around 83 g CO_2 eq.*MJ^{-1}.

However, the calculation of the CF considers the application of fermentation residues on the field which causes significant nitrous oxide emissions as shown in Figure 4-3.

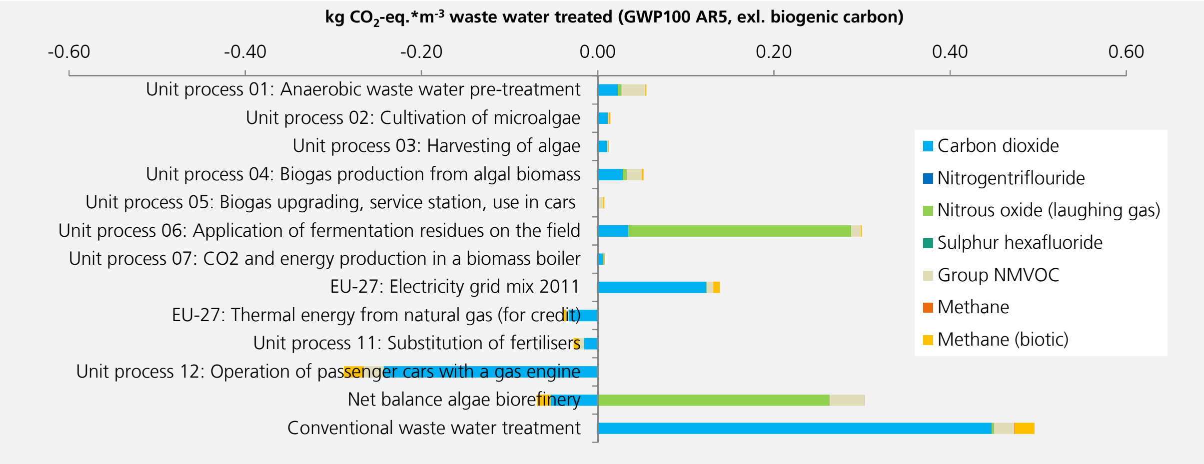

Figure 4-3: Contribution analysis of global warming potential per m^3 of waste water treated (GWP100 AR5 excl. biogenic carbon)

GHG emissions into the air resulting from the storage and application of algae digestate on the field have not been measured yet. They depend strongly on the type of soil, application technique, climate conditions, time of application, and the composition of the digestate, and therefore are highly variable (Yoshida et al. 2013). However, in case of fermentation residues produced by fermentation of bio-waste or manure, measurements of GHG emission are available in literature (Moller et al. 2009; Bruun et al. 2006; Cuhls et al. 2014; Wulf 2002). Although these measurements were carried out in northern European countries under different conditions, these values are used as a first approximation.

The calculation of GHG emissions carried out by (Cuhls et al. 2014) is based on the assumptions made by the International Panel on Climate Change (IPCC) which suggests a methodology to estimate soil N_2O emissions based on mineral and organic fertilizers, and also for the mineralization of N from crop residues added to soil ((IPCC 2007)). In this case, it is considered that 1.25 % (uncertainty range from 0.3% to 3%) of the soluble nitrogen added is converted into N_2O (IPCC 2007).

Table 4-1 summarises emissions factors of digestate application for methane, ammonia, nitrous oxide, and biogenic carbon dioxide.

Table 4-1: Emission factors in literature for the application of digestate on the field

Emission factors				References	Remark
CH_4	NH_3	N_2O	CO_2 (biotic)		
0.02* NH_3, max. 8 $g*t^{-1}$ digestate	$0.3*NH_4^+$-N	0,0125[1]* MFE[2]+ 0.05 org. N		Table 5-10 in (Cuhls et al. 2014)	Application of liquid digestate
No value is given	0.075 up to 0.114	0.013 up to 0.017[3]	0.86 up to 0.96 CO_2-C[4]	(Bruun et al. 2006; Moller et al. 2009)	Denmark (digestate from bio-waste)

Greenhouse gas emissions from the storage of digestate were measured to contribute to around 1 % of direct GHG emissions from biomass treatment, storage, and application and are therefore neglected within this study (Cuhls et al. 2014). During anaerobic digestion of algae around 40 % of N is converted to ammonium (N-NH_4^+). That corresponds to 1.28 g N-NH_4^+ $*L^{-1}$ digestate and around 66 kg N-$NH_4^+*d^{-1}$.

In general, the fertilisation effect of organic fertilisers can range from 5 to 85 % if good fertilisation practice is applied (Reinhold 2008). According to Reinhold, the fertilisation effect of organic fertilisers expressed as mineral nitrogen can be approximated by means of NH_4^+-N + NO_3-N (Reinhold 2008). Due to a low content of NO_3 measured in the digestate NO_3 is neglected.

Consequently, the mineral fertilise equivalent (MFE) is estimated to be equal to the amount of N-NH_4^+ = 70 $kg*d^{-1}$. Following to a large extend the calculation formulas given by (Cuhls et al. 2014) which were presented in Table 4-1, emissions caused by the application of algae digestate were calculated and are shown in Table 4-2. The amount of organic nitrogen is calculated based on the nitrogen content of algae considering ammonium release during fermentation.

[1] In the first year approx. 1.25 % of soluble nitrogen is converted to N_2O if good agricultural practice is applied (IPCC 2007).

[2] MFE: Mineral fertilise equivalent

[3] Emissions coefficients represent the difference between normal agricultural practice only using inorganic fertilizers and use of digestate supplemented with inorganic fertilizers according to Danish legislation.

[4] The rest fraction of carbon remains in the soil.

Table 4-2: Emissions caused by application of algae digestate

	Emissions of 51 m^3 digestate (base line scenario, 1 day)				
	CH_4 [kg*d^{-1}]	NH_3 [kg*d^{-1}]	N_2O [kg*d^{-1}]	CO_2 (biotic) [kg*d^{-1}]	C fixed in soil [kg*d^{-1}]
Algae digestion residues	0.02* 70 *1.2 = 1.68	0.3 * 70 = 21	0.0125 * 70 + 0.05*91 = 5.4	0.9*988* 44/12= 3 260	0.1*988= 99

The amount of ammonia that is not emitted into the air is available to the plants. As in (Knappe et al. 2012) it is assumed that the amount not emitted replaces nitrogen from mineral fertiliser by 100 %.

Of course, mineral fertilisers have the same N_2O emissions which are estimated to be 1.25 % of N content. Considering the losses of nitrogen through ammonia emissions around 49 kg mineral N*d^{-1} are replaced. This leads to approximately 49 kg N * 1.25 % = 0.6 kg N_2O emissions into the air per day which are considered as credit.

It should be also mentioned that as shown by (Signor, Cerri, Carlos Eduardo Pellegrino 2013) and summarized in Figure 4-4, in reality N_2O emission factors vary a lot. This means further research is needed to investigate GHG emissions from disposal of fermentation residues in detail.

Crop	N_2O emission factor (%)	Location	Reference
Rapeseed, corn and sugarcane	3.00-5.00	Based on average data from literature	(Crutzen et al. 2008)
Soybean	0.55-1.97	Argentina	(Ciampitti et al. 2008)
Pasture for bale	0.28-0.62	Scotland	(Smith et al. 1998)
Potato	0.86-1.90	Scotland	(Smith et al. 1998)
Winter wheat	0.17	Scotland	(Smith et al. 1998)
Spring barley	0.67	Scotland	(Smith et al. 1998)
Winter wheat	1.68	China	(Chen et al. 2008)
Forest	0.10-0.03	USA	(Delaune et al. 1998)
No-till	2.80	Brazil	(Passianoto et al. 2003)
Conventional till	0.90	Brazil	(Passianoto et al. 2003)
Pasture (mineral fertilizer)	0.17	Netherlands	(Schils et al. 2008)
Pasture (mineral fertilizer and cow manure)	0.29	Netherlands	(Schils et al. 2008)
Pasture	0.35	China	(Zhang & Han 2008)
Abandoned agriculture area	0.52	China	(Zhang & Han 2008)
Sugarcane (acid drainage soil)	21.00	Australia	(Denmead et al. 2010)
Sugarcane (silt-clayey soil)	2.80	Australia	(Denmead et al. 2010)
No-till	0.20	Brazil	(Giacomini et al. 2006)
Reduced till	0.25	Brazil	(Giacomini et al. 2006)
No-till and conventional till in the Brazilian Savannah	0.03	Brazil	(Metay et al. 2007)
Pasture in the Amazon	2.80	Brazil	(Neill et al. 2005)
Meta-analysis study	0.70-1.20	-	(Bouwman & Boumans 2002)
Meta-analysis study	0.17-2.90	-	(Novoa & Tejeda 2006)

Figure 4-4: Crops and N_2O emission factors reported by several authors around the world, Source: (Signor, Cerri, Carlos Eduardo Pellegrino 2013)

Furthermore, assumptions for N_2O emissions referring to conventional waste water treatment are needed. In particular for oxidation ditches together with the application of sewage sludge on the field no values are available. Therefore, futher measurements are needed.

In addition, it should be analysed whether composting of residues is economic feasible since composting can reduce GHG emissions (Cuhls et al. 2014).

5 References

Aqualia (2014): Measurements and design parameters carried out in the EU-funded project »Industrial scale Demonstration of Sustainable Algae Culture for Biofuels Production« (All-Gas), 2014.

Beal, C. M.; Smith, C. H.; Webber, M. E.; Ruoff, R. S.; Hebner, R. E. (2011): A Framework to Report the Production of Renewable Diesel from Algae. In *Bioenerg. Res.* 4 (1), pp. 36–60. DOI: 10.1007/s12155-010-9099-x.

Bradley, T.; Maga, D.; Antón, S. (2015): Unified approach to Life Cycle Assessment between three unique algae biofuel facilities. In *Applied Energy. DOI:* 10.1016/j.apenergy.2014.12.087.

Bruun, S.; Hansen, T. L.; Christensen, T. H.; Magid, J.; Jensen, L. S. (2006): Application of processed organic municipal solid waste on agricultural land – a scenario analysis. In *Environ Model Assess* 11 (3), pp. 251–265. DOI: 10.1007/s10666-005-9028-0.

Cuhls, C.; Mähl, B.; Clemens, J. (2014): Ermittlung der Emissionssituation bei der Verwertung von Bioabfällen. Edited by Umweltbundesamt. gewitra.

IPCC (2007): Climate Change 2007. Mitigation of Climate Change. Contribution of working group III to the fourth assessment report of the Intergovernmental Panel on Climate Change. Intergovernmental Panel on Climate Change (IPCC). Cambridge, New York. Available online at http://www.ipcc.ch/publications_and_data/publications_ipcc_fourth_assessment_report_wg3_report_mitigation_of_climate_change.htm.

IPCC (2014): Data Distribution Centre. Intergovernmental Panel on Climate Change (IPCC). Available online at http://www.ipcc-data.org/, checked on 7/24/2014.

Molero Cortés, J. (2006): Life Cycle Assessment (LCA) as a Decision Support Tool (DST) for the ecoproduction of olive oil. Task 3.3 Implementation of Life Cycle Inventory in Ribera Baja (Navarra, Spain). Fundación LEIA: Environment and energy unit. Córdoba, España.

Moller, J.; Boldrin, A.; Christensen, T. H. (2009): Anaerobic digestion and digestate use: accounting of greenhouse gases and global warming contribution. In *Waste Management & Research* 27 (8), pp. 813–824. DOI: 10.1177/0734242X09344876.

Mulder, K.; Hagens, N. J. (2008): Energy Return on Investment: Toward a Consistent Framework. In *AMBIO: A Journal of the Human Environment* 37 (2), pp. 74–79. DOI: 10.1579/0044-7447(2008)37[74:EROITA]2.0.CO;2.

Reinhold, J. (2008): Ein Vorschlag zur Ableitung der Stickstoffwirksamkeit organischer Dünger aus stofflicher Zusammensetzung und Humusreproduktionsleistung. Bioplan Dr. Reinhold und Dr. Müller GmbH. D - 14542 Werder.

Sengupta, D.; Mukherjee, R.; Sikdar, S. K. (2015): Moving to a decision point in sustainability analyses. In Jiří Jaromír Klemeš (Ed.): Assessing and Measuring Environmental Impact and Sustainability. Kidlington, Oxford, UK: Butterworth-Heinemann (Elsevier), pp. 87–129.

Signor, D.; Cerri, Carlos Eduardo Pellegrino (2013): Nitrous oxide emissions in agricultural soils: a review. In *Pesqui. Agropecu. Trop.* 43 (3), pp. 322–338. DOI: 10.1590/S1983-40632013000300014.

U.S. Department of Energy (2013): GREET Model. The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model. Version October 2013: Argonne National Laboratory. Available online at https://greet.es.anl.gov/, checked on 5/14/2014.

Wulf, S. (2002): Untersuchung der Emission direkt und indirekt klimawirksamer Spurengase (NH_3, N_2O und CH_4) während der Lagerung und nach der Ausbringung von Kofermentationsrückständen sowie Entwicklung von Verminderungsstrategien. (DBU-AZ 08912) Abschlussbericht. Edited by DBU. Institut für Technologie, Bundesforschungsanstalt für Landwirtschaft (FAL); Institut für Bodenkunde und Standortlehre, FG Bodenchemie, Universität; Institut für Landtechnik, Universität Bonn; Institut für Pflanzenernährung (IPE), Universität Bonn; Kuratorium für Technik und Bauwesen in der Landwirtschaft (KTBL).

Yoshida, H.; Christensen, T. H.; Scheutz, C. (2013): Life cycle assessment of sewage sludge management: a review. In *Waste management & research : the journal of the International Solid Wastes and Public Cleansing Association, ISWA* 31 (11), pp. 1083–1101. DOI: 10.1177/0734242X13504446.