CLEEN
Cluster for Energy and Environment

Conceptual level techno-economic assessment to produce biogas, lipids and fertilizers from microalgae

Subtask 6.1.3 Optimal use of algal biomass
CCSP Program WP 6

Marja Nappa, Eemeli Hytönen, Pertti Karinen, Mona Arnold

CLEEN
Cluster for Energy and Environment

Outline

- Background
- Approach for techno-economic evaluation
- Concept definitions
- Process and financial assumptions
- Results
- Conclusions

Background

- The study is carried out in the work package 6 of the Carbon Capture and Storage programme (CCSP)
- The aim of subtask 6.1.3 *Optimal Use of Algae* is to study feasibility of the utilisation options of algal biomass.
- The focus is on mass production of algal biomass for CO_2 capture. Selected large scale products are biogas, lipids and fertilizers.

CLEEN
Cluster for Energy and Environment

Approach for techno-economic evaluation

- Conceptual level
- Excel software (no simulation tool used)

- Process definitions for every concepts
  - Input data is gained from literature and from discussions with WP6 partners
- Mass and energy balances based on concept definitions
  - Electricity
  - Heat
  - CO_2
  - Algal biomass
  - Nutrients
  - Solvent, flocculants
  - Products
- Cost calculations
- Sensitivity analysis

Approach for techno-economic evaluation

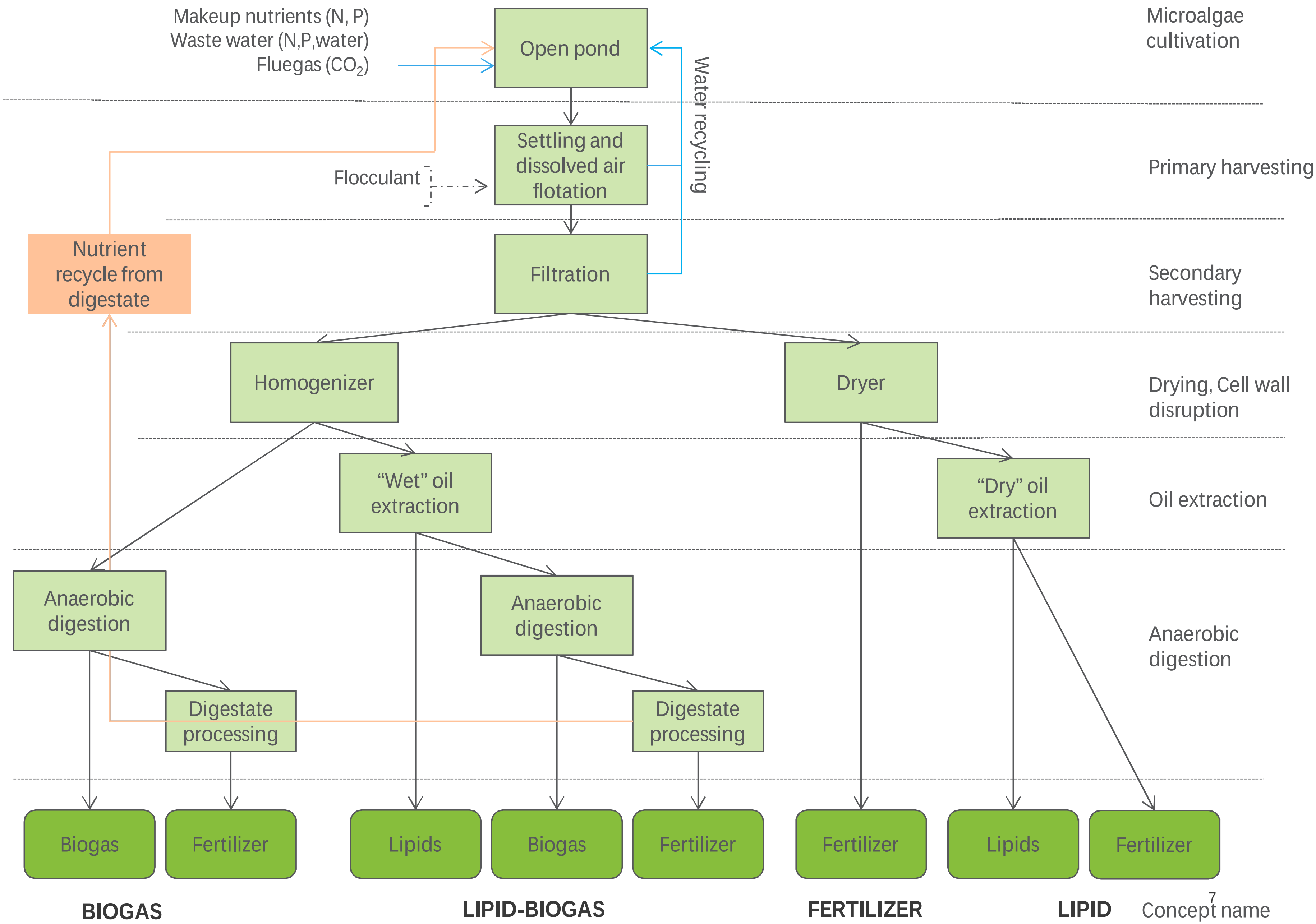
- Evaluated costs items
  - Variable costs
    - Based on mass and energy balances and prices
  - Fixed costs
    - Operating labour
      - 25 ha / person
    - Maintenance 2 % of total capital investment
    - Administration and non-operating labour 1.5 x operating labour
    - Other 1 % of total capital investment
    - Capital charge

- Capital expenses
  - Rough estimate for capital costs have been evaluated based Beneman & Oswald 1996 work. Unit operations which are not included on that work are estimated based on NREL 2012 and Delrue et al. 2012. All prices have been updated to 2014 euros.
  - Annual capital charge is estimated to be 10 % of total capital investment.

Concept definitions

- Four different concepts are evaluated in this study based on product portfolio.
  - Name of the concepts tells the main product(s)
- Concepts
  1. BIOGAS
     - Biogas production
     - Fertilizer production from residual
  2. LIPID-BIOGAS
     - Lipid separation before biogas production
     - Fertilizer production from residual
  3. LIPID
     - Lipid production
     - Fertilizer production from residual biomass
  4. FERTILIZER
     - Fertilizer production

Concept definitions



Concept definitions

- Every concept include two scenarios. Different lipid levels (10% and 30%) are evaluated in scenarios.
- Lipid rich scenario contains less proteins than other scenario, and respectively less nitrogen and phosphorous.

Table. Alga compositions in scenarios.

	scenario 1	scenario 2
Lipid	30 %	10 %
Proteins	35 %	45 %
Carbohydrates	35 %	45 %
N *	5.0 %	8.7 %
P *	0.8 %	1.3 %

* Typical amounts

Composition of three main components in algae.
(Kwietniewska & Tys, 2014)

Proteins	$C_5H_7NO_2$
Lipids	$C_{57}H_{10}4O_6$
Carbohydrates	$(C_6H_{10}O_5)n$

CLEEN
Cluster for Energy and Environment

Assumptions

Productivity and capacity

- Productivity
  - Productivity assumption is seen one of the major contributor for large variability in results of techno-economic assessments in literature. Huge variation in lipid growth assumptions can be found from different techno-economic and environmental assessments (5.5 to 110 t/ha/year) (Quinn & Davis 2014).
  - Realistic, but still optimistic value for biomass productivity **25 g/m^2/day** is selected in this study. Value corresponds 9 to 27 t/ha/year lipids (lipid content 10% or 30% respectively). **Same biomass productivity is used with both lipid contents.**
- Capacity and CO_2 usage
  - A coal fired power plant which generates 500 MW (size of Meri-Pori power plant in Finland) electric power produces around 360 t/h CO_2. This amount of CO_2 (75% efficiency) serves roughly 13 000 ha microalgae cultivation in open ponds with productivity of 25 g/m^2/day.
  - The selected capacity in the study is **4000 ha** corresponding 110 t/h CO_2 in fluegas which is available from 150 MW power plant.

Assumptions

- Carbon capture by algae
  - CO_2 from nearby power plant fluegas
    - input concentration of 12.5%.
    - 75 % of CO_2 in fluegas is consumed by algae, rest is loosed in atmosphere.
  - Need of CO_2 is estimated based on algae main components and their composition (see table below).
  - To provide CO_2 to the ponds
    - Sumps with the depth of 1 m are located in ponds and CO_2 spargers in the bottom of sumps provides fine bubbles for efficient CO_2 transfer. (Lundquist et al. 2010)
    - The other option was technology suggested by WP 6.1.1 (bubble-type-absorption column), however sufficient data for calculations was not found.

Alga composition			Carbon capture kg CO2 / kg			
Lipids	Carbo-hydrates	Protein	Lipids	Carbo-hydrates	Protein	Alga
10 %	45 %	45 %	2.83	1.63	1.95	**1.89**
30 %	35 %	35 %	2.83	1.63	1.95	**2.10**

CLEEN
Cluster for Energy and Environment

Assumptions

- Municipal waste water used as a water and nutrient source
  - Typical amounts for N and P used: N 35 mg/L, P 7.5 mg/L (Lundquist et al. 2010).
- Carbon balance may be affected also by organic carbon in waste water.
  - Waste water as an additional carbon source, light as an energy source. (photoheterotrophic)
  - The amount of carbon is estimated based on biological oxygen demand (BOD) using BOD/TOC ratio 1 (TOC: total organic carbon) (Metcalf & Eddy 2003). BOD 200mg/l is adopted from Lundquist et al. (2010).
- Additional nutrients are purchased when necessary: urea and diammonium phosphate (DAP).
- Zero price/credit for make-up waste water as well for outgoing waste water from process is assumed.
- 95 % of process water is circulated back to cultivation, 5 % is waste water from the system

Technology and assumptions
Cultivation

- Open raceway ponds are selected as cultivation architecture as they are found at least two times more economic than photobioreactors (Quinn & Davis 2014)
- 95 % of process water is circulated back to cultivation, 5 % is waste water from the system
- Open pond depth 0.2 m
- Evaporation in ponds 0.06 cm/day (NREL 2012)

Technology and assumptions
Harvesting

- Selected harvesting method for primary harvesting contains settling and dissolved air flotation (DAF). For secondary harvesting filter press is selected.
- The energy consumption for harvesting was hard to estimate as the data in literature is difficult compare because of different units and lack of data such as initial concentration. Also the range of given data is large.
- For settling and DAF energy consumption of 0.1 kWh/kg dry algae is used.
- For filtration energy consumption 0.5 kWh/m3 (Wiley et al. 2011) is selected, this corresponds 0.01 kWh/kg dry algae.

Table. Literature data for primary harvesting

unit operation	Power consumption from literature		Dry solids in the begining	Power consumption dry weight basis (kW / kg)	Adopted from
DAF	1.5 - 20	kWh/m3	-	-	Wiley 2011
DAF	0.07 -1.25	kWh/kg dry algae	0.001–0.5%	0.07 -1.25	Udom et al. 2013
DAF	0.3	kWh/m3	0.4-1.2 %	0.025-0.075	Zamalloa et al. 2011, Viitasaari 1995
SWAT*	0.08	kWh/m3	0.02-0.06%	0.13-0.4	http://www.asio.cz/en/operation-swat-286840
*includes both flocculation and filtration					

CLEEN
Cluster for Energy and Environment

Technology and assumptions

Cell disruption and extraction

- The study contains cell disruption for enhance lipid extraction process and biogas production. For cell disruption homogenization is selected.
- Hexane extraction is used for both dry and wet oil separation (Lundquist et al 2010 and NREL 2012)
  - Extraction to solvent ratio, wet: 5 (solvent / dry biomass, NREL 2012)
  - Extraction to solvent ratio, dry: 3 (solvent / dry solids)
  - Solvent loss of circulation 0.3 %
  - Heat consumption is based on evaporation heat of solvent
- Thermal drying is applied for both algae biomass and digestate drying with thermal efficiency of 85%.

Assumptions
Anaerobic digestion

- Methane yield in anaerobic digestion (AD) is based on theoretical yield. Theoretical methane potential depends on chemical composition of the biomass to be digested, yield is calculated from equation below (Sialve et al. 2009; Kwietniewska & Tys 2014).
- Dissimilation of organic matter 70 %.

$$C_aH_bO_cN_d + \left(\frac{4a-b-2c+3d}{4}\right) H_2O \rightarrow \left(\frac{4a+b-2c-3d}{8}\right) CH_4 + \left(\frac{4a-b+2c+3d}{8}\right) CO_2 + d\ NH_3$$

Methane yield in anaerobic digestion				Biogas CH4 fraction
	lipid	1.014	l CH4 / g-VS	70 %
	rest algae	0.456	l CH4 / g-VS	50 %
	water consumption	0.4g / g VS		

CLEEN
Cluster for Energy and Environment

Assumptions

specific power/energy consumptions and yields

Unit operations			Estimate reference
Cultivation (Mixing)	1.875	kW/ha	NREL 2012; Lundquist et al. 2010
CO_2 distribution	1	kW/ha	Lundquist et al. 2010
Setling & DAF	0.1	kWh/m3	Udom et al. 2013; Zamalloa et al. 2011
Filtration	0.5	kWh/m3	Wiley 2011
Thermal drying	0.032	kW/kg evaporated	
Extraction, dry	0.012	kWh/kg dry biomass	Lundquist et al. 2010
Extraction, wet	0.276	kWh/kg dry biomass	NREL 2012
Pumping	0.045	kWh/m3	approximated from NREL 2012
Anaerobic digestion, electric	0.085	kWh/kg-TS	NREL 2012; Delrue 2012
Anaerobic digestion, heat	0.22	kWh/kg-TS	NREL 2012

Yields in unit processes		
	%	Reference / comments
Primary harvesting	96	NREL 2012, harvesting tot 95 %
Secondary harvesting	99	NREL 2012, harvesting tot 95 %
Drying of algae cell mass	99	
Separation of algae oil from cell mass	85.5	NREL 2012, Disruption 90 % and extraction 95 %
Dissimilation of organic matter in AD	70	Lundquist et al. 2010
Dewatering of solid digestate	97	
Drying of solid digestate	99	

CLEEN
Cluster for Energy and Environment

Prices

- Products
  - Lipids are assumed 600 €/t
  - Biogas (CH_4 basis) 40 €/MWh
  - Biofertilizer price estimated based on its nitrogen content and urea price. 730 € / t nitrogen. Similar nitrogen basis prise estimates can be found in literature (730 €/t from Delrue et al 2012; 500€/t from Lundquist et al. 2010)
- Electricity 45 €/MWh
- Steam price 35 €/MWh
- Flocculation chemicals 10 000 €/t (Chitosan, alibaba.com)
- Solvent (hexane) 1 000 €/t (Alibaba.com)
- Urea 260 €/t
- DAP 390 €/t

Results – mass balance

- Dry algal biomass production is 316 800 t/year for all concepts.
- The capture of CO_2 is 700 000 t/year at maximum, which is gained from 7,5Mt fluegas (containing 12.5 % CO_2) flow.
- Makeup waste water amount depends slightly on concept being in average 24 Mt/year. Makeup waste water is the water which is used to replace evaporated water and the water removed from system to avoid accumulation of harmful components.
- Nutrients N and P to cultivation are circulated from liquid digestate in anaerobic digestion and also supplied by makeup wastewater, however additional purchased nutrients are needed, urea (11-52 kt/year) and DAP (4-18 kt/year) are used. The amount of them depends on concept and scenario, they are much lower in concepts with biogas production than in other concepts.
- Total flow in cultivation is 42 700 m3/h, which is more than river Aura in Finland. Evaporation is 1000 m3/h and waste water removed 2000 m3/h (17 Mt/year) depending slightly on concept.

Results – mass balance

- Biogas is produced in two concepts, lipids in two concepts and fertilizer is produced in all concepts either from whole biomass, or from lipid extraction residual or from solid digestate.

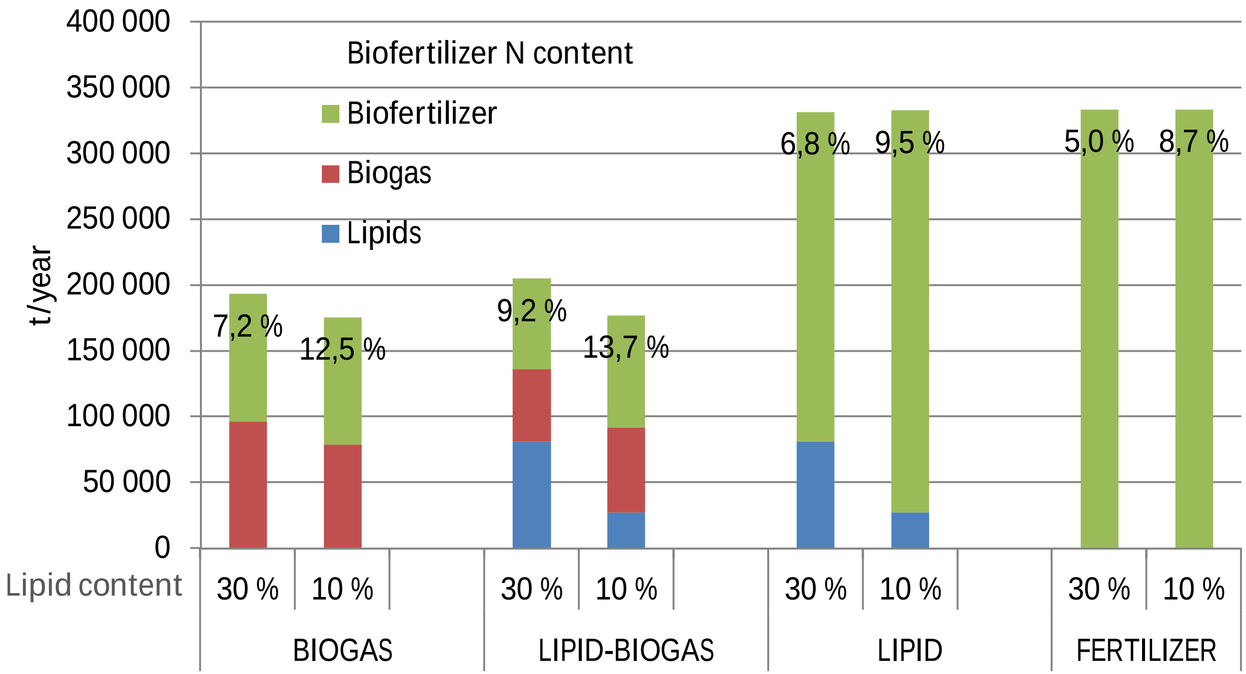


Figure. Biogas, lipid and fertilizer production. Nitrogen content of fertilizer shown as a number.

Results – CO_2 fixation potential

- CO_2 fixation capacity depends on product.
  - Biogas production releases CO_2, thus lowering the CO_2 fixation capacity compared to other concepts.
  - The amount depends on biogas production strategy. 20-30% of captured CO_2 is released in anaerobic.
- CO_2 fixation capacity depends on scenario (i.e. lipid content)
  - 10-18 % difference CO_2 capture amount between scenarios.
- CO_2 emissions from electricity and heat production were not evaluated as they were not scope of this study
- In addition to CO_2 in fluegas there was C available in make-up waste water. This has a minor effect on carbon balance as over 99% of carbon comes from fluegas.

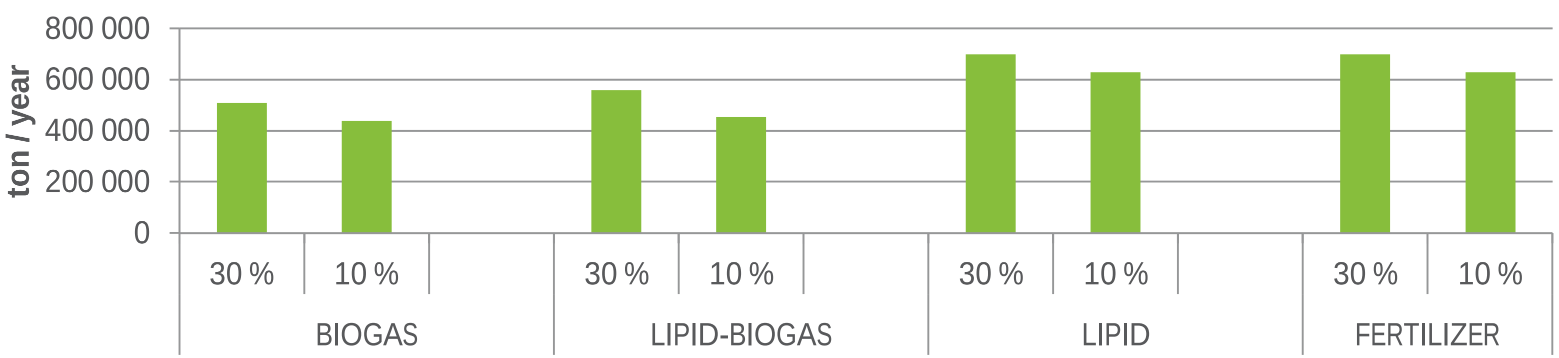
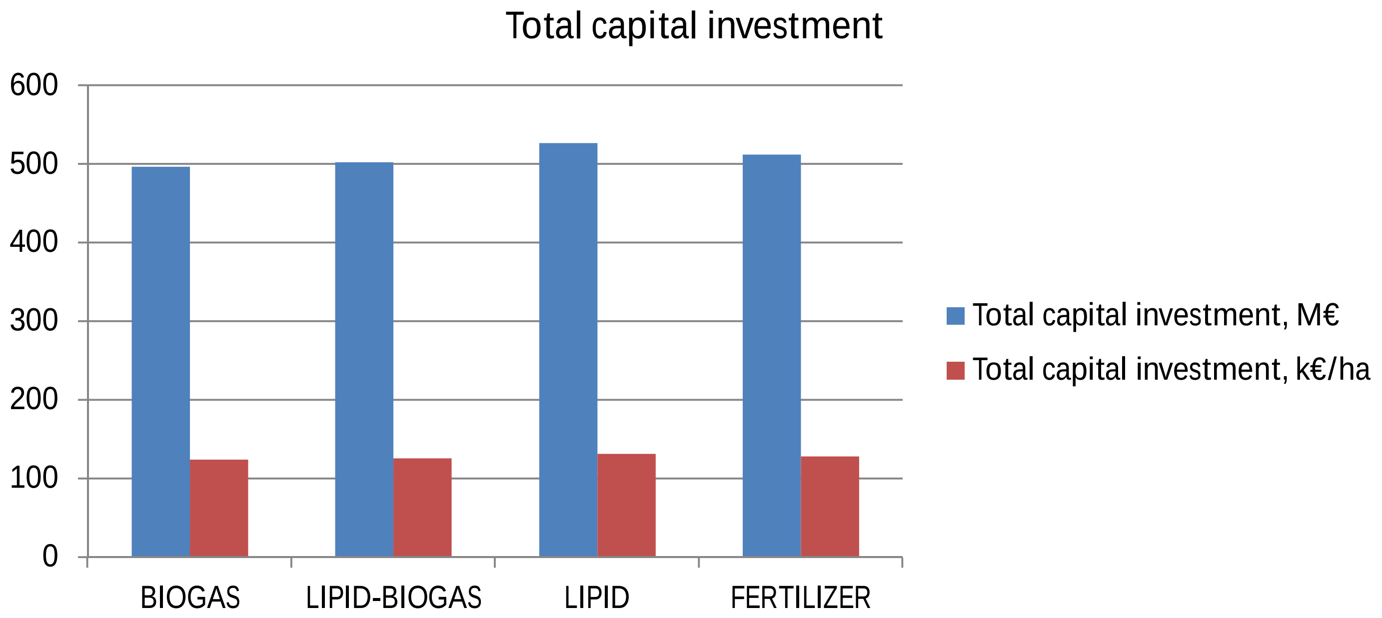


Figure. CO_2 fixation potential in concepts.

CLEEN
Cluster for Energy and Environment

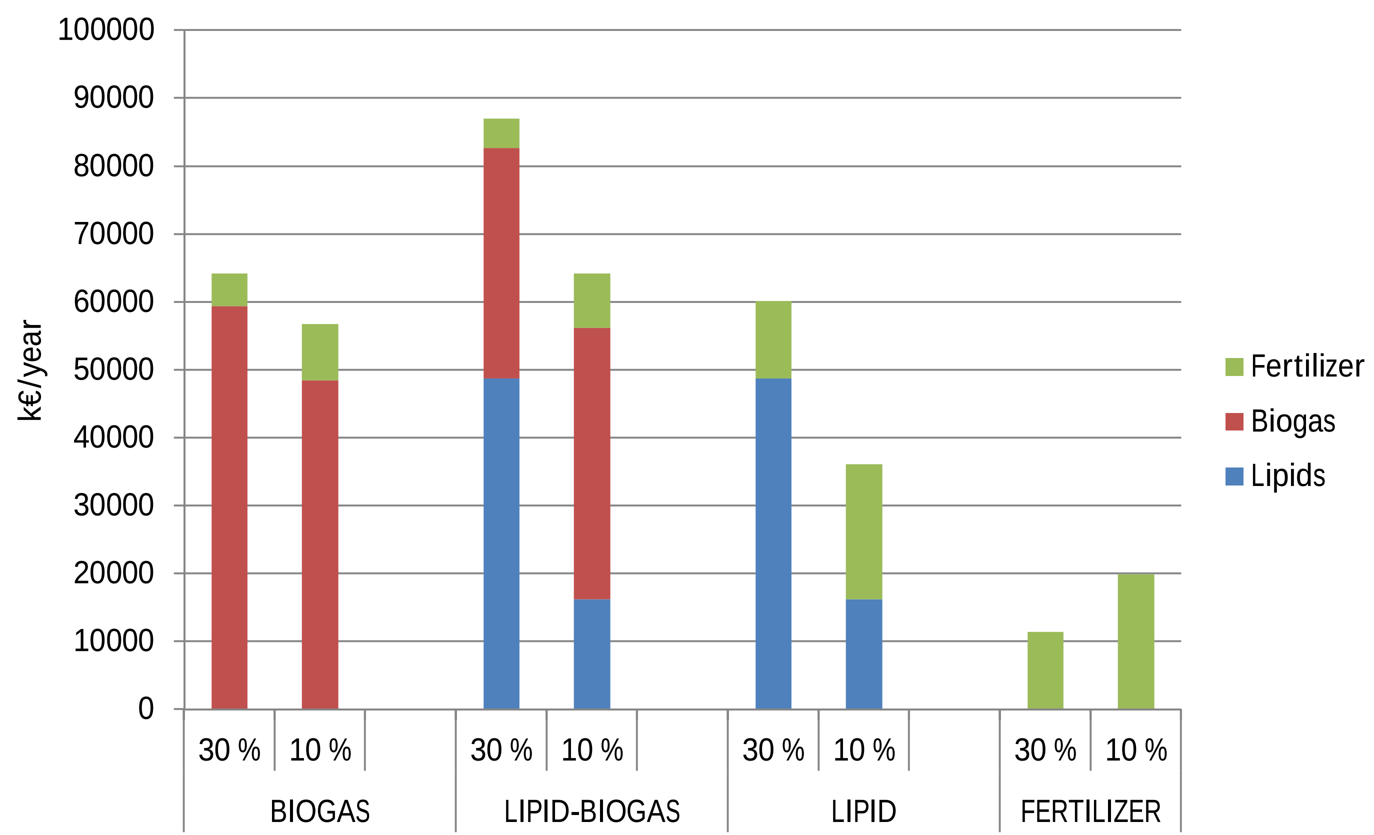
Capital expenses

- Estimates for capital expenses are around 124 to 132 k€/ha for all concepts



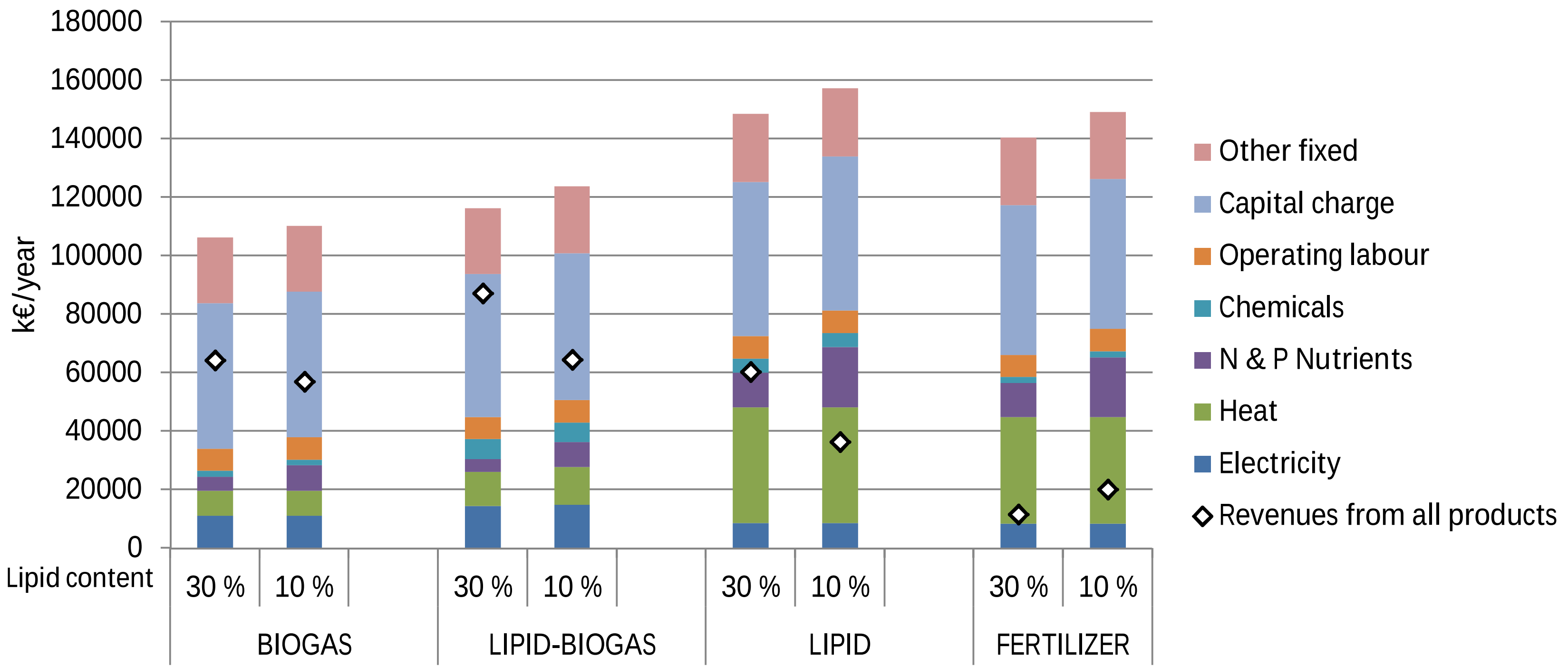
Results - Revenues

- Co-production of lipids and biofuels gives the highest revenues.
- Revenues from fertilizer are low compared to revenues from biofuel products.



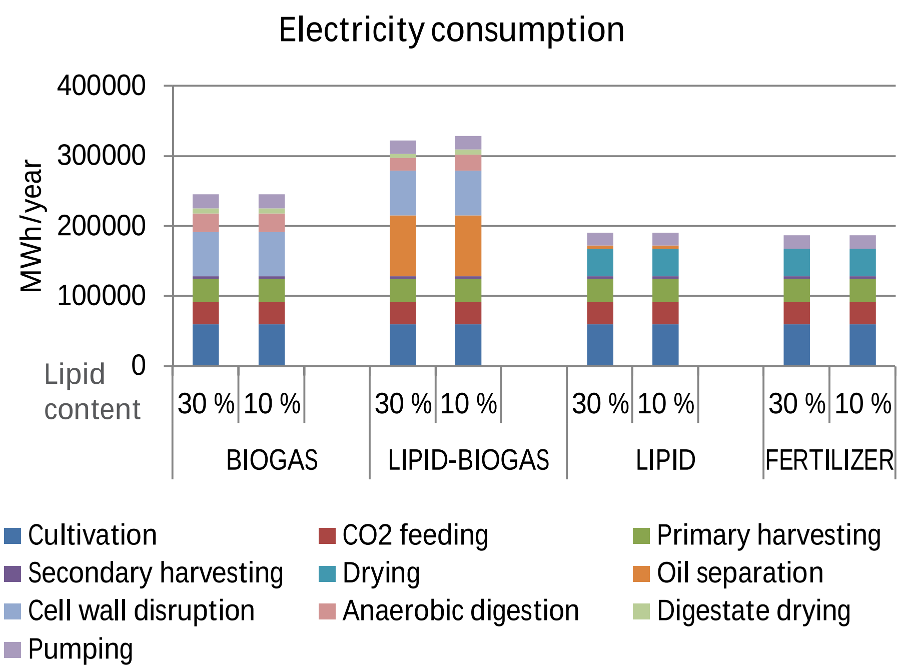
Results – costs and revenues

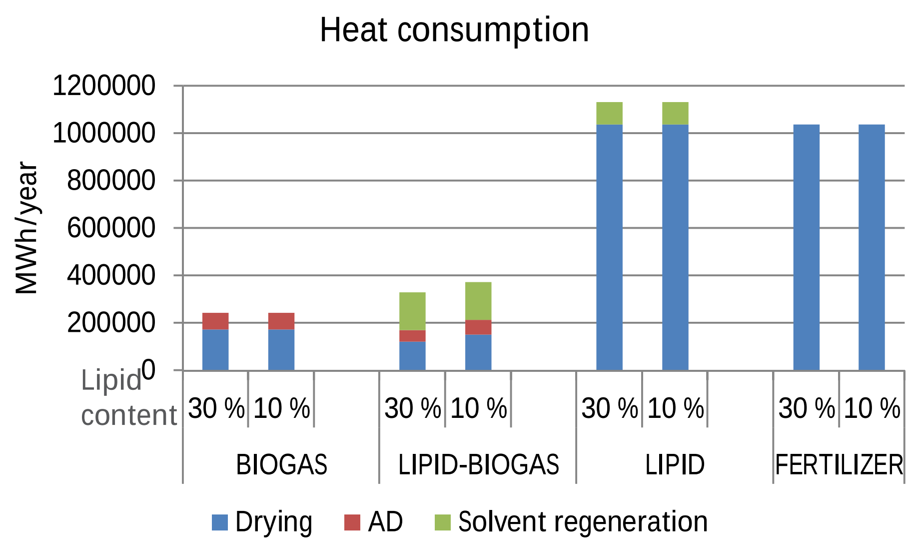
- Profit in all concepts is negative
- Capital charge and other fixed costs are large in all concepts.
  - 10-year plant life was assumed, for longer plant life the annual charge decreases.
- Other major cost contributors are heat, electricity and nutrients.
  - The share of heat is high in concepts with algal biomass drying.
  - The share of nutrients is lower in concepts with biogas production than in other concepts.



Results - energy consumption

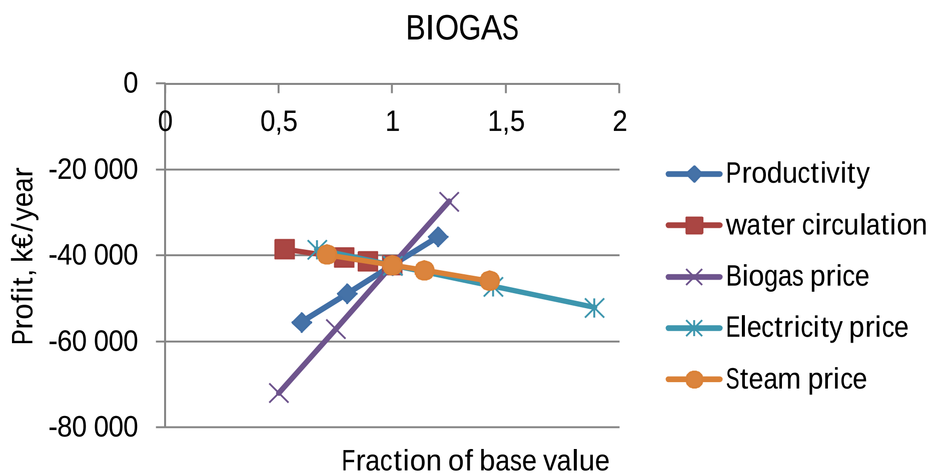
- Heat
  - Drying energy consumption is big in lipid and fertilizer concepts, where algal biomass is dried.
- Electricity
  - The selected cell wall disruption and wet oil separation technologies have high electricity consumption

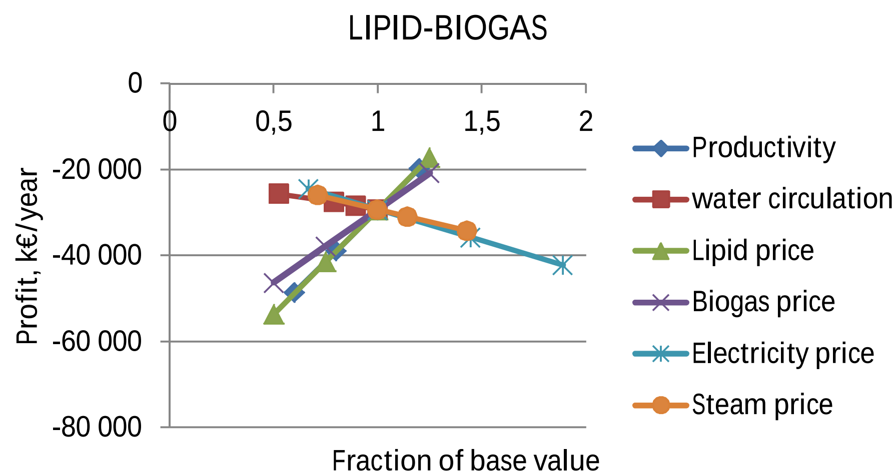


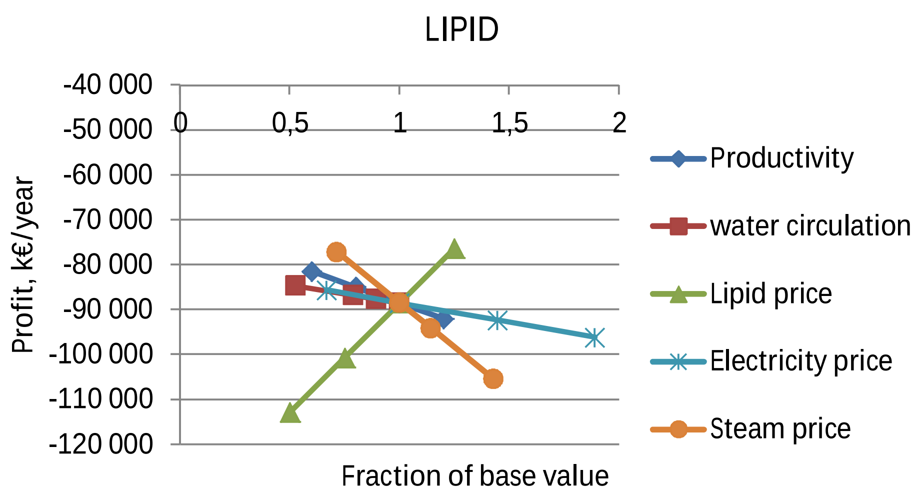


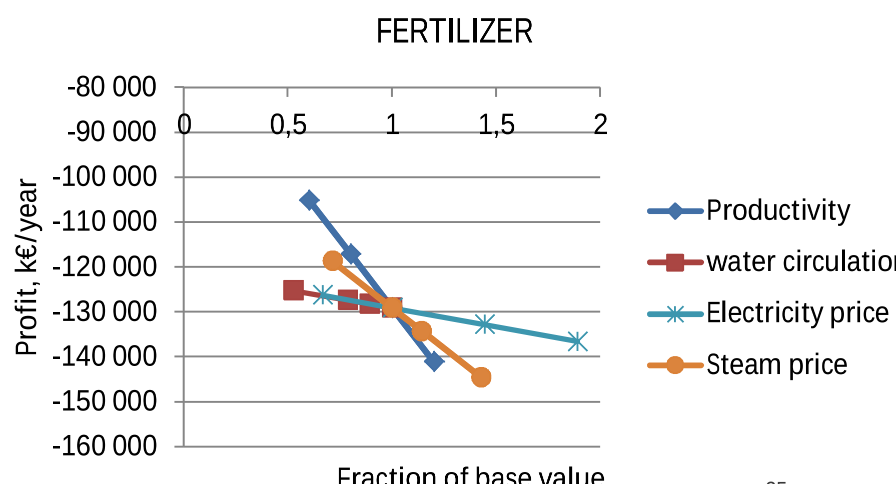
Sensitivity analysis

- Sensitivity analysis is performed for scenarios with lipid content 30%
- Profit is most sensitive to product prices and productivity.
- Higher productivity increases profit in BIOGAS and LIPID-BIOGAS concepts. In LIPID and FERTILZERR concepts it decreases profit.









CLEEN
Cluster for Energy and Environment

Conclusions

- Capital charge is the major cost contributor in all concepts.
- Energy cost is high in concepts where algal biomass is dried.
- Nutrient recycling from biogas production lowers significantly the purchased nutrient need.
- The most promising concept is LIPID-BIOGAS
- High lipid content is beneficial in biogas and lipid production. However, it was assumed that productivity is same for two scenarios and does not depend on lipid content.
- Profit is most sensitive to product prices, productivity and plant life time.

CLEEN
Cluster for Energy and Environment

References

- ANL; NREL; PNNL, Renewable Diesel from Algal Lipids: An Integrated Baseline for Cost, Emissions, and Resource Potential from a Harmonized Model, ANL/ESD/12-4; NREL/TP-5100-55431; PNNL-21437. Argonne, IL: Argonne National Laboratory; Golden, CO: National Renewable Energy Laboratory; Richland, WA: Pacific Northwest National Laboratory 2012.
- Delrue, F., Setier P.-A., Sahut, C., Cournac, L., Roubaud, A. G. & Froment, A.-K., An economic, sustainability, and energetic model of biodiesel production from microalgae, *Bioresour Technol* **111** (2012) 191–200.
- Kwietniewska, N. & Tys, J., Process characteristics, inhibition factors and methane yields of anaerobic digestion process, with particular focus on microalgal biomass fermentation, *Renewable Sustainable Energy Rev* **34** (2014) 491–500.
- Lundquist, T.J., I.C. Woertz, Quinn, N.W.T, Benemann, J.R. A Realistic Technology and Engineering Assessment of Algae Biofuel Production, Energy Biosciences Institute, University of California 2010
- Metcalf & Eddy Inc., *Wastewater engineering: treatment and reuse*, 4th ed., McGraw-Hill 2003, p. 97.
- Moody, J.W., Mcginty, C.M., Quinn, J.C., Global evaluation of biofuel potential from microalgae. Proceedings of the National Academy of Sciences 2014.
- Quinn, J.C. & Davis, R. The potentials and challenges of algae based biofuels: A review of the techno-economic, life cycle, and resource assessment modeling. Bioresour. Technol. (2014), available at http://dx.doi.org/10.1016/j.biortech.2014.10.075
- Sialve, B. & Bernet, N., Bernard, O, Anaerobic digestion of microalgae as a necessary step to make microalgal biodiesel sustainable, *Biotechnol. Adv.* **27** (2009) 409-416.
- Udom, I., Zaribaf, B.H., Halfhide, T., Gillie, B., Dalrymple, O., Zhang, Q. & Ergas, S.J. Harvesting microalgae grown on wastewater, *Bioresour.Technol.* 139 (2013) 101-106.
- Uduman, N., Qi, Y. Qi, Danquah, M.K., Forde,G.M., and Hoadley, A., Dewatering of microalgal cultures: A major bottleneck to algae-based fuels, *J. Renewable Sustainable Energy* **2** (2010) .
- Uggetti, E., Sialve, B., Trably, E. & Steyer J, Integrating microalgae production with anaerobic digestion: a biorefinery approach, *Biofuels, Bioprod. Bioref.* **8** (2014) 516–529.
- Ward, A.J., Lewis, D.M., Green, F.B., Anaerobic digestion of algae biomass: A review, Algal Research 5 (2014) pp.204–214.
- Weyer, K.M., Bush, D.R., Darzins, A., Willson, B.D, Theoretical maximum algal oil production, *Bioenergy Res.* ***3*** (2009) 204–213.
- Wiley, P.E., Campbell, J.E., McKuin, B. Production of Biodiesel and Biogas from Algae: A Review of Process Train Options. *Water Environ. Res.* **83** (2011) 326-338.
- Zamalloa, C., Vulsteke, E., Albrect, J., Verstraete, W. The techno-economic potential of renewable energy through the anaerobic digestion of microalgae. *Bioresour Technol.* **102** (2011) 1149–1158.