Overview of SMORP project and main results

F. Romagnoli[1], B. Ievina[1], M. Dzikēvičs[1], Maksims Feofilovs[1]

[1] Institute of Energy Systems and Environment, RTU (Latvia)

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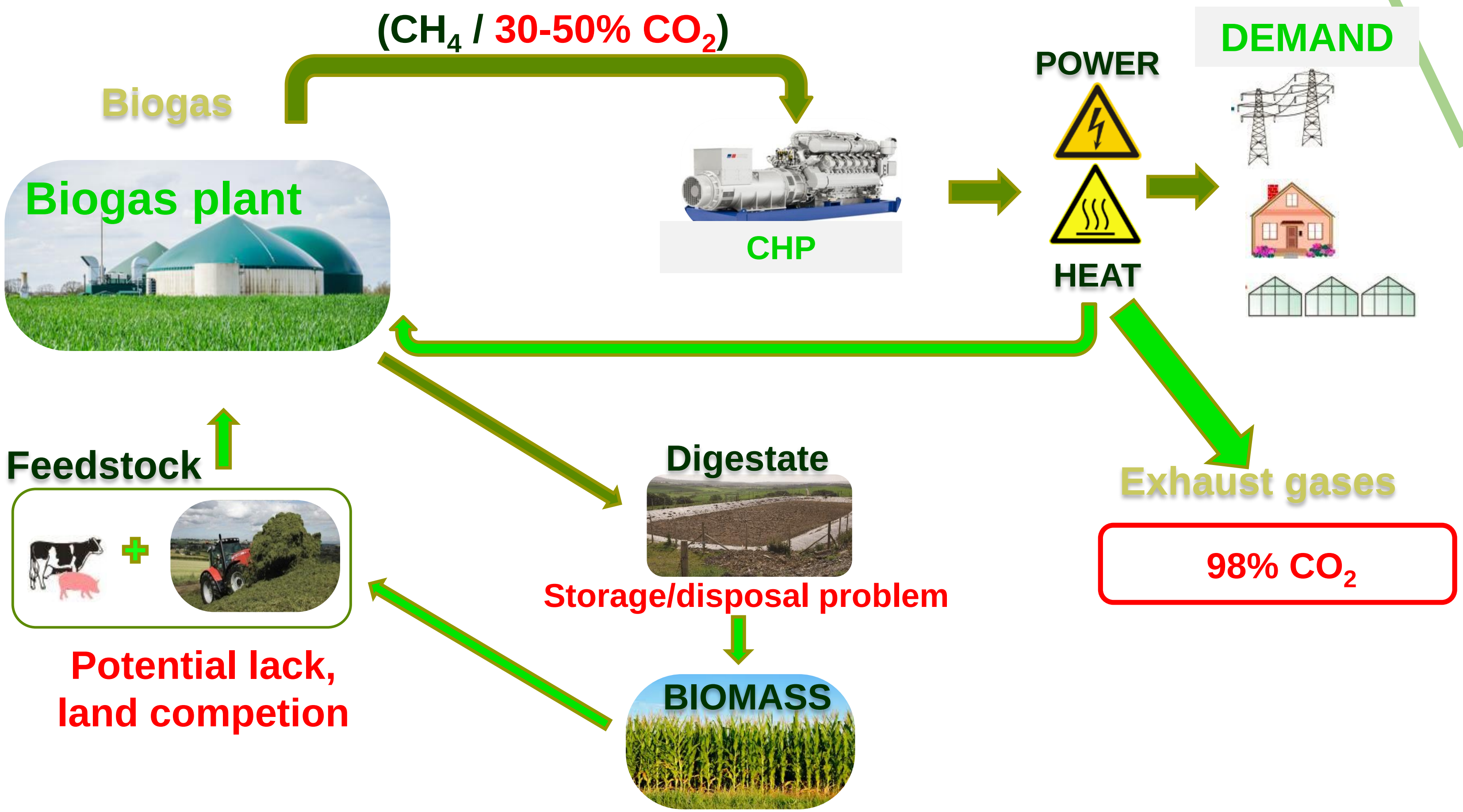
Background and topicalities

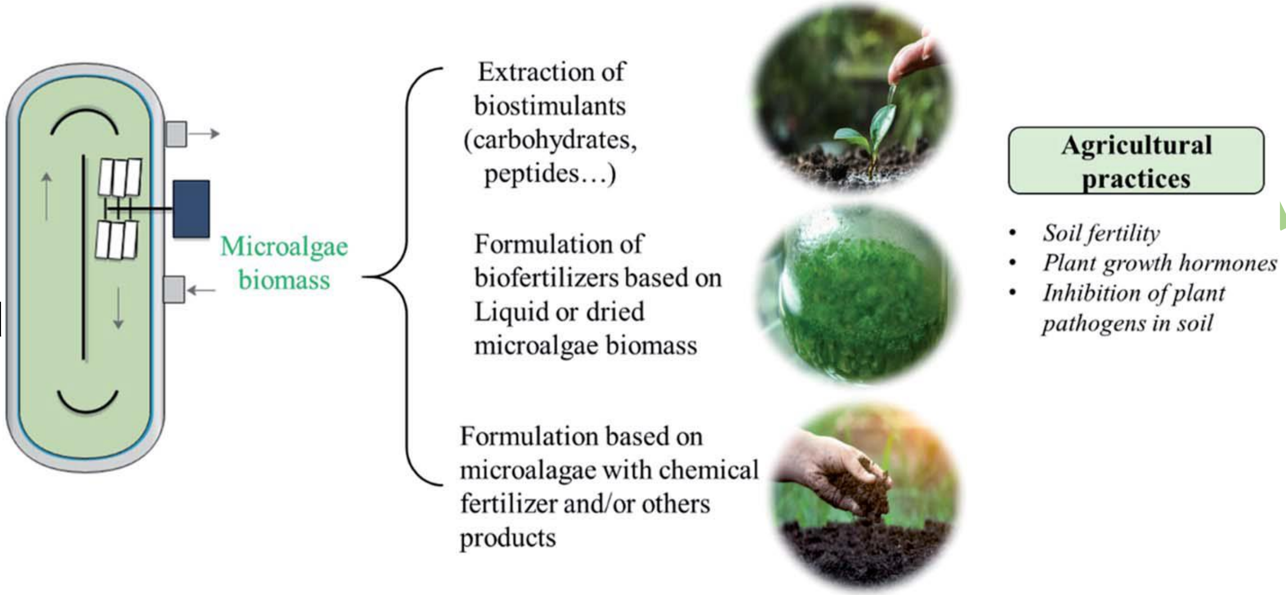
Restriction on nutrient that can be returned to land according to:

- EC Nitrates Directive (91/676/EEC)
- Nitrate Vulnerable Zone (NVZ)
- Nitrates and Phosphates land overloads are now restricted



Why microalgae in this context?

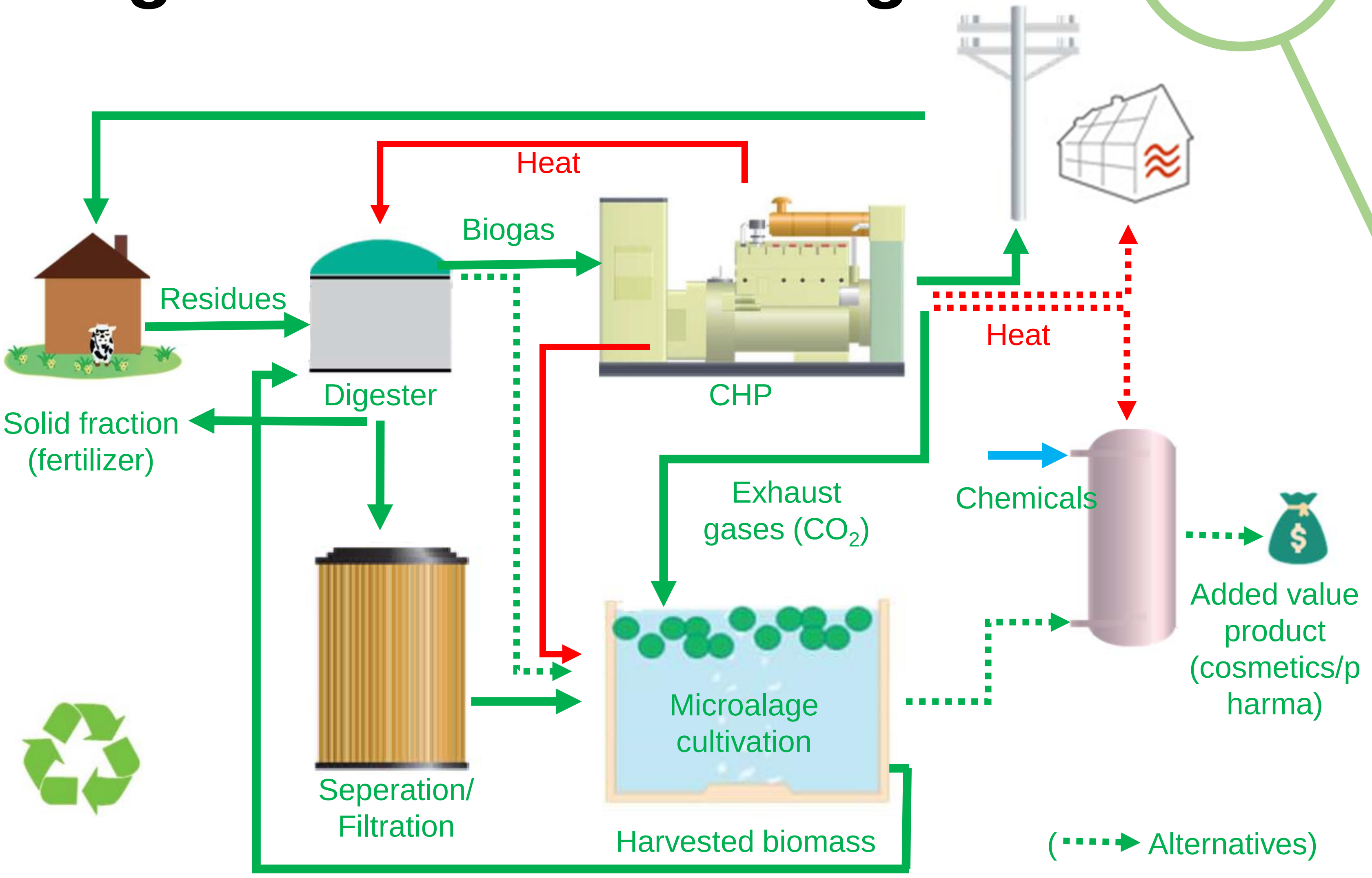
- Overall environmental benefit to **remove macropollutants and nutrients from different wastewater treatment systems** (e.g. biogas digestate)
- Beneficial interface for treatment of exhaust gases and flue gas emissions from biogas plant due to:
  - **High CO_2 rate fixation**
  - **Adaptability of growing under an high level of CO_2**
- Opportunity for a flexible and **viable circular economy solutions implementing biorefinery concept** (i.e. value added products and biofuels)
- **Higher production rate** compared to the terrestrial biomass (5-10 times faster)



Source: Doha Elalami e al., 2021 Anaerobic digestion and agronomic applications of microalgae for its sustainable valorization.

Close-loop with digestate and microalgae

- Liquid digestate as culture medium
- CO_2 recirculatation
- Microalgae digestate as fertilizer



State-of-art of microalgae growing technology

FACTORS	OPEN PONDS	PHOTOBIOREACTORS
Space requirement	High	Low
Evaporation loss	High	Low
CO_2 absorption efficiency	Low	High
Maintenance	Easy	Difficult
Risk of contamination	High	Low
Biomass quality	Variable	Reproducible (constant)
Energy input for mixing	Low	Medium/High
Operation Cost	Batch / Continuous	Batch / Continuous
Setup and capital cost	Low	High
Effect of light intensity	Depending on depth	More homogenous

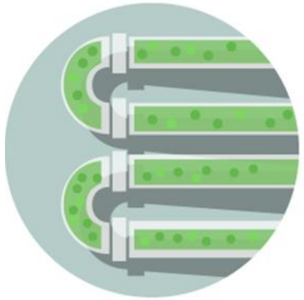
OPPORTUNITY FOR A "HYBRID" OPTIMIZED SYSTEM

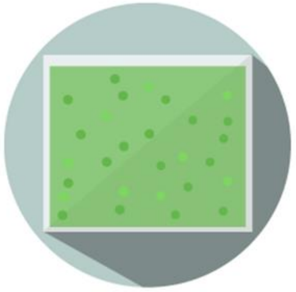
OPEN PONDS


cascade


conventional

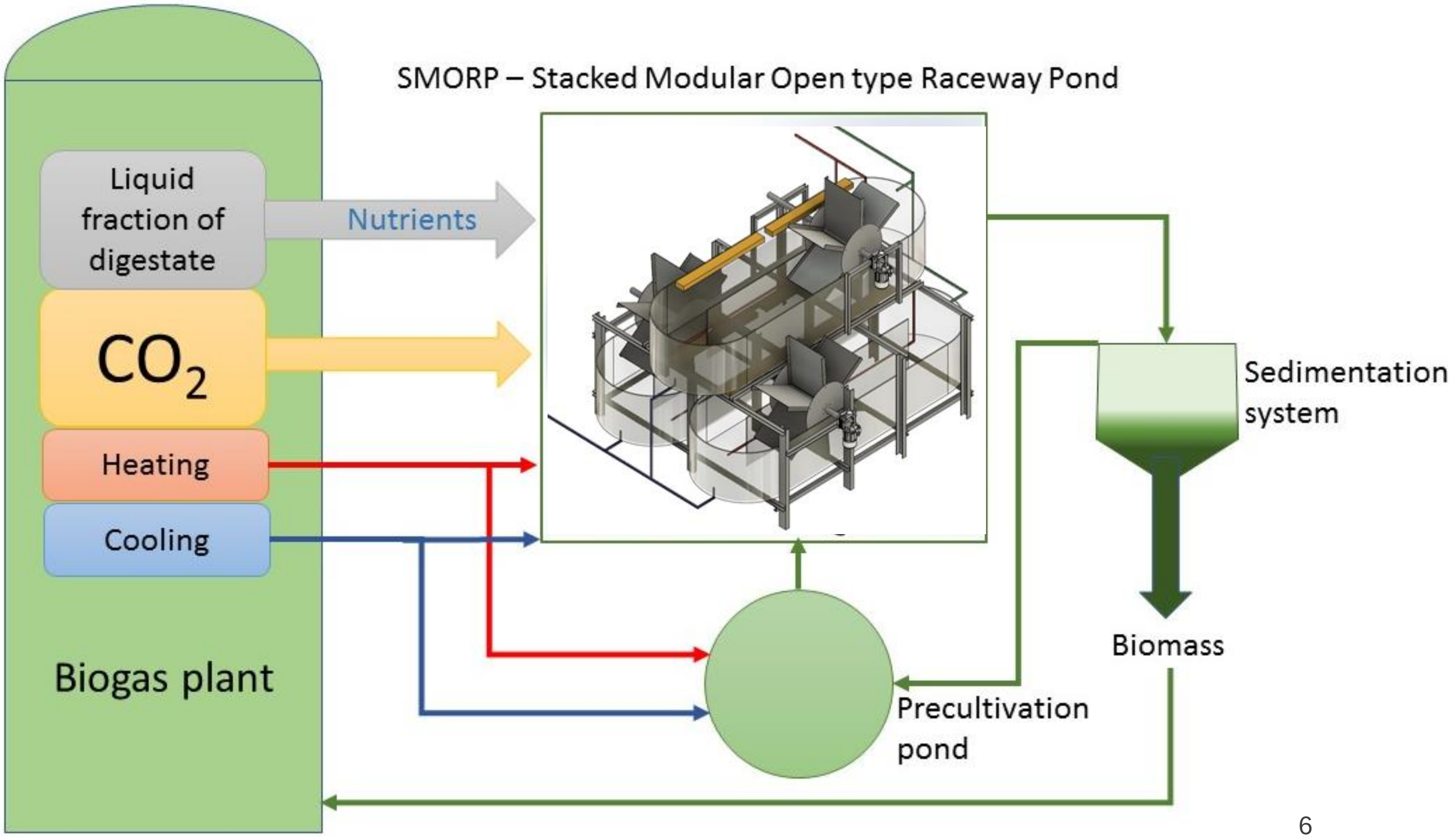
PHOTOBIOREACTORS (CLOSED SYSTEM)


tubolar


flat panel

Modular staked open ponds for microalgae growing coupled with biogas plant (SMORP)

- Solution for the digestate and nutrient recicurlation
- Possibility to recover up to 25% CO_2
- Implementation of hybrid solution between open and close system
- Reduced area respect conventional open
- Higher biomass per unit of growing media (effect from transparent material and LED lightning system)



Technological and reactor designs

Single pond dimensions:

- ○ L = 3m; W = 1m; H=0.5 m
- ○ A= 3.6 m^2

Type of material:

- ○ Acrylic

Type of microalgae:

- ○ *Chlorella sorokiniana* (implemented in the test)

Installation:

- ○ in a real Latvian biogas plant (Agrolecava)

Research problem

Best microalgae species ???

Sun light

Excess CO_2

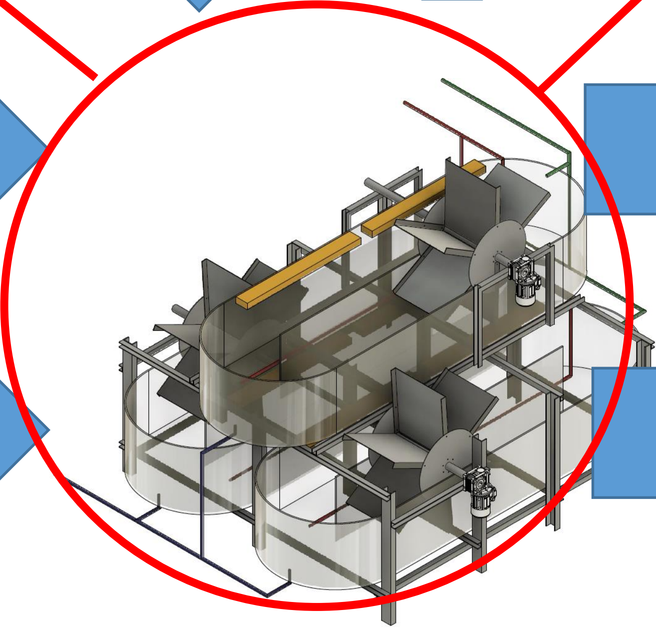
Optimum design ???
- Size (volume, area)
- Type of microalgae strain

Nutrient source (i.e. centrate)

Liters per batch/day?

CO_2 (i.e. flue gases)

Kg per hour?



Algal biomass

Productivity [kg/d] ???

Treated Water

Optimum operating conditions ????

Research method: tools and approaches

Growth empirical modelling

- Excel and System Dynamics models

Laboratory tests

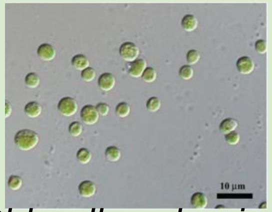
- Type of microalgae strain (*Chlorella vulgaris, Chlorella sorokiniana, Chlamydomonas reinhardtii*)
- Growing parameters - i.e. light intensity and types (blue/red vs full spectrum), temperature
- Nutrient (i.e. effect of the use of digestate and dilution)
- CO_2 effects on growing
- Biomethane Potential test

Optimization of SMORP pilot

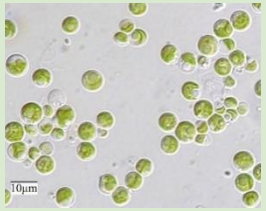
- Pilot test and validation of the empirical model

Sustainability assessment

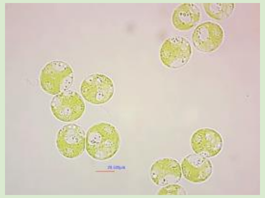
- Life Cycle Sustainability Assessment including E-LCA, LCC and S-LCA



Chlorella vulgaris



Chlorella sorokiniana



Chlamydomonas reinhardtii

Microalgae growth kinetics

- **Monod-Haldane (effects of substrate change intensity on growth rate)**

$$\mu = \mu_{max} \frac{S}{k_s + S}$$

μ - specific growth rate, d^{-1} or hr^{-1}
μ_{max} - maximum specific growth rate, d^{-1} or hr^{-1}
S – concentration of the substrate, g/l
k_s – half saturation constant, g/l

- **Steele (effects of light intensity on growth rate)**

$$\mu = \mu_{max} \frac{I}{I_{opt}} e^{\left(1 - \frac{I}{I_{opt}}\right)}$$

I – light intensity, μmol m^{-2} s^{-1}
I_{opt} – optimal light intensity, μmol m^{-2} s^{-1}

- **Beer-Lambert (change of light intensity with depth)**

$$I_z = I_0 \, e^{-k_a \cdot Bt \cdot z}$$

I_z - local light intensity received by algal cells at z depth, μmol m^{-2} s^{-1}
z – depth, m
I_0 - light intensity at the external surface of the pond, μmol m^{-2} s^{-1}
k_a - biomass light absorption (extinction) coefficient, m^2 kg^{-1}

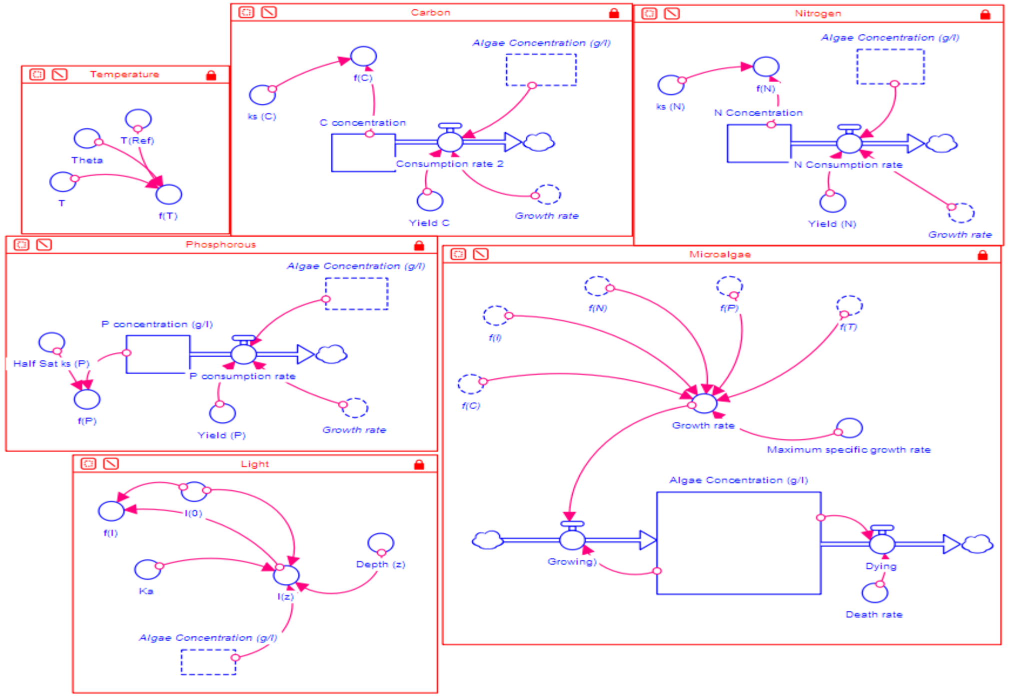
- **Biomass concentration over time:**

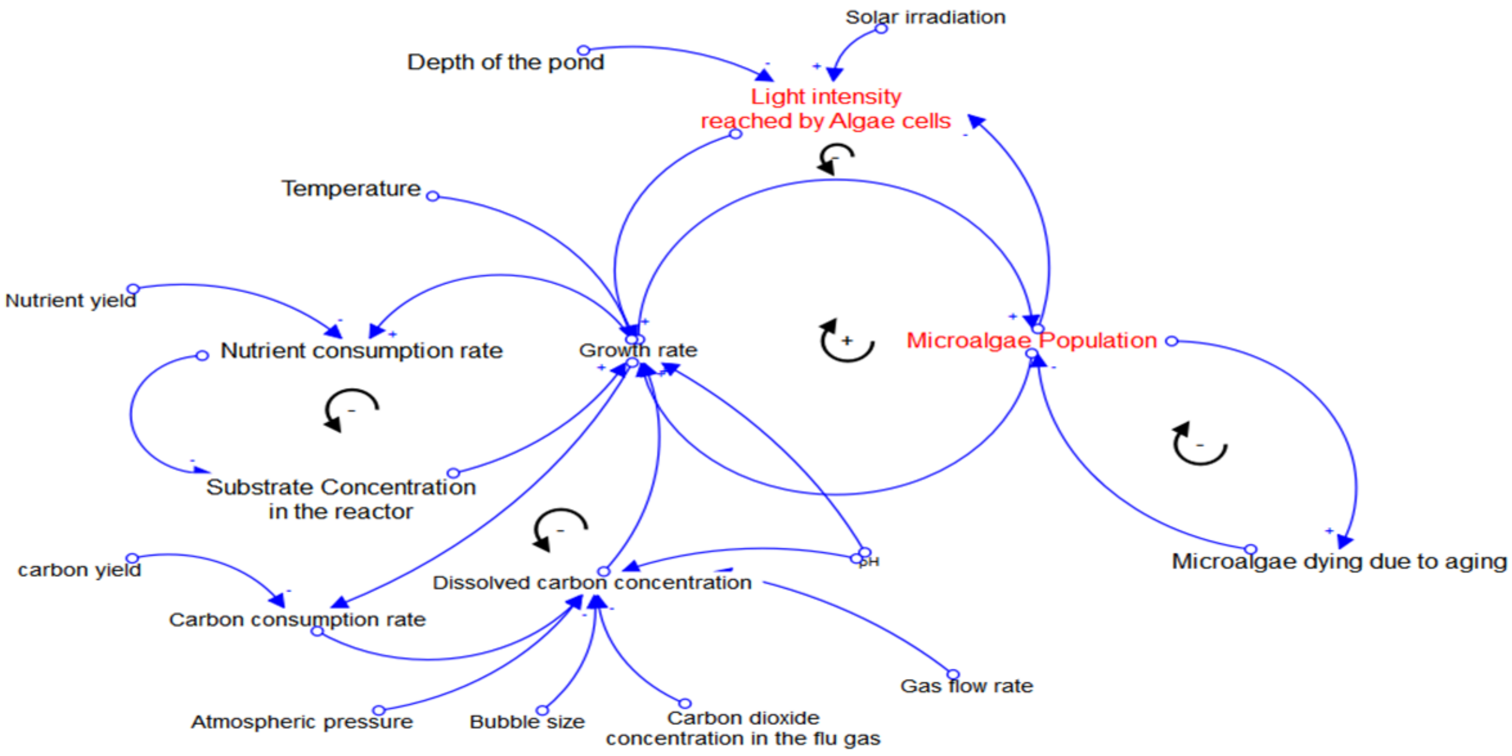
$$B_t = B_0 \cdot e^{\mu \cdot \Delta t}$$

B_0 – Biomass concentration at t=0, kg m^{-3}
B_t – Biomass concentration at t=t, kg m^{-3}, kg m^{-3}

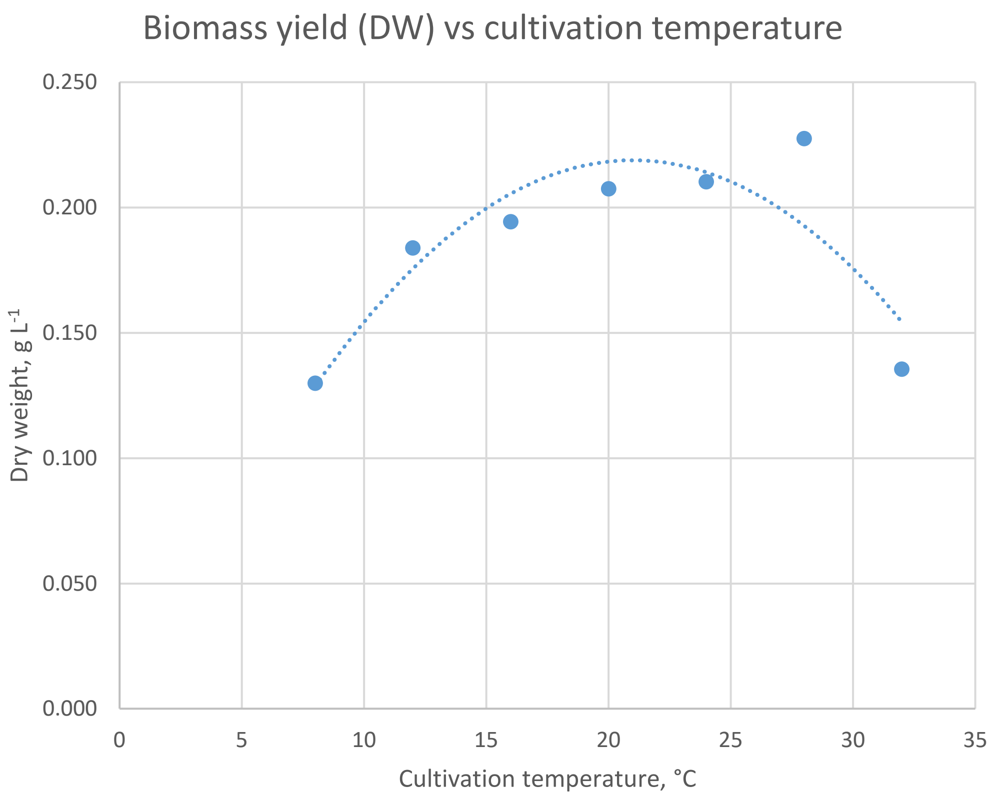
System Dynamics tool

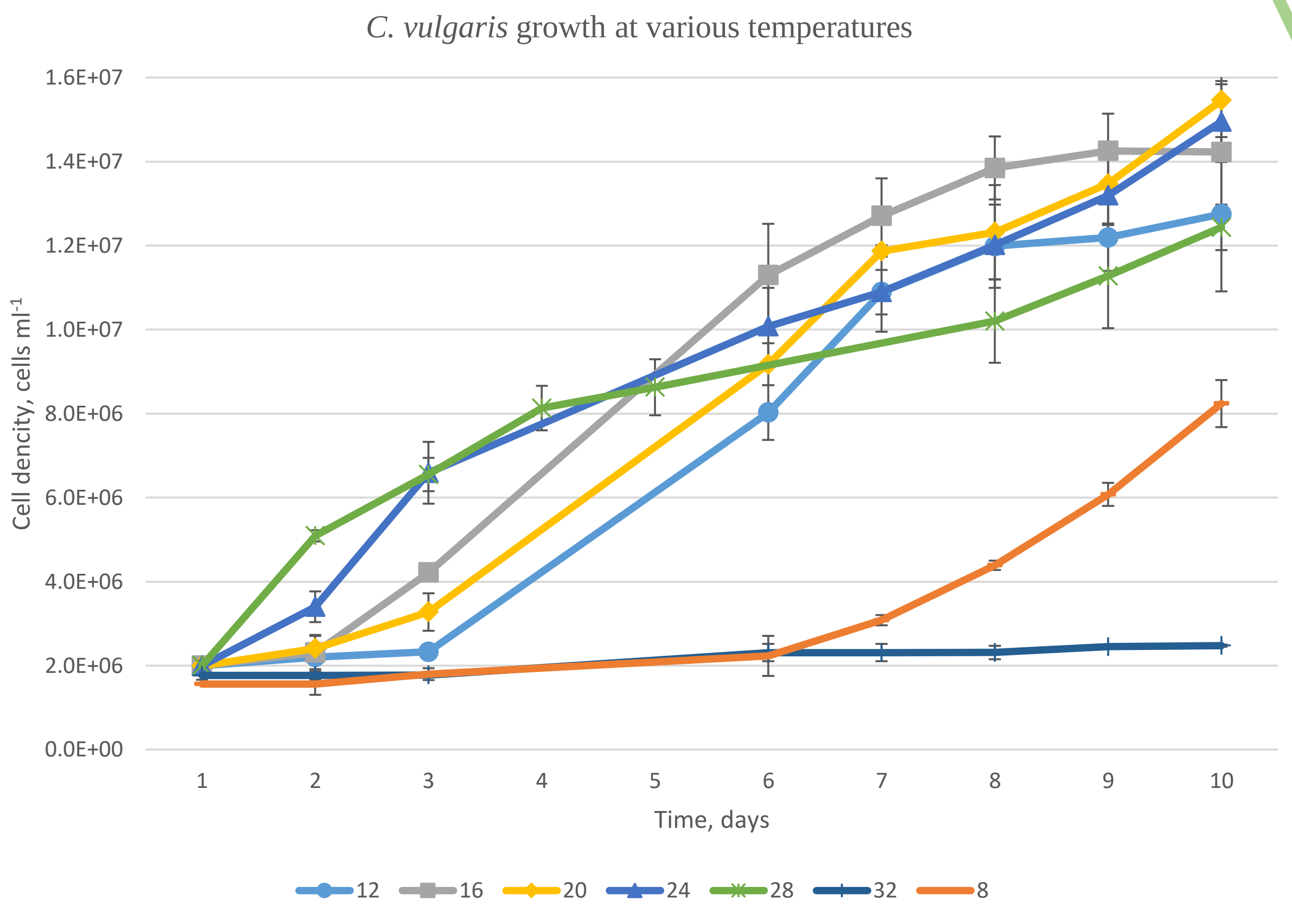
- **Growth empirical modelling** → use of complex system modelling, i.e. System Dynamics





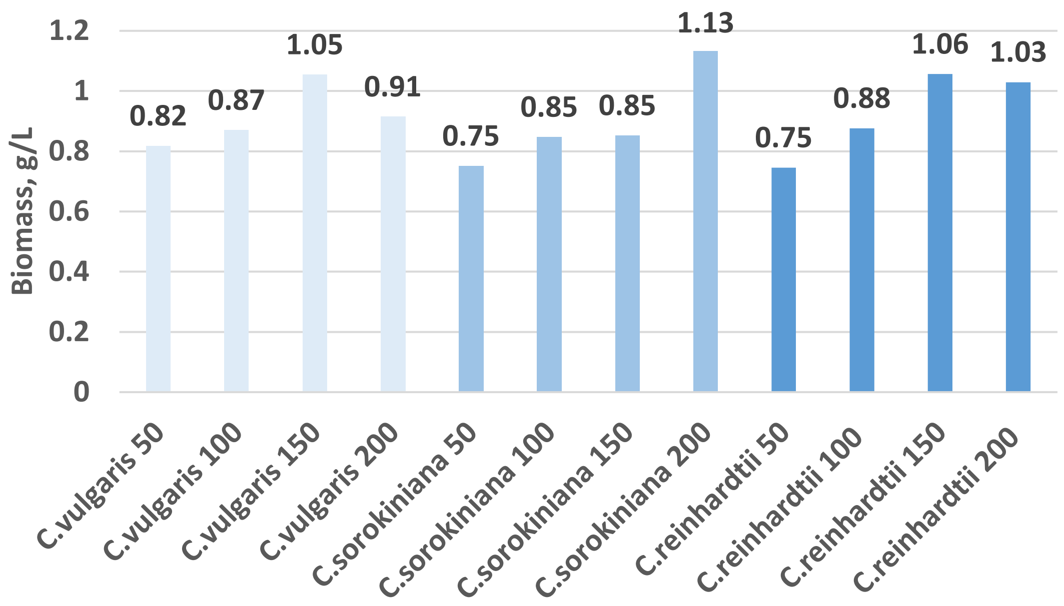
Laboratory tests: Temperature (*C. vulgaris*)



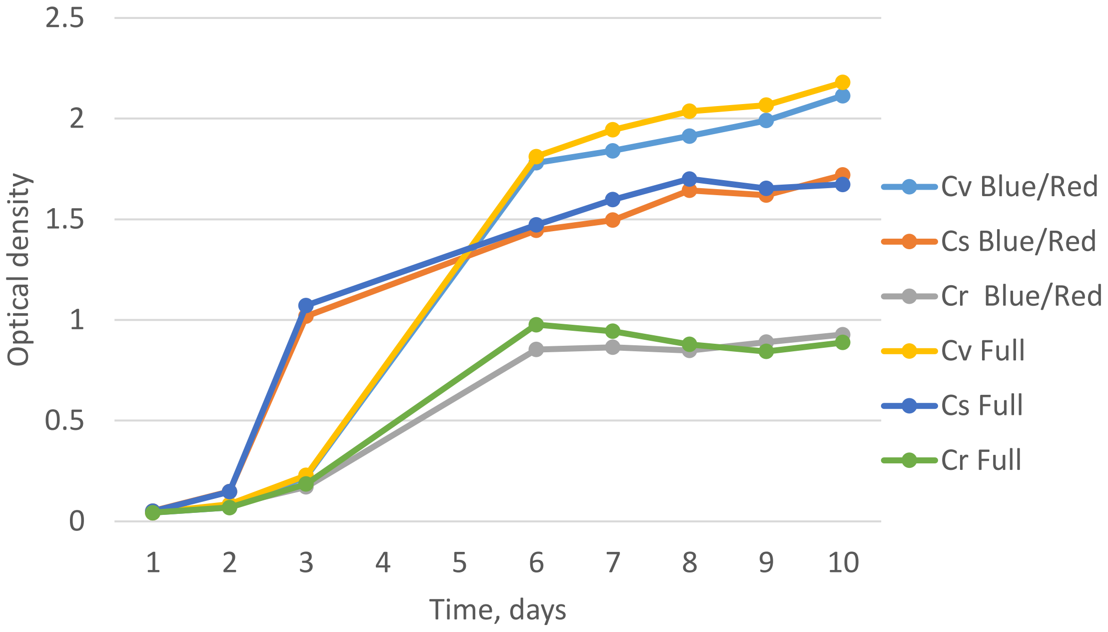


Laboratory tests: Light (intensity, spectrum blue/red)

Full spectrum at different light intensity 50, 100, 200 µmol m^2 s^{-1}



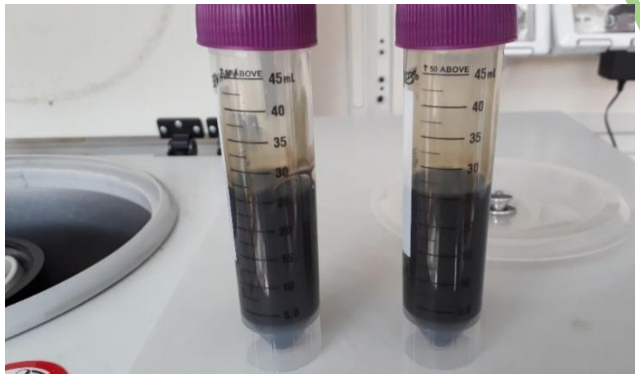
Full spectrum vs Red/blue LED lights



Laboratory tests: use of digestate (2020-21)

MATERIAL and METHODS

1. Type of microalgae*: Chlorella vulgaris 211-11j c*
2. BG-11 growth medium in Erlenmeyer flasks with baffles and 0.2 µm PTFE membrane screw caps
3. Room temperature in low light conditions on rotary shaker at 150 rpm
4. Various dilution digestate at 28 °C and 5600 lux LED illumination under photoperiod of 16:8 h (ligh:dark)
5. Cultivation in batch conditions for 10 days
6. Daily growth rate was assessed by optical density (OD) measurements with UV/VIS spectrophotometer at 750 nm
7. biomass yield was determined of all cultures based on dry weight
8. Nutrient removal assessment: measurement before and after hte batch test
9. Initial values of OD and pH were measured
10. Digestate was autoclaved and centrifuged (part also filtered using 1.6 µm filters).
11. Testing of 1, 3 and 5% digestate - dilution with distilled water



Row undiluted centrate with characteristic dark colour

Microalgae cultivated in various digestate dilution rate compared with the control (on the left).

Laboratory tests: use of digestate (2020)

***Chlorella vulgaris* 211-11j**

Parameter	Unit	1C	1CF
Suspended solids	g/L	2.45	1.70
Chemical oxygen demand (COD)	mg/L	23210	9580
Total nitrogen	mg/L	11770	6780
Total phosphorus	mg/L	319	157
Nitrate nitrogen NO_3-N	mg/L	<0.07	<0.07
Ammonia nitrogen NH_4-N	mg/L	3080	2460
Turbidity	mg/L	NA	7840

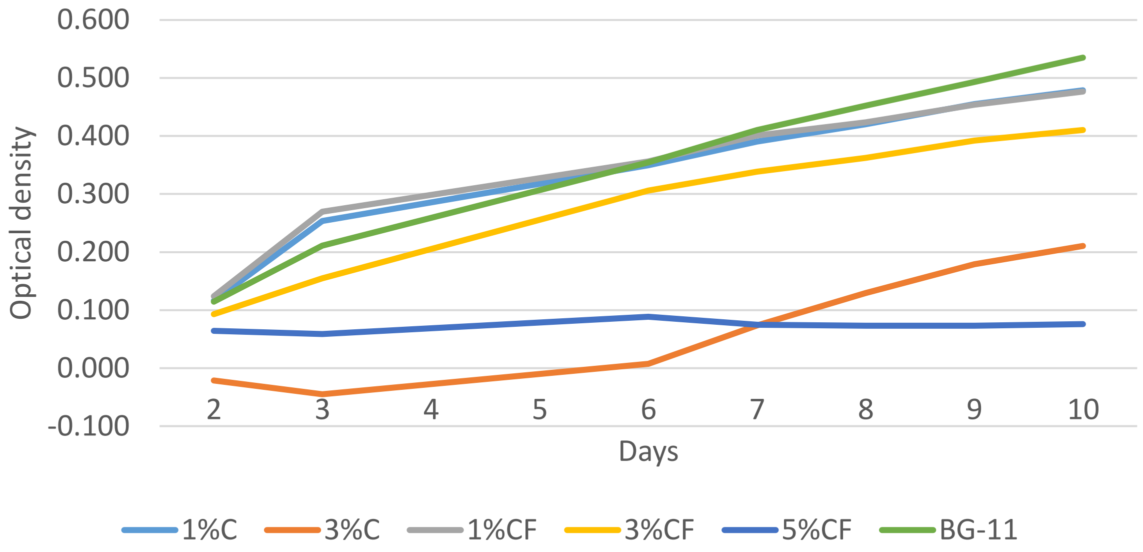
Initial composition of anaerobic digestion centrate.
1C – centrifuged
1CF – centrifuged and filtered
NA – data not available.

Dilution rate	Optical density	pH
100%	6.1	8.08/10
1%C	0.051	9.23
3%C	0.214	9.44
1%CF	0.031	9.05
3%CF	0.049	9.29
5%CF	0.083	9.35
BG-11	0.001	7.85

Initial optical density and pH of various dilutions of centrate.
BG-11 – control growth medium,
C – centrifuged,
CF – filtered digestate.

Laboratory tests: use of digestate (2020)

- **Microalgae growth in various concentration centrate**



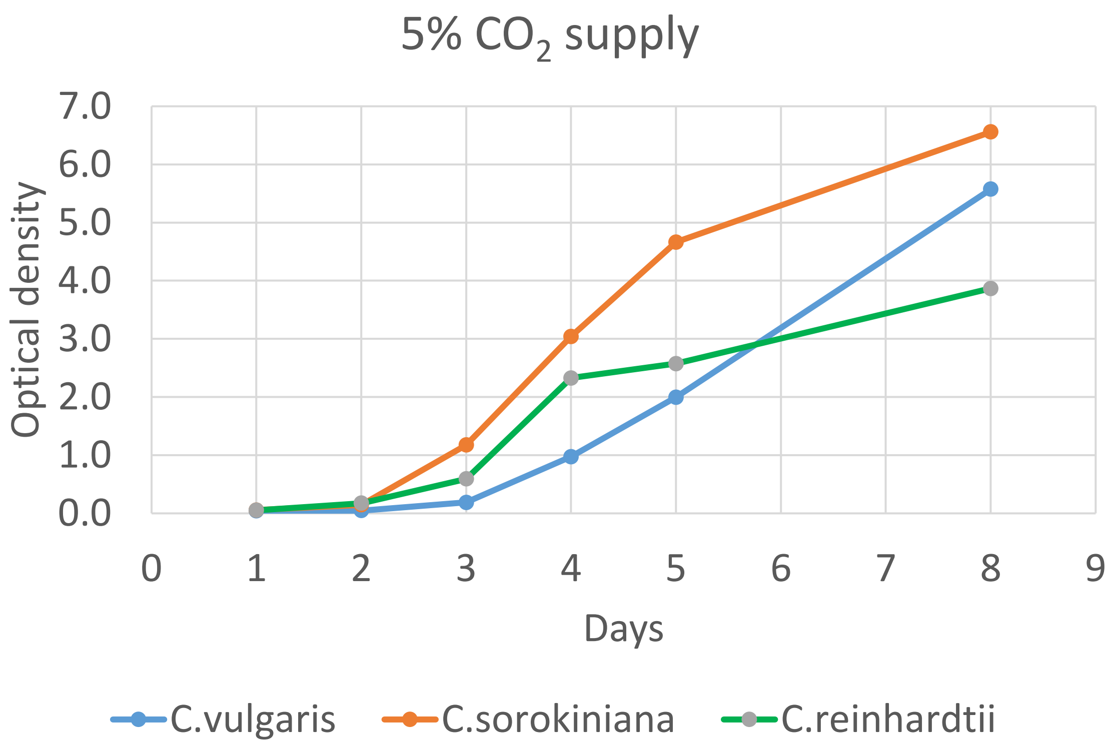
- **Nutrient removal of digestate with microalgae treatment.**

	1%	After treatment	Removal rate [%]	3%	After treatment	Removal rate [%]	5%	After treatment	Removal rate [%]
Suspended solids	17	N	NA	51	N	NA	85	N	NA
COD	95.8	109	-13.8	287.4	292	-1.6	479	411	14.2
Total N	67.8	20.4	69.9	203.4	50.8	75.0	339	99.4	70.7
Total P	1.57	0.212	86.5	4.71	1.46	69.0	7.85	4.26	45.7
NO3-N	N	12.7	NA	N	12.6	NA	N	11.8	NA
NH4-N	24.6	7.6	69.1	73.8	30	59.3	123	86	30.1

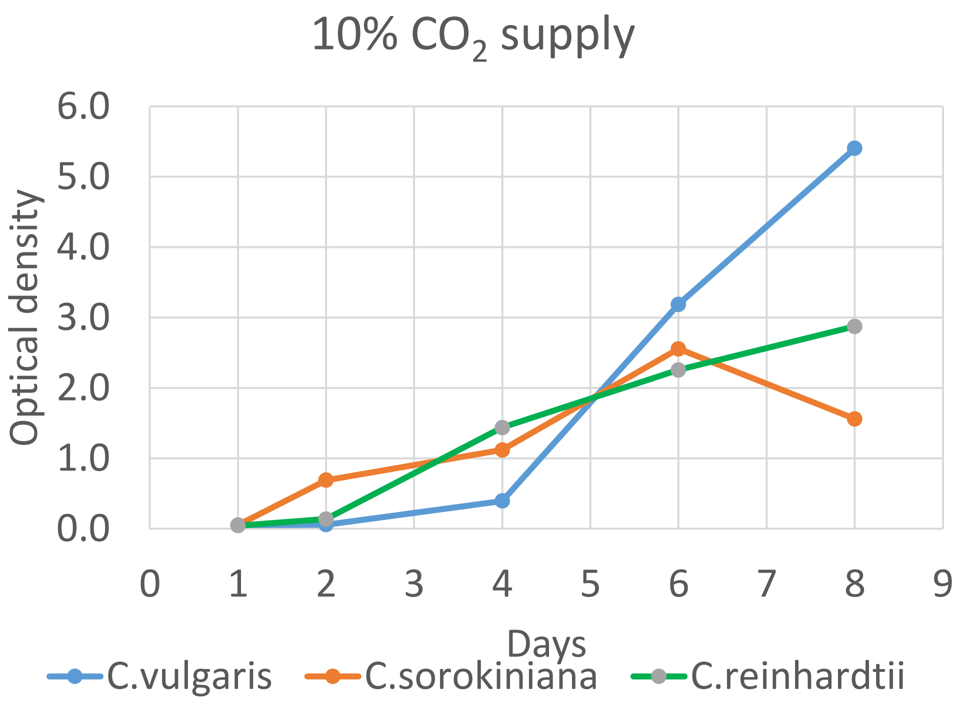
N – not performed, NA – not applicable

Laboratory tests: use of CO_2

Chlorella vulgaris* 211-11j, *Chlorella sorokiniana* and *Chlamydomonas reinhardtii



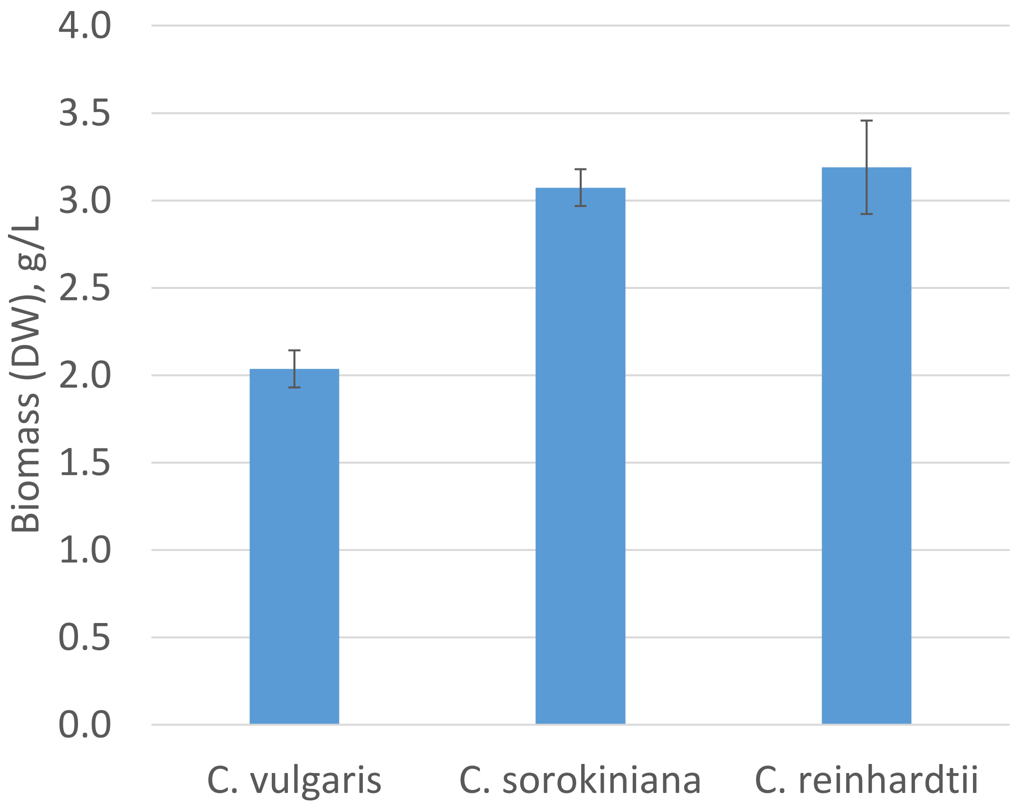
Growth of C. vulgaris, C. sorokiniana and C. reinhardtii in 5% CO_2



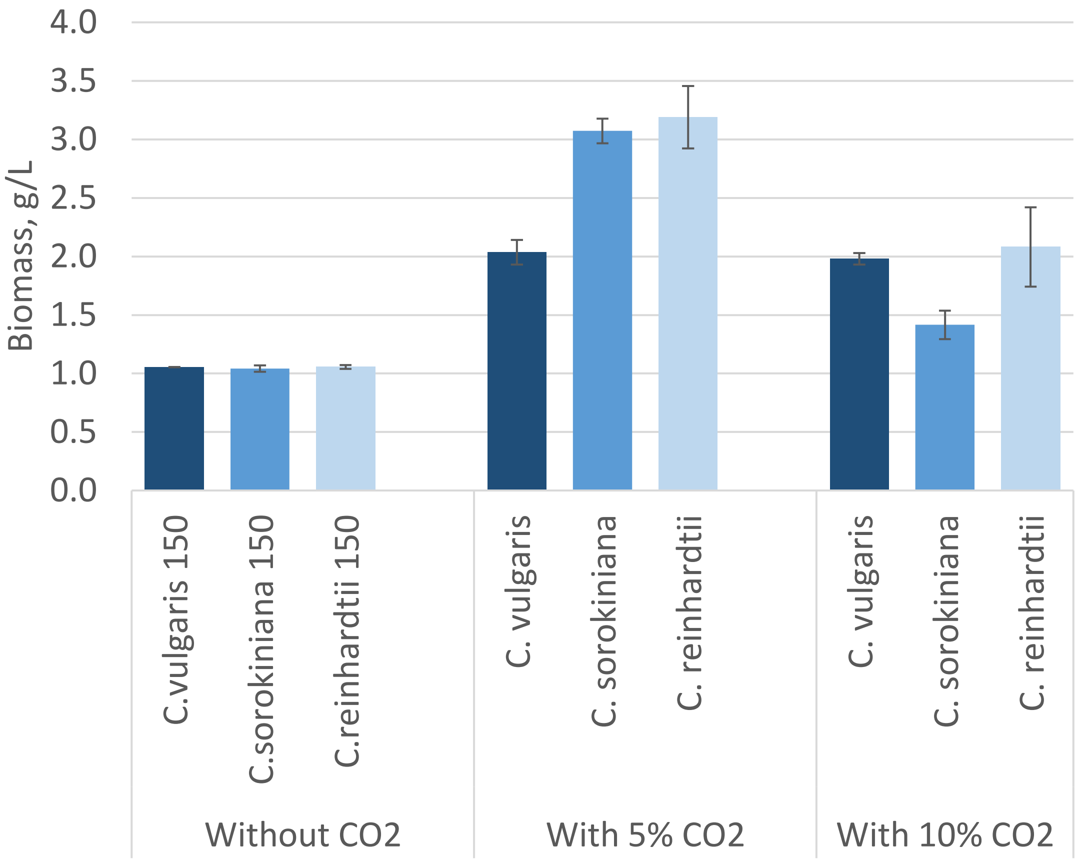
Growth of C. vulgaris, C. sorokiniana and C. reinhardtii in 10% CO_2

Laboratory tests: use of CO_2

Chlorella vulgaris* 211-11j, *Chlorella sorokiniana* and *Chlamydomonas reinhardtii



Total biomass produced on the day 8 of *C. vulgaris*, C. *sorokiniana* and *C. reinhardtii* cultivated in 5% CO_2 mix.

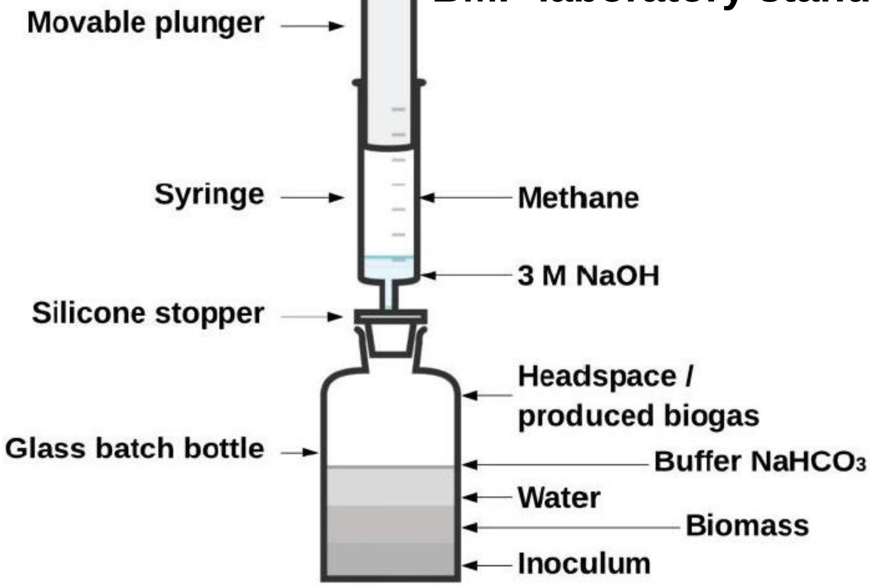


Comparison of microalgae biomass yield at different CO_2 sparging rates.

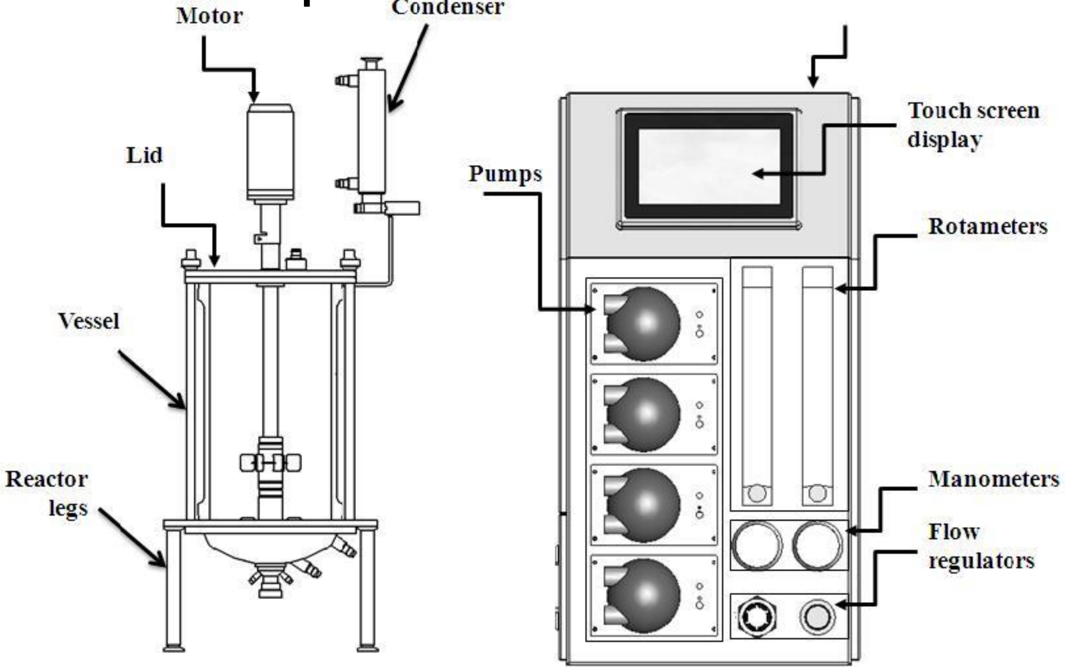
Laboratory tests: BMP

- 100 ml media bottles with a working volume of 60 ml
- Batch tests in triplicates with a TS ratio of A/I 1:3 for each type of microalgae used (i.e. *Chlorella Vulgaris, Chlorella Sorokiniana and Chlamydomonas Reinhardtii*)
- Mesophilic temperature (37ºC) in a ECOCell © incubator and lasted for 30 days
- Growing microalage in a photobioreactor providing them a source of CO_2 from a airflow into the photobioreactor (EDF BIO-4 bioprocess controller ©)
- The nominal size of the photobioreactor: 5 L.

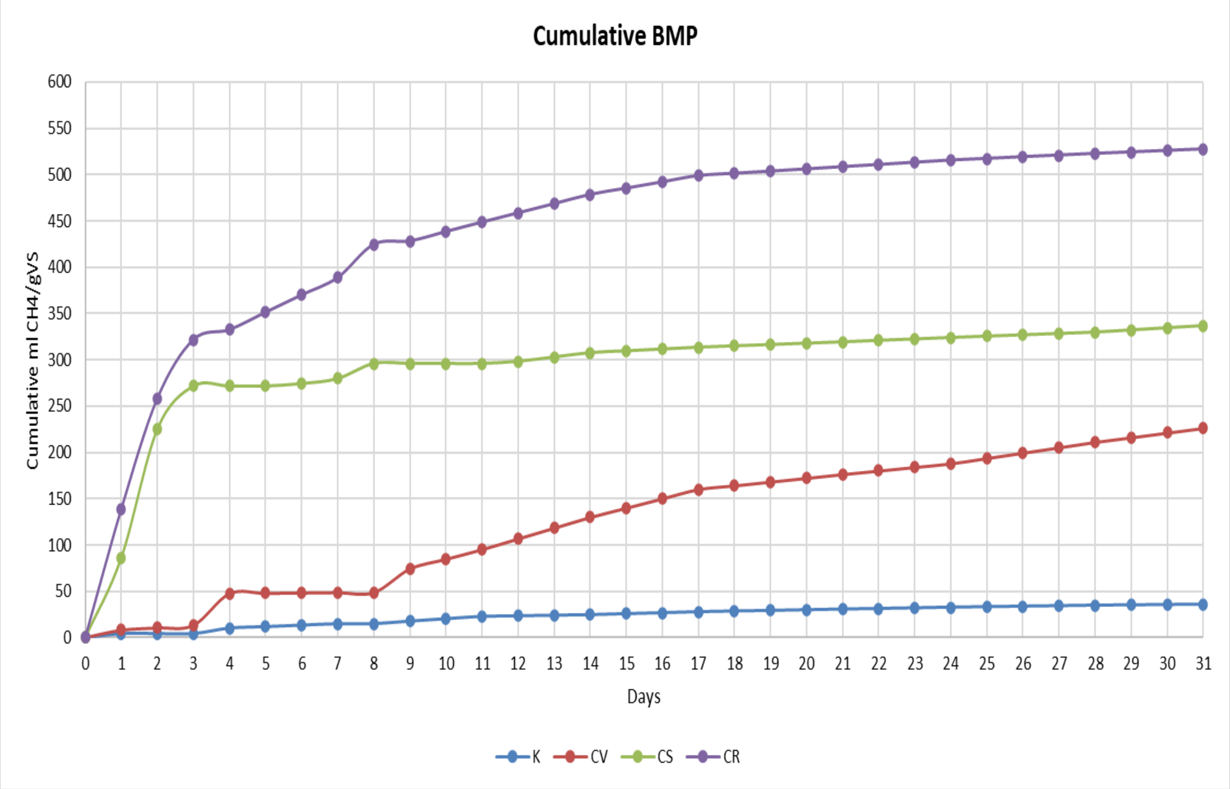
BMP laboratory stand



EDF- BIO-4 bioprocess controller ©



Laboratory tests: BMP



Comparison of results from this study experimental results and literature.

Algae species	Methane yield, [ml CH_4/g_{VS}]	Methane yield, literature [ml CH_4/g_{VS}]
Chlorella Vulgaris	226.26	337 (Zhao, et al., 2014) 228 (Perazzoli, et al., 2013) 229 (Park, et al., 2013)
Chlorella Sorokiniana	336.85	275 (Mohamed, et al., 2019)
Chlamydomonas Reinhardtii	527.43	387 (Mussgnug, et al., 2010)

Laboratory tests: BMP

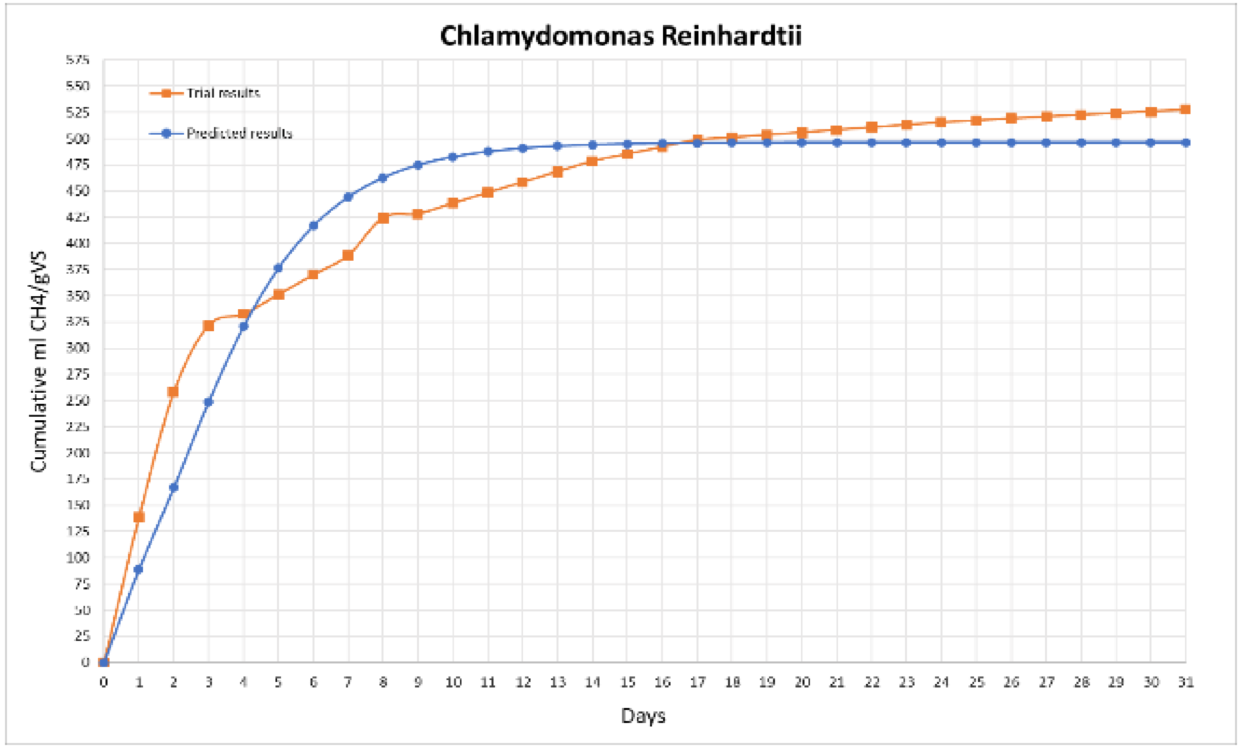
- Theoretical BMP results according to Buswell formula

$$C_nH_aO_b + \left(n - \frac{a}{4} - \frac{b}{2}\right) H_2O \rightarrow \left(\frac{n}{2} + \frac{a}{8} - \frac{b}{4}\right) CH_4 + \left(\frac{n}{2} - \frac{a}{8} + \frac{b}{4}\right) CO_2$$

Algae species	Methane yield [ml CH_4/g_{VS}]
Chlorella Vulgaris	628.23
Chlorella Sorokiniana	662.95
Chlamydomonas Reinhardtii	659.81

- Regression analysis with Gompertz equation

$$M(t) = P \cdot exp\left\{-exp\left[\frac{R_{max} \cdot e}{P}(\lambda - t) + 1\right]\right\}$$

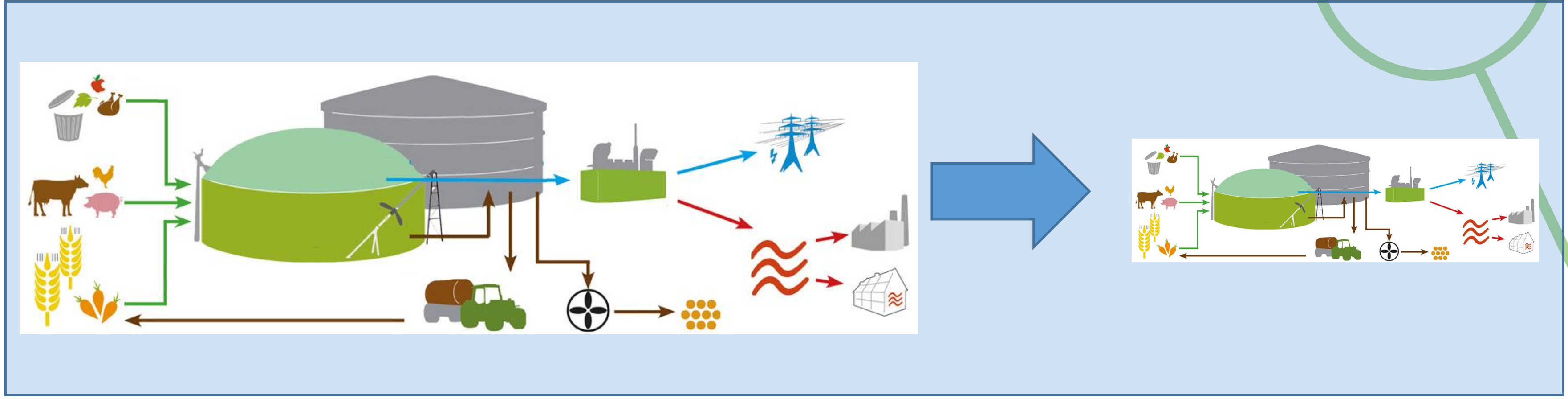


LCA study

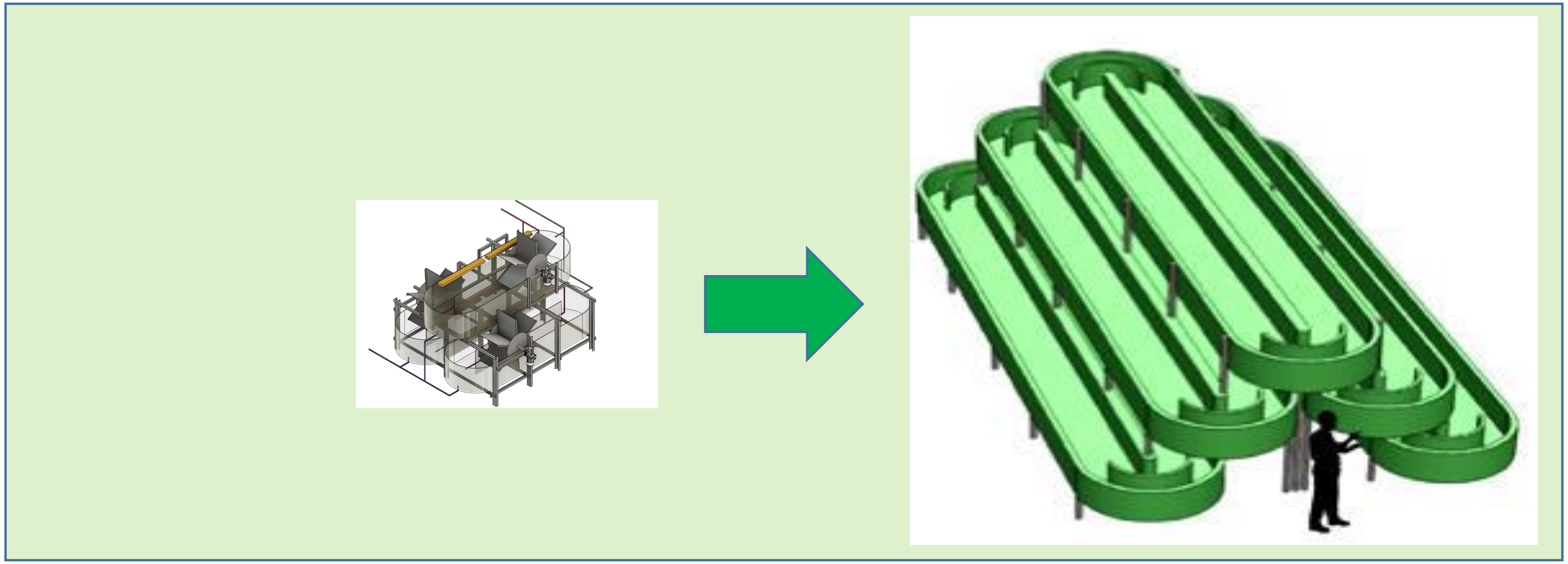
MAIN ASSUMPTION

- ❑ Comparison of 2 scenarios

  - o Real biogas plant scaled-down of 6 times **(scenario 1)**



  - o SMORP scaled-up system **(scenario 2)**

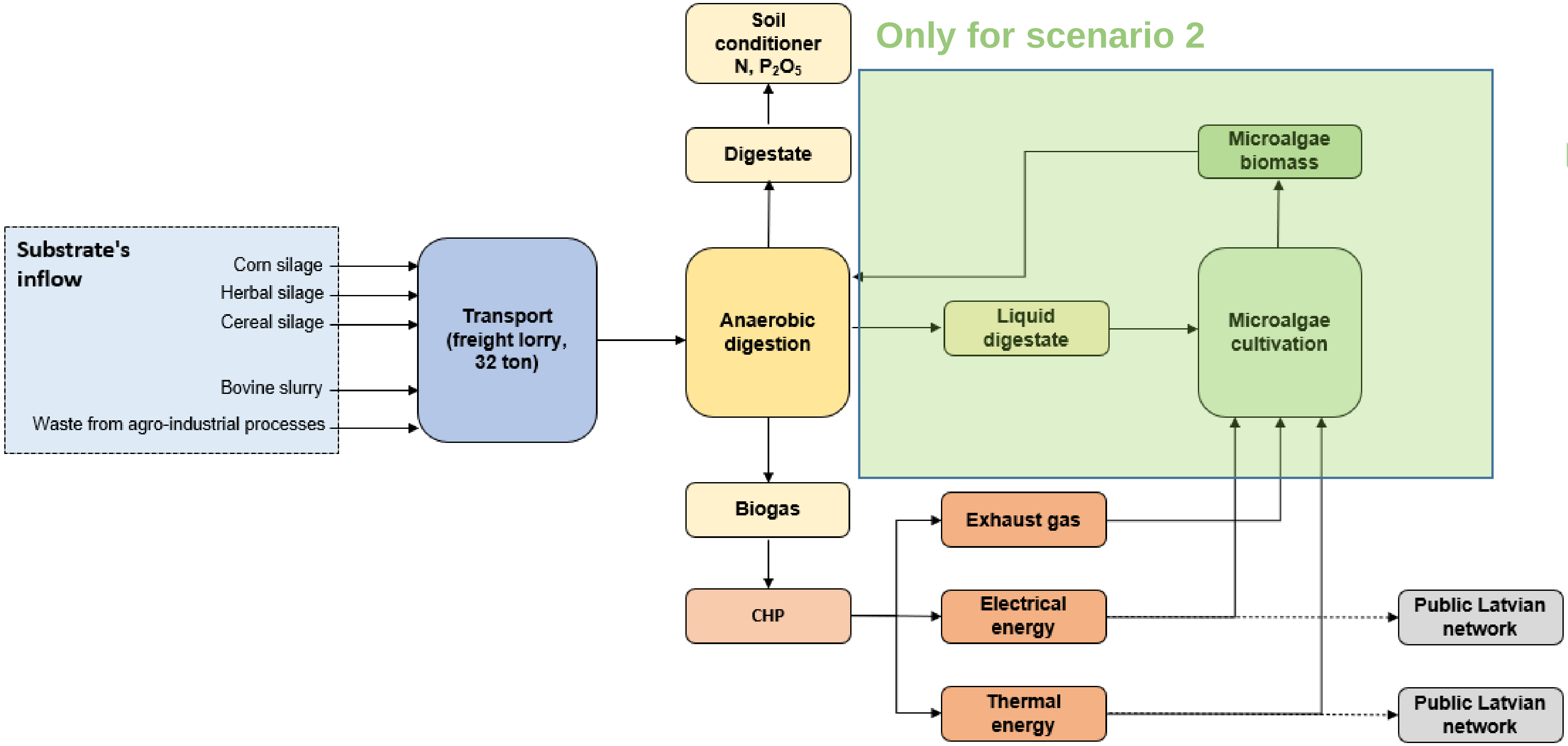


- ❑ ISO Standards 14040-44

LCA study

Goal and scope

- ❑ Comparison of 2 scenarios
  - ○ Real biogas plant scaled-down of 6 times - **scenario 1**
  - ○ SMORP scaled-up system - **scenario 2**
- ❑ Functional unit: 5.000 tons of digestate produced by the biogas plant
- ❑ *Chlorella vulgaris*
- ❑ IMPACT 2002+
- ❑ SIMAPRO software
- ❑ ECOINVENT database 3.5



LCA study

Life Cycle inventory

- **Scenario 1**
  - Biogas plant operator
  - Literature

- Biogas yearly produced: 1.320.760 m^3
- Digestate yearly produced: 5.000 tons (liquid + solid)
- Internal heat consumption: around 11%
- Internal electricity consumption: around 9%
- Electricity into the grid: 2.342.336 kWh/year (avoided)
- Heat into the grid: 1.208.717 kWh/year (avoided)
- Waste heat: 751.488 kWh/year
- All digestate used as fertilizer

- **Scenario 2**
  - Biogas plant operator
  - Literature
  - Technical calculation from SMORP

- 46 SMORP modules (i.e. 230 ponds)
- Shape: 5 stocked ponds
  - length 11,0m
  - width 1,0 m
- SMORP ponds area: 2 468 m^2
- Land use: 1 487 m^2 of (i.e. 0,15 ha)
- SMORP volume: 991 m^3
- Electricity consumption: 9.5% + 9% (sceneario 1 + SMORP concept)
- Heat consumption: 45% + 11% (sceneario 1 + SMORP concept)
- Liquid digestate used as nutrient / Ehaust gases used as C source

LCA study

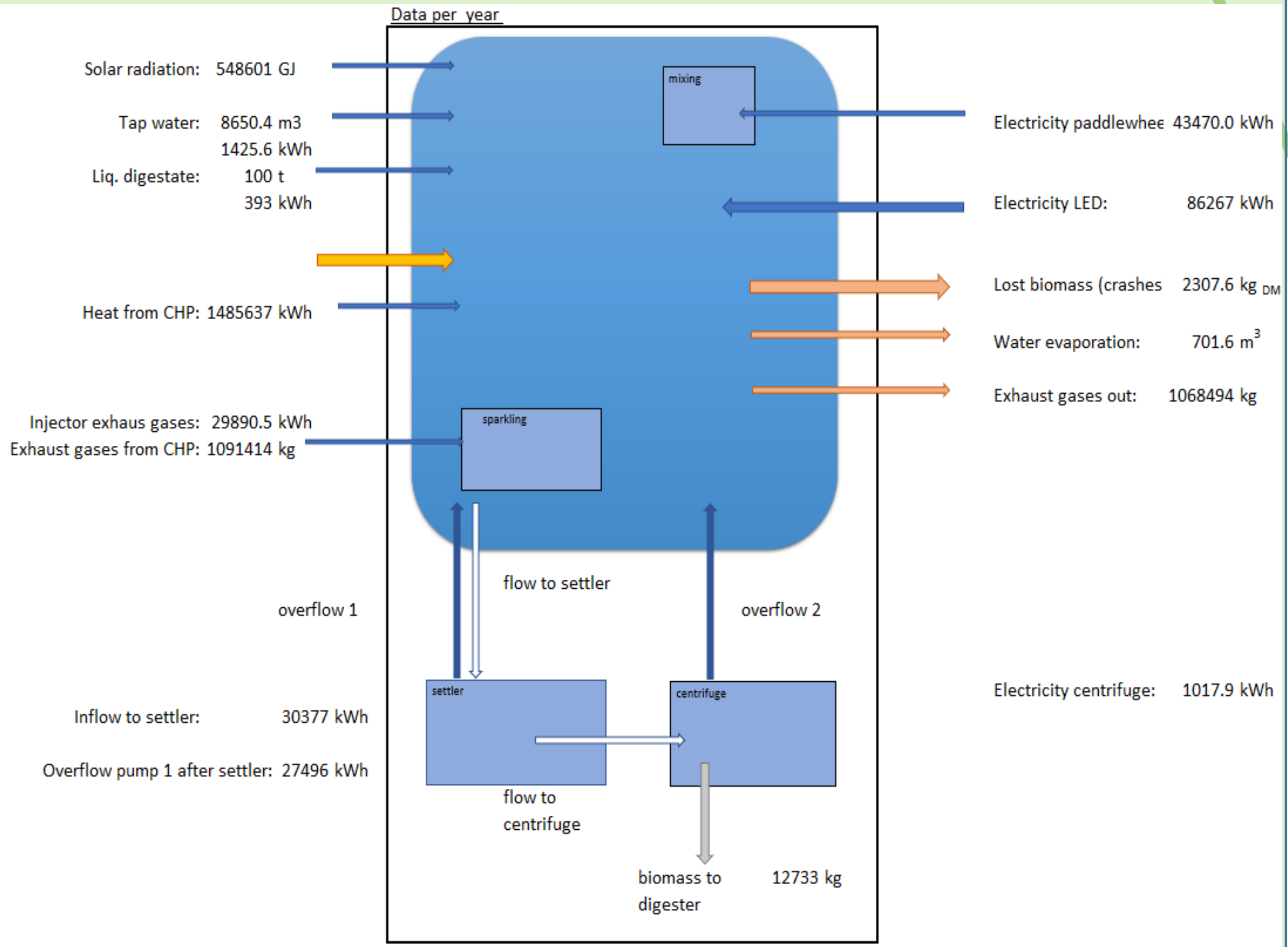
Life Cycle inventory (data sources)

❑ Scenario 2

CONSIDERED TECHNICAL ASPECTS

- Monthly temperature in the greenhouse: 15-27ºC
- Monthly outside mean temperature: -4.7-16,9ºC
- Solar radiation (decreased by the presence of the greenhouse)
- Evaporation
- Heat losses through walls (dispersion)
- Convention losses

- Mass balance
- Pumping system depending on several parameters:
  Flow [Q], Internal diameter [d], water speed, Conc. load losses [J], Distr. Load losses [K], K inlet, K outlet, Lenght [L], Section [a], pumps idraulic yield [%], pumps organic yield [%], pumps electric yield [%], working time, volume required, Viscosity H_2O/air, density H_2O/air, Reynolds nr., Power [W]



LCA study

Life Cycle inventory (data sources)

❑ Scenario 2

CONSIDERED TECHNICAL ASPECTS

- Materials

Component	Material - Description	Amount
Cultivation ponds	Plexiglas	240.871
Centrifuge (body)	Steel	2024
Centrifuge (electrical engine)	Generic electrical engine	152
Gas injector pipe	Polyethylene	8280
Paddle wheel (electrical motor)	Die-cast Aluminium*	228
Paddle wheel (gearbox/adapter)	Die-cast Aluminium*	159
Paddle wheel (paddle)	Polyvinyl chloride**	322
Paddle wheel (frame)	Steel	322
LED (transformer)	Aluminium / Copper	36,8 / 9,2
LED (lamp)	Emitting diode	46
LED (lamp)	Aluminium / copper	920 / 46
Greenhouse	Ecoinvent database	4508
Heat exchanger	Steel	12.885
Control unit (SCADA)	Generic control cabinet	0,01
Control unit (electronics)	Electronics	184
Settling tank	Steel	552,0
Water pump	Polypropylene / steel	138 / 13,8
Water pump (electronics)	Electronics for control unit	13,8

LCA study

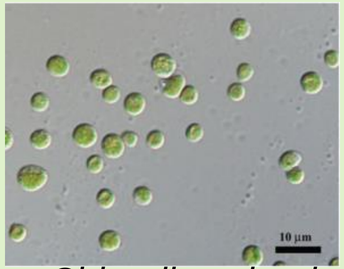
Life Cycle inventory (data sources)

❑ Scenario 2

CONSIDERED BIOLOGICAL ASPECTS

- Type of microalgae: *Chlorella vulgaris*
  - *Carbohydrates:* *15%*
  - *Proteins:* *55%*
  - *Lipids:* *18%*
  - *Rest:* *7%*
  - *Organic anions and ash:* *5%*
- Photosynthetically active radiation (PAR): 50 μmol phot m^2/s
- Photosynthetic efficiency on daylight: 1.50%
- Biomass concentration in the pond: 0.3 kg_{DM}/m^3
- Biomass daily production: 25 $g \cdot (m^2 \cdot day)^{-1}$
- Flue gas composition:
  - *CO_2%:* *7%*
  - *C%:* *2%*
- Flue gas uptake: 1.80 kg CO_2/kg_{DM}
- CO_2 uptake efficiency: 30%
- Total uptaken CO_2: 2920 $kgCO_2$ /year

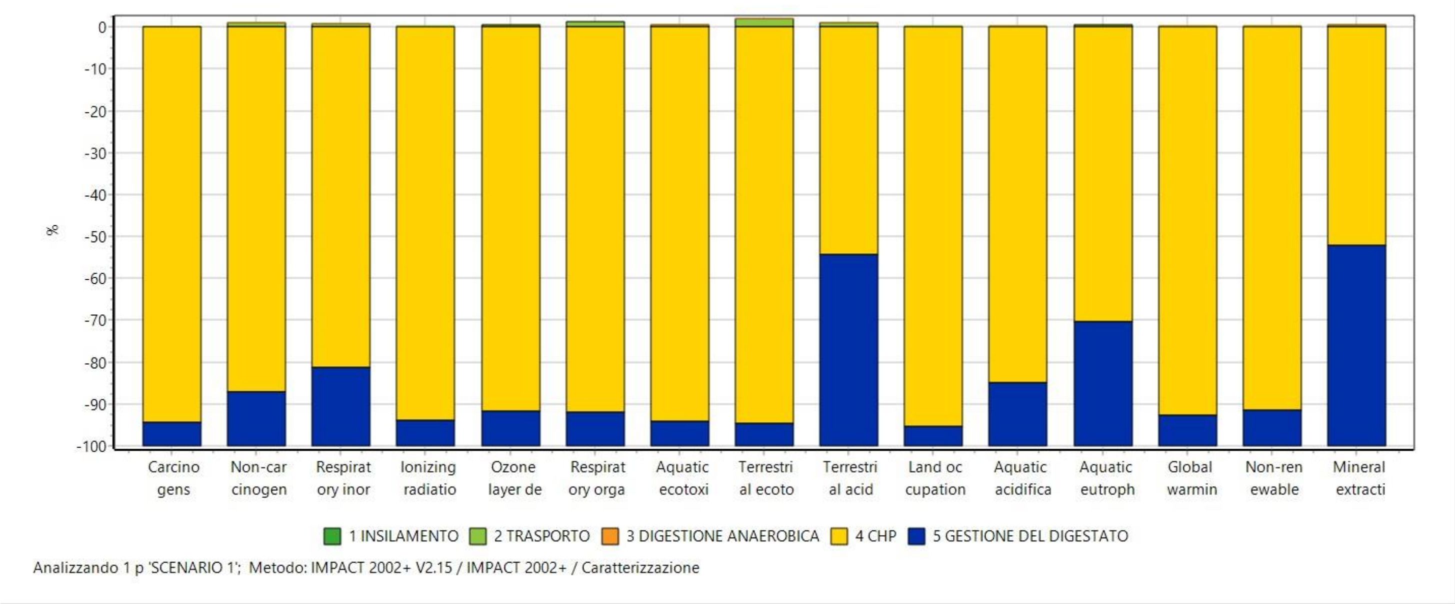
- Carbon content of dry matter: 0.54 g/g
- N content of protein: 0.16 g/g of protein
- P content of dry matter: 0.0027 g/g_{DM}
- Light/dars cycle: 16:8
- Biomass produced (dry matter): 12733.16 kg_{DM}/year
- Amount of liquid digestate: 6.0 kg/kg_{DM}



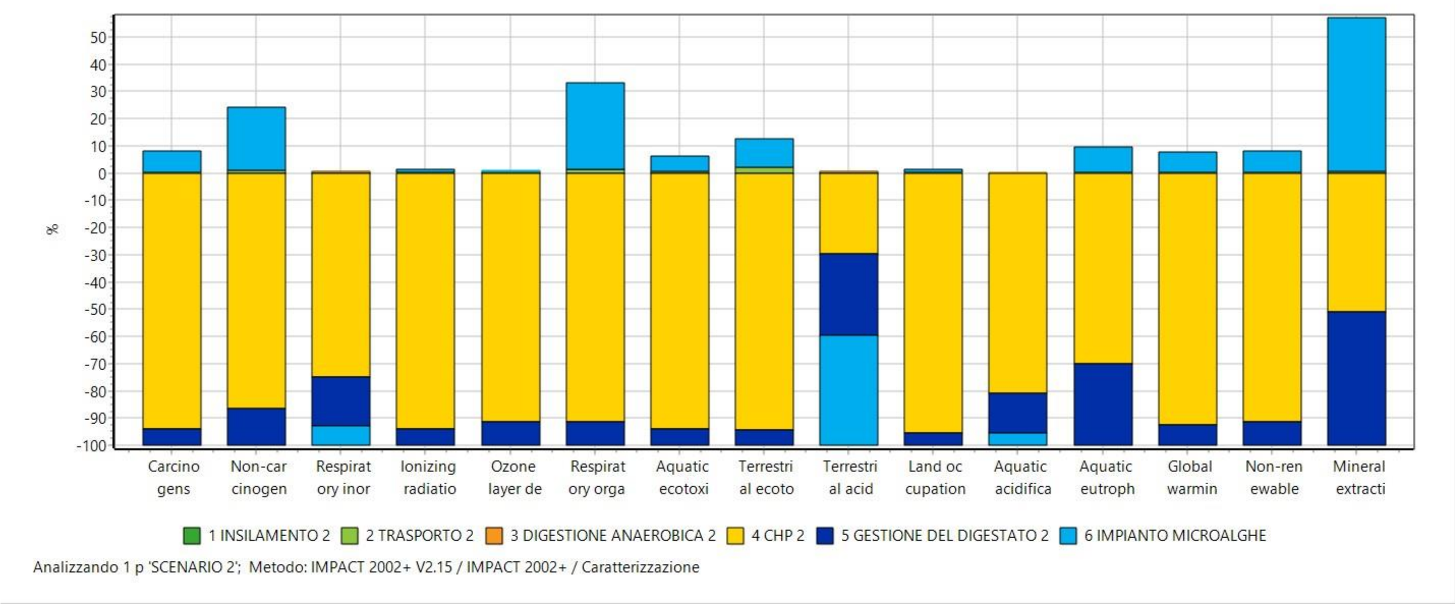
Chlorella vulgaris

LCA study

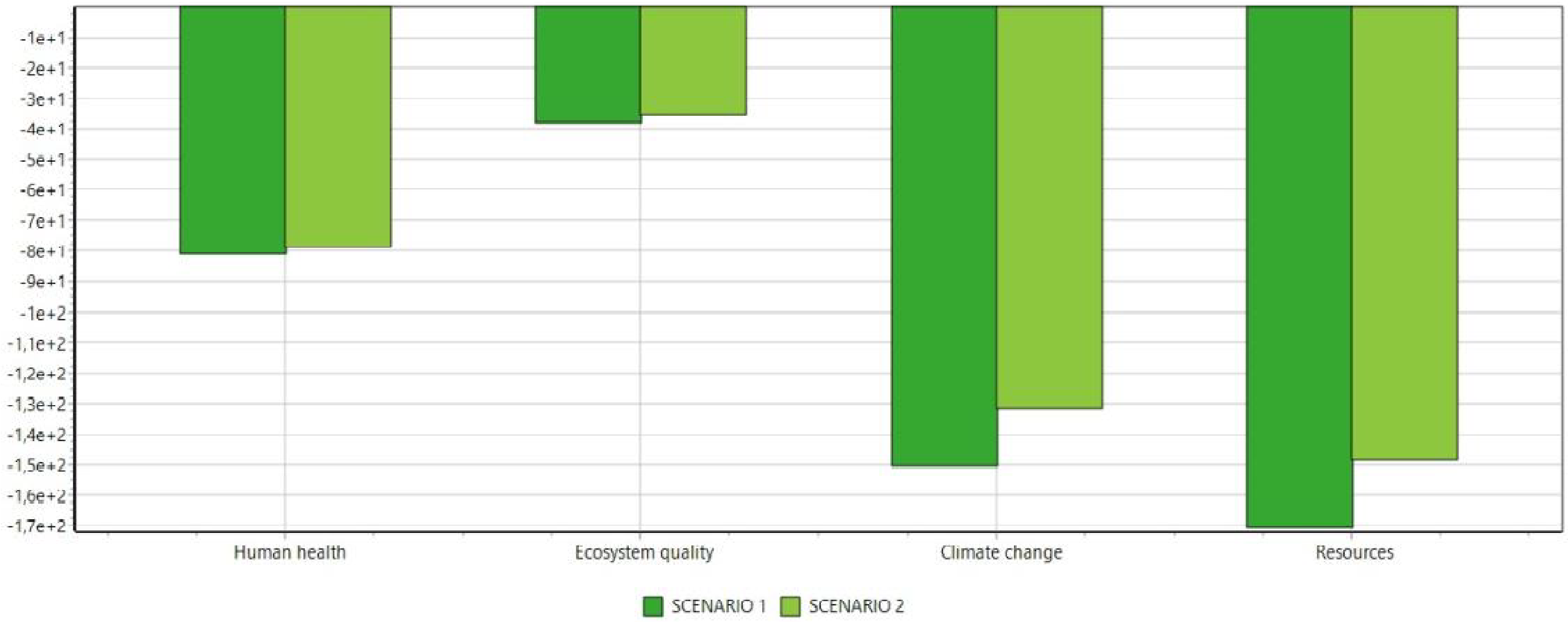
Scenario 1



Scenario 2



LCA study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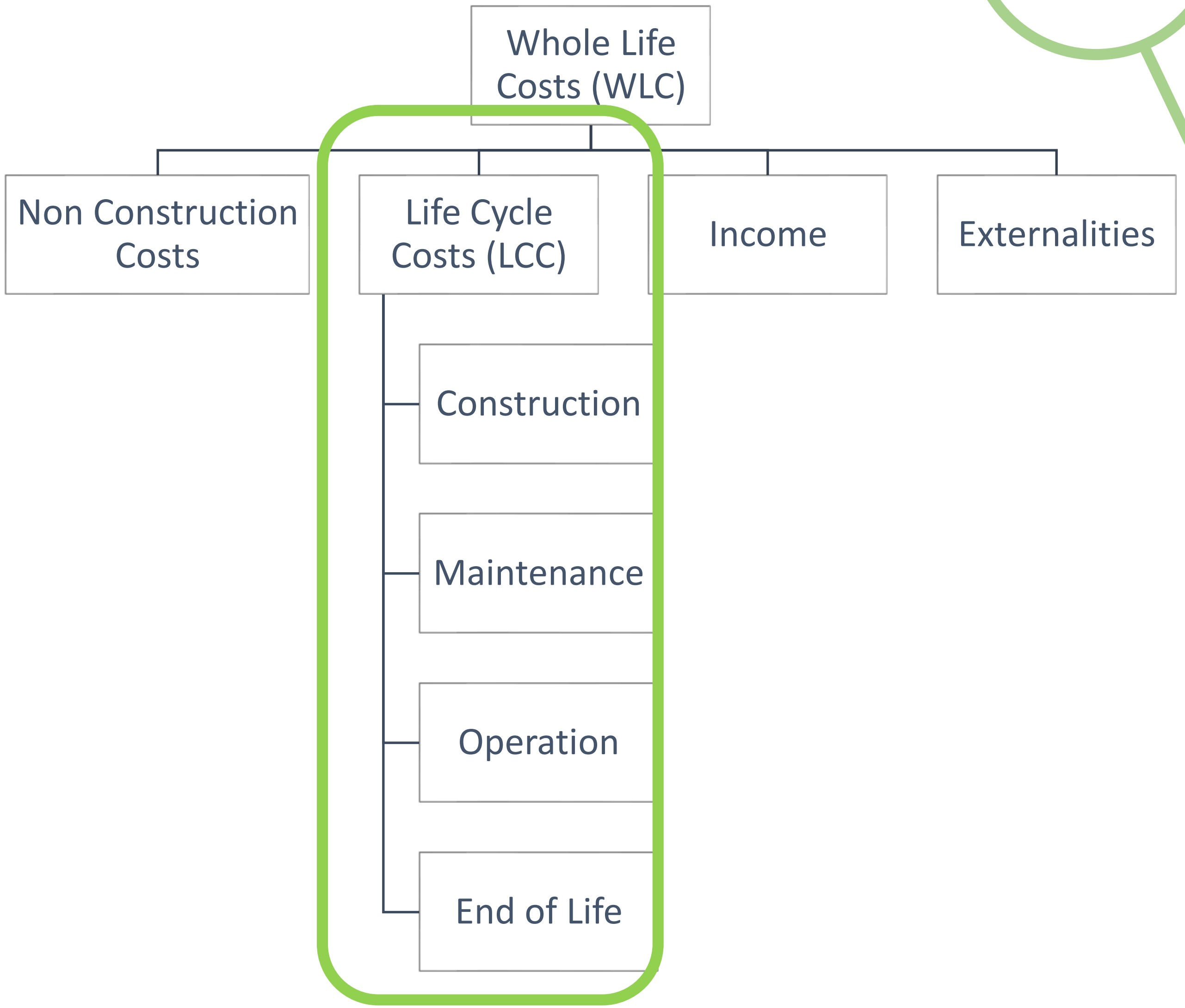
-1e+2
-1,1e+2
-1,2e+2
-1,3e+2
-1,4e+2
-1,5e+2
-1,6e+2
-1,7e+2
Human health
Ecosystem quality
Climate change
Resources
SCENARIO 1
SCENARIO 2

Life Cycle Costing

- Methodology for systematic economic evaluation of life-cycle costs over a certain period of time

- Considering:
  - Construction
  - Maintenance
  - Operation
  - End of life

- ISO 15686-5



LCC study

Assumption and Methods

- ❑ Evaluation of the investment on an existing biogas plant
  - ○ Real biogas plant scaled-down of 6 times - **scenario 1**
  - ○ SMORP scaled-up system - **scenario 2**
- ❑ Scaling factor for SMORP

$$S_{ECC} = E_{CC0} \times \left(\frac{S_S}{S_0}\right)^N$$

- ❑ NET PRESENT VALUE

$$NPV = \sum_{t=0}^{n} \frac{S_0}{(1+i)^0} + \frac{S_1}{(1+i)^1} + \cdots + \frac{S_n}{(1+i)^n}$$

- ❑ INTERNAL RATE OF RETURN

$$RR = \left[\sum_{t=0}^{n} \frac{S_t}{(1+i)^t}\right] = 0$$

Results scenario 2

- NPV of 2.573.935 €
- IRR of 14,1%.

LCC study

Inventory

Parameters	Unit measures
Electricity price	€/kWh
Heat price	€/kWh
Electricity sold	kWh
Heat sold	kWh
Incomes from electricity	€/year
Incomes from heat	€/year
Digestate feeding	€/year
CO_2 injection system	€/year
Open Raceway Ponds	€/year
Structural and Civil Construction	€/year
Control unit	€/year
Electricity price	€/year
Heat price	€/kWh
Electricity sold	€/kWh
Heat sold	kWh/year
Incomes from electricity	kWh/year
Incomes from heat	€/year
Total of incomes	€/year

Parameters	Unit measures
Electrical energy (country net)	€/year
Heat energy (country net)	€/year
Management cost	€/year
Purchase of biomass for AD	€/year
Transport of biomass for AD	€/year
Transport of digestated	€/year
Salary of employees	€/year
External consultations	€/year
Insurances	€/year
Substrate analysis	€/year

LCA/LCC study: criticalities

- SMORP couple system (**scenario 2**) compared to the business-as-usual (i.e., **scenario 1**) is viable from an economic point of view: positive NPV value (i.e. 2.573.935 €) and good IRR (i.e., 14,1%)

- From an environmental perspective the results from the business-as-usual (**scenario 1**) are still better

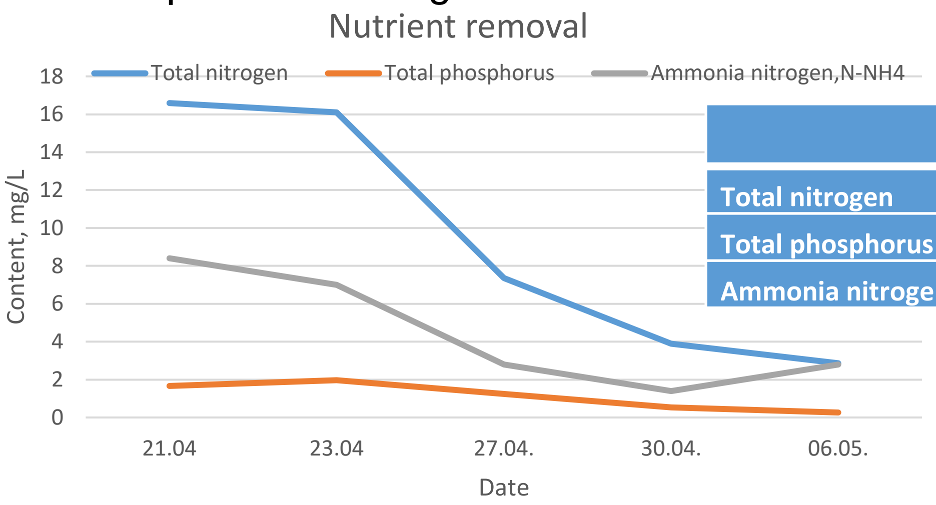
- Selling the produced microalgae biomass (price 35 €/ kg_{DM}) is alternative

- Too high energy consumption per produced microalgae = 1,7 $kWh/kg_{F.W.}$ (against 0,2 $kWh/kg_{F.W.}$)

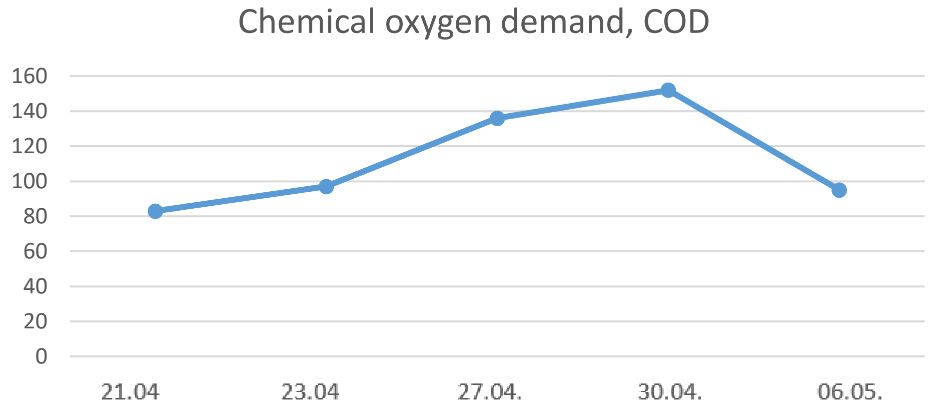
- This a prospective LCA of a hypothetical scaled-up process that can undergo a complete maturation of the technology in the future, and the effect of adding renewable energies

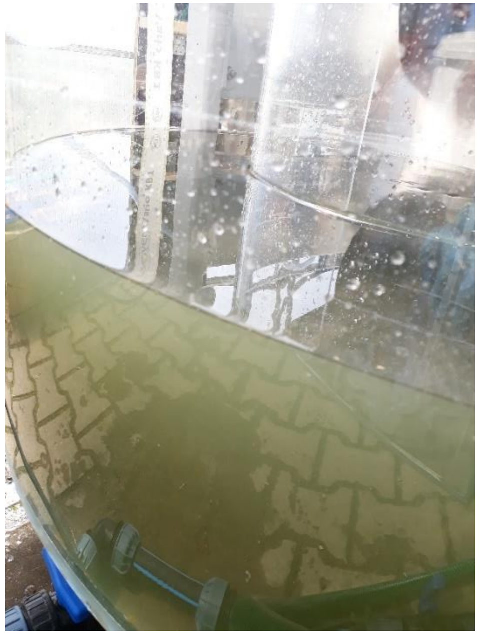
Pilot test at Agrolecava

- *C. sorokiniana* inoculated with pre-cultivated biomass at the rate of ~ 1.5%.
- Pond filled with TAP water: 20 cm depth.
- 2 L of pre-treated digestate



	Removal rate, %
Total nitrogen	82.8
Total phosphorus	84.8
Ammonia nitrogen, N-NH4	66.7

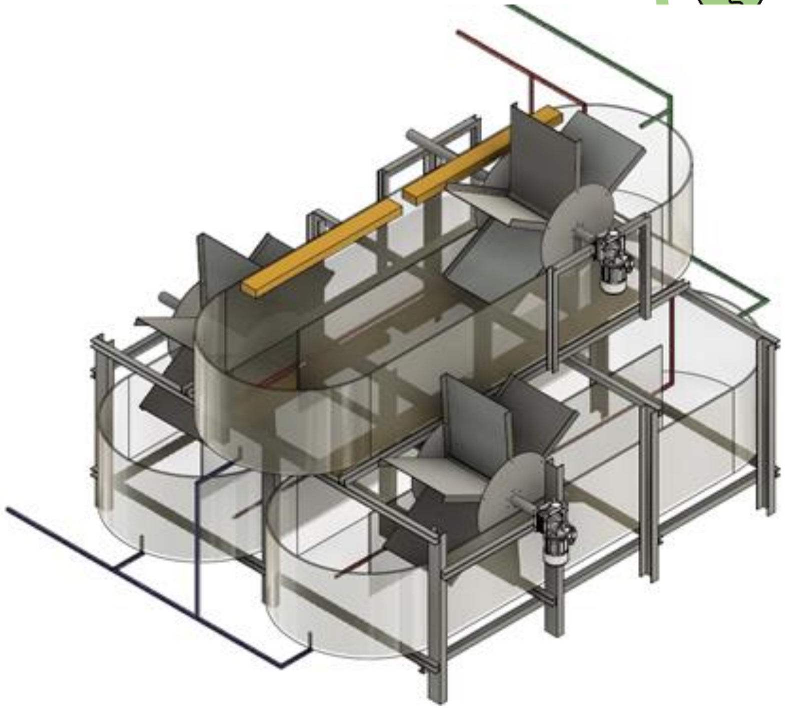




Conclusions

- SMORP is a circular economy solution for digestate management and CO_2 recirculation from biogas plants within a microalgae cultivation system has the potential to be implemented in Baltic context
- The overall sustainability of the proposed solution needs to be investigated since depending on the overall optimization of the system as well as on the scaling up of the proposed pilot
- The optimization of the demo system needs more experimental tests and a more sensitive tuning of the system (i.e. regulation of temperature, pH, nutrient flow and light)
- Microalgae can grow in liquid digestate centrate
- High optical density can seriously inhibit microalgae growth: need of dilution and digestate pre-treatment prior microalgae (centrifugation fallowed by filtration) – which drawbacks for energy consumption
- Temperature could represent an obstacle for the implementation in North conditions without a better greenhouse heating system
- The overall sustainability assessment should include S-LCA
- Further tests coupled with WWTP
- Viability to be assessed if SMORP included in a wider biorefinery

Francesco Romagnoli, Ph.D., Professor
Riga Technical University
Institute of Energy Systems and Environment
Āzenes iela 12/1, LV-1048, Riga, Latvia
Tel.: +371 67089923
Mob. : +371 28354151
e-mail: francesco.romagnoli@rtu.lv



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