MELISSA
MICRO-ECOLOGICAL
LIFE SUPPORT SYSTEM
ALTERNATIVE

CREATING
A CIRCULAR
FUTURE

MICROALGAE BIOFACADE TO DEVELOP SUSTAINABLE BUILDINGS:
SYSTEM MODELING WITH MODELICA

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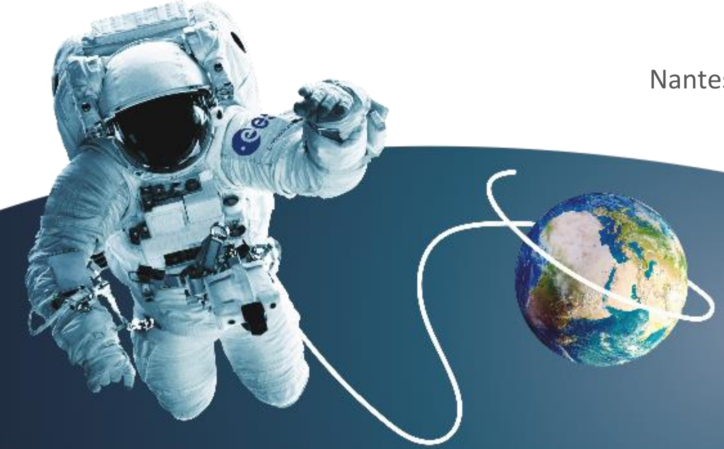
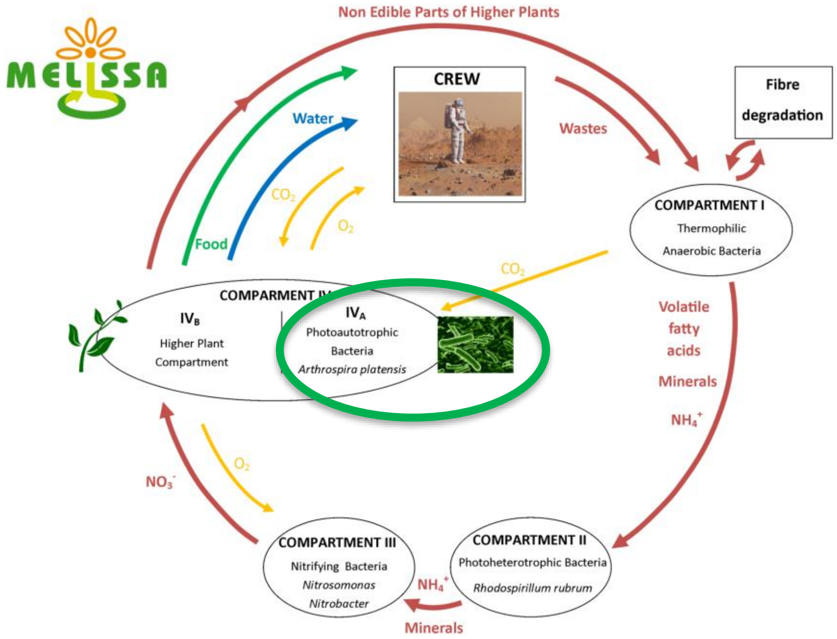


http://www.gepea.fr/

BIOFACADE: CONTEXT



<u>MELiSSA regenerative life support systems</u>

photosynthetic organisms (compartment IV) ability to produce edible biomass while enabling to treat gas and liquid effluents

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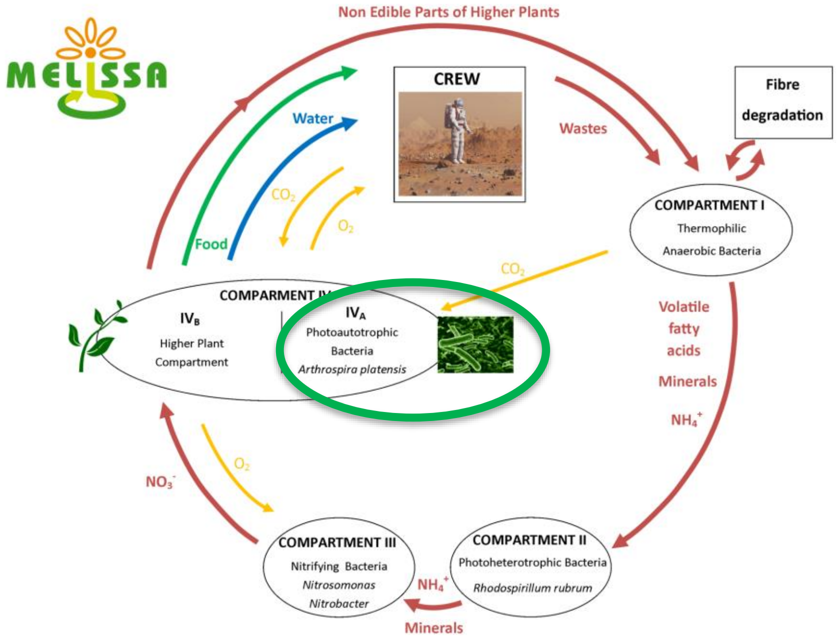

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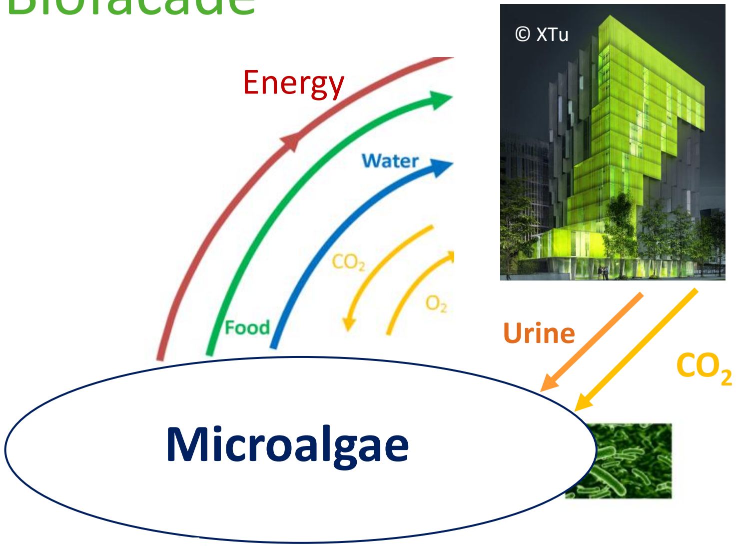
BIOFACADE: CONTEXT

Biofacade



Terrestrial application of MELiSSA loop concepts

A vertical flat-panel **photobioreactor (PBR),** on external building **wall** to connect **building metabolism** and **microalgal metabolism**

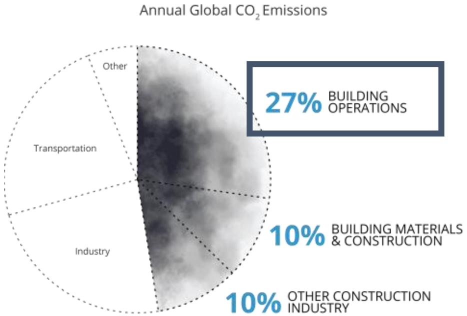
WHY CULTIVATING MICROALGAE ON BUILDING FACADE ?

Challenges :

1. Cost-efficiency of microalgae cultivation systems
2. Land competition
3. Pollution from the use of synthetic nutrients
4. Buildings : about 30% of greenhouse gas (GHG) emissions

Moroccan phosphate mine

Eutrophication of aquatic environment



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Solutions :

1. Sharing construction materials of buildings and cultivation systems
2. Using illuminated building walls
3. Recycle the nutrients produced by the building
4. Heat and matter exchanges

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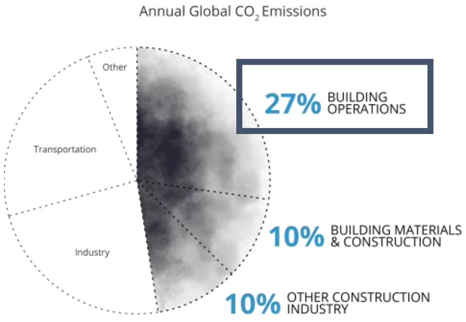

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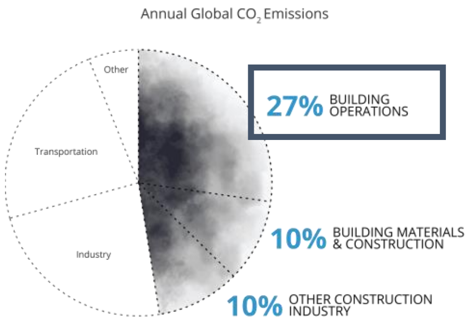

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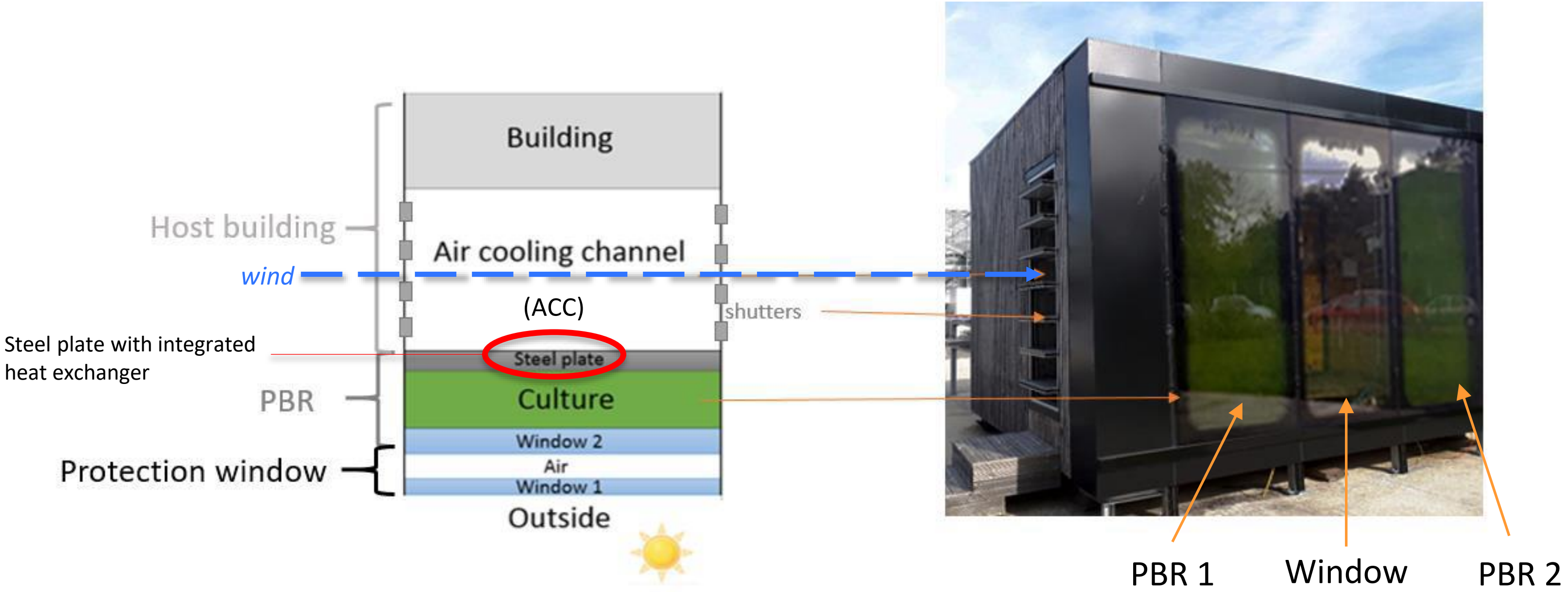
Ambitions :

1. **Decrease human** footprint by improving building energy performances thanks to the **biofacade that can act as an insulator and a waste treatment plant** (wastewater and flue gas)
2. Produce **high quality** and **quantity of biomass** with a **cost-effective** and **sustainable** process

MICROALGAE-BASED BIOFACADE: DEFINITION

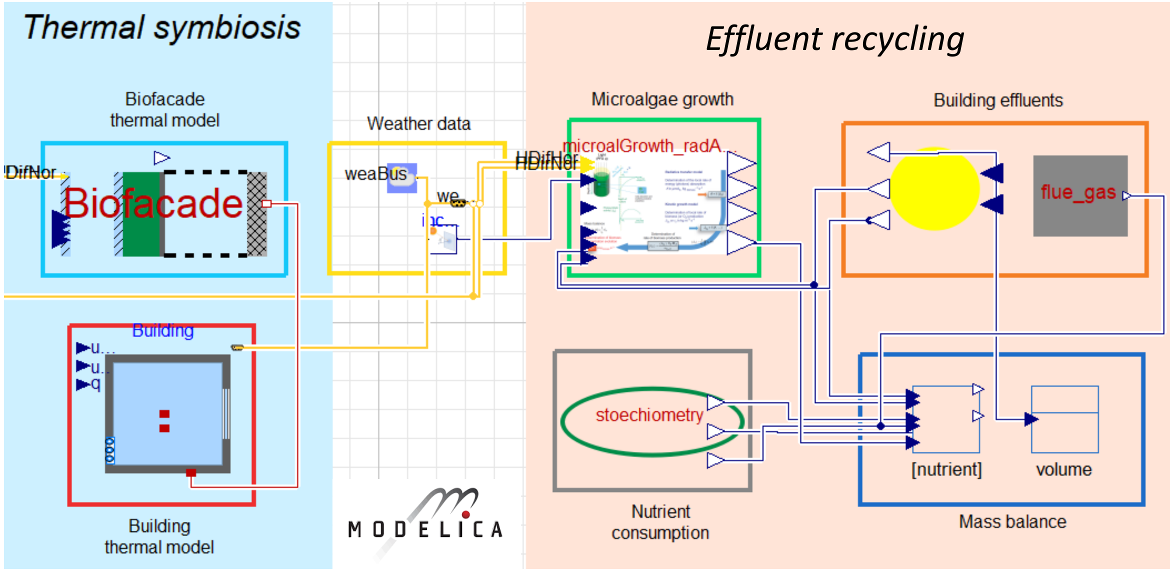
European patent: « Curtain walls for the industrial optimized production of microalgae on building walls »
By X-Tu Architecture and GEPEA (UMR CNRS / Nantes université / ONIRIS / IMT Atlantique)



Double layer ventilated façade on the building to cultivate microalgae

MICROALGAE-BASED BIOFACADE: OBJECTIVE

How to create a symbiosis between the microalgae culture and its host building and evaluate the impact towards the implementation of a sustainable system?



Screenshot of the system model in Dymola 2021

Dynamic model of the biofacade-building system to study and size the exchange loops between the building and the façade PBRs

OUTLINE OF THE PRESENTATION

I. Thermal model

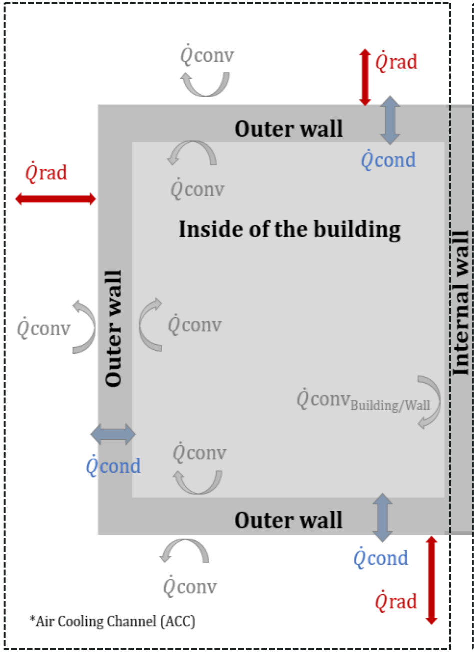
II. Effluent recycling model

III. Conclusion: system model

THERMAL MODEL BUILDING –BIOFACADE: DEFINITION

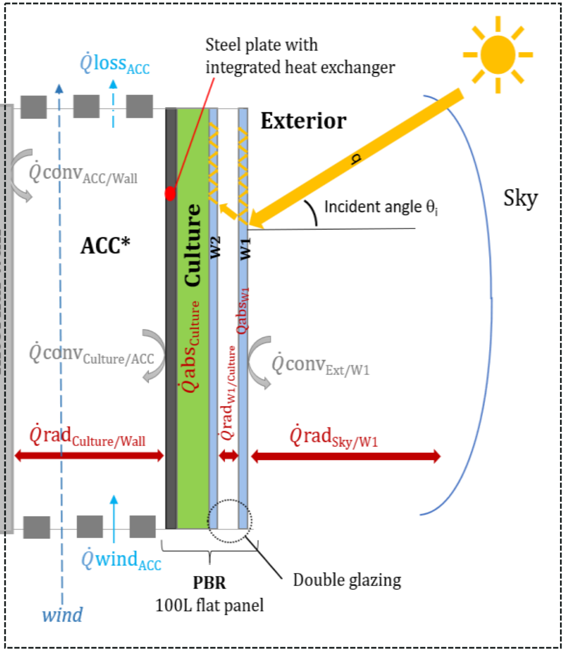
Wetter *et al.* (2014)

Modelica Buildings library : Room model



Todisco *et al.* (2022)

Biofacade thermal and optical model



$$\frac{dT_{building}}{dt} = \sum flux + Q_{reg}$$

$$\frac{dT_{culture}}{dt} = \sum flux + Q_{reg}$$

$$Annual\ consumption = \int_{j=1}^{j=365} Q_{reg}$$

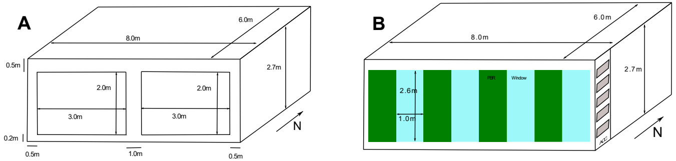
with Q_{reg} is the heating/cooling capacity required to maintain building air temperature and culture medium temperature within the set point ranges

Calculate the energy consumption for thermal regulation of the air inside the building and of the culture medium temperature according to the location

THERMAL MODEL BUILDING –BIOFACADE: CASE STUDY

Simulation conditions :

- 48m^2 standard heavy weight building with thermal regulation 20°C-27°C
- 8m^2 microalgae biofacade (alternating windows and PBRs) with thermal regulation 15°C-35 °C
- Locations : Nantes (France) and Los-Angeles (USA)



A) Standard building B) building with a microalgae biofacade

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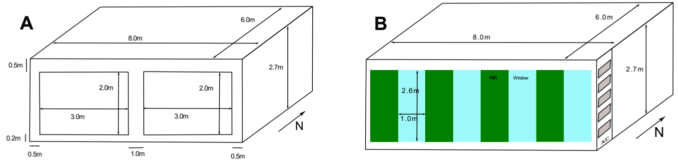

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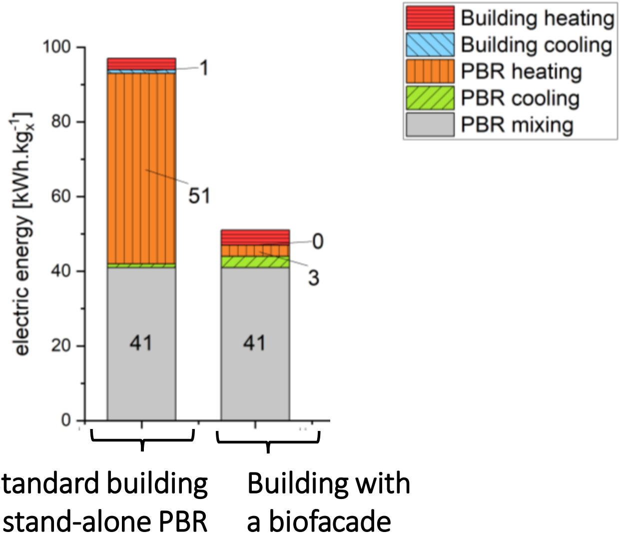

Annual electric energy consumption for building and PBR thermal regulation and culture mixing by air injection

	Nantes (France)	**Los-Angeles (USA)**
Theoretical surface productivity (kg.m^{-2}.year^{-1})	3	4,6

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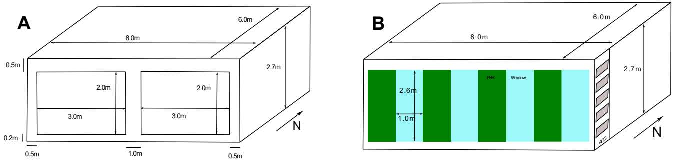

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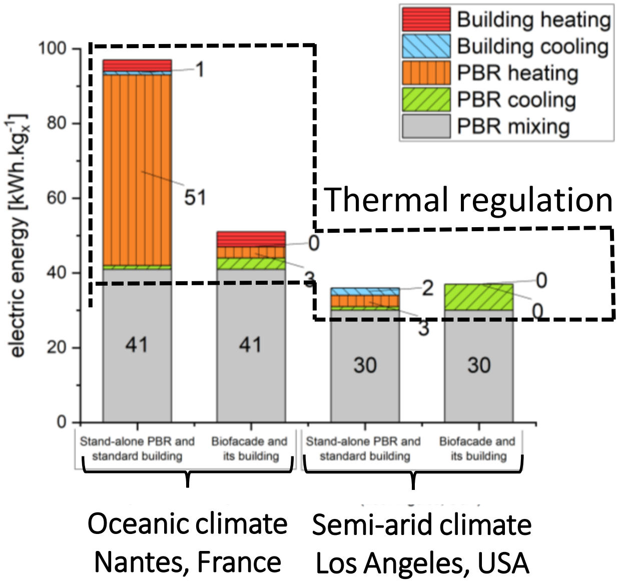

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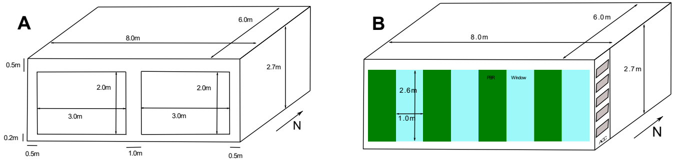

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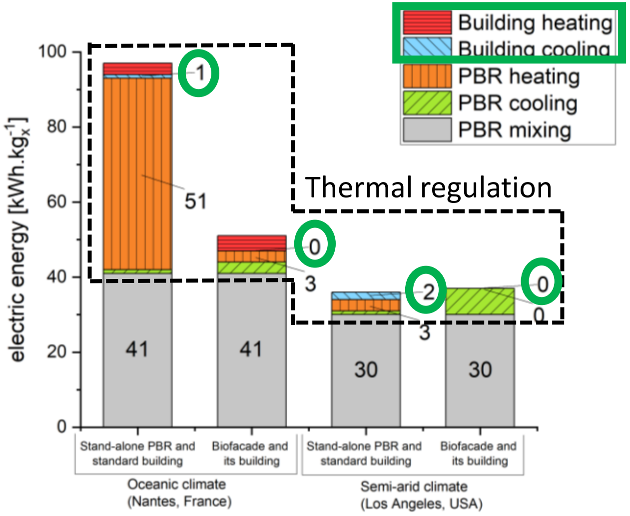

Annual electric energy consumption for building and PBR thermal regulation and culture mixing by air injection

↘↘ Building cooling demand (curtain wall effect)

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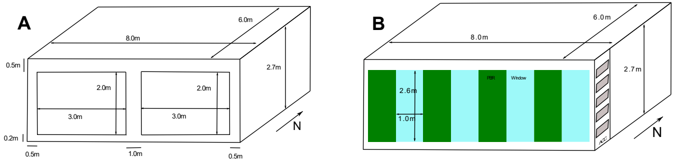

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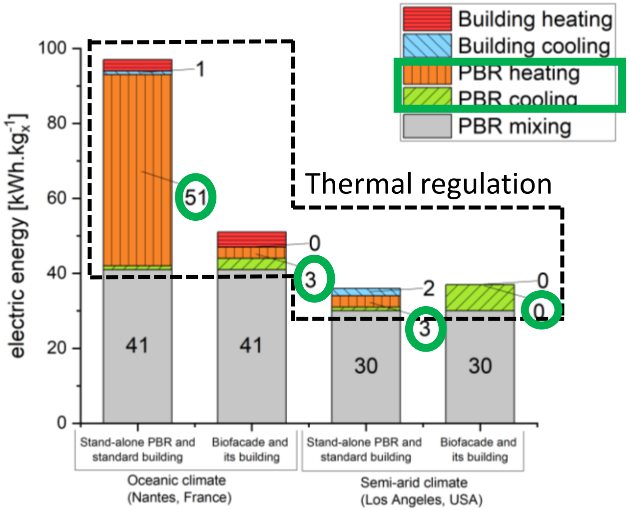

Annual electric energy consumption for building and PBR thermal regulation and culture mixing by air injection

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↘↘ PBR heating demand

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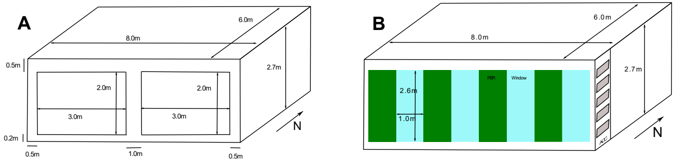

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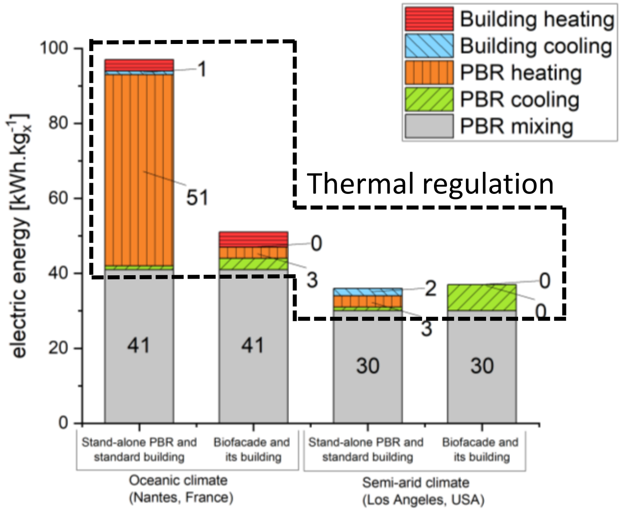

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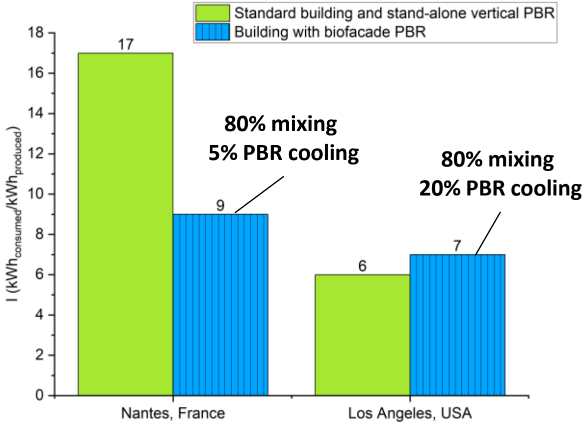

Ratio of the annual energy consumed by the system over the energy produced by the biomass

	Nantes (France)	Los-Angeles (USA)
Theoretical surface productivity (kg.m^{-2}.year^{-1})	3	4,6

Thanks to the biofacade the energy consumption of the system is halved in temperate climate and unchanged in semi-arid climate

Perspectives: optimization of culture mixing and passive PBR cooling

EFFLUENT RECYCLING MODEL: DEFINITION

Simulating the use of building effluents as nutrient source for microalgae culture

Yellow water as nitrogen and phosphorus resource for microalgae production

Input → Equations → Output

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  ↳ Bisinella *et al.* (2020)
    Flow
    Nutrient concentrations

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- Microalgae growth → Pruvost *et al.* (2012)

$$<rx_{lim}> = \underset{\text{Photolimited growth}}{\boxed{<rx>}} \times \underset{\text{Nutrient limitation}}{\boxed{\frac{[NH_4]}{K_N+[NH_4]} \times \frac{[PO_4]}{K_P+[PO_4]} \times \frac{[C_T]}{K_C+[C_T]}}}$$

with $<rx>$ biomass productivity in light limited condition:

$\frac{dCx}{dt} =<rx> -(\boldsymbol{D} \times Cx)$ and K_N=1.75 mM, K_P=0.11 mM, K_C=0.03mM

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- Nutrient consumption → Hadj-Romdhane *et al.* (2012)

Element i	**C**	**N**	**P**
Quantity of i consumed by quantity of biomass produced: Y_i (kg_i/kg_x)	1,832	0,119	0,028

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Stoichiometry

Chlorella vulgaris :

$HCO_3^- + 0{,}495H_2O + 0{,}159NH_4^+ + 0{,}006SO_2^{4-} + 0{,}007PO_4^{3-} \rightarrow CH_{1{,}750}O_{0{,}413}N_{0{,}159}S_{0{,}006}P_{0{,}007} + 1{,}129O_2 + 0{,}874OH^-$

Equations

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Output

Mass balance:

$$\frac{d[I]}{dt} = \underbrace{D \times [I]_{in} - D}_{\text{Flow}} \times \underbrace{[I] - Y_i \times < rx_{lim} >}_{\text{Microalgae consumption}}$$

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Output

- Biomass productivity (g.m^{-2}.d^{-1})
- Purification efficiency (%) :

$$\eta = \frac{[I]_{WW} - [I]_{sPBR}}{[I]_{WW}} \times 100$$

- Environmental impact ($kgCO_{2eq}$)

Mass balance:

$$\frac{d[I]}{dt} = \underbrace{\boxed{D \times [I]_{in} - D}}_{\text{Flow}} \times \underbrace{\boxed{[I] - Y_i \times < rx_{lim} >}}_{\text{Microalgae consumption}}$$

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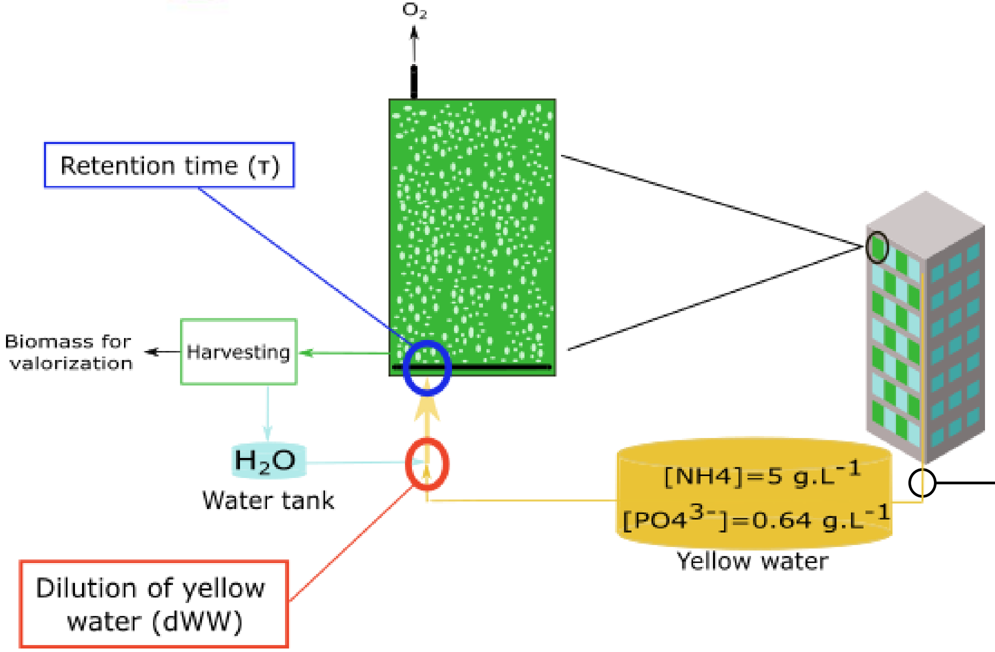
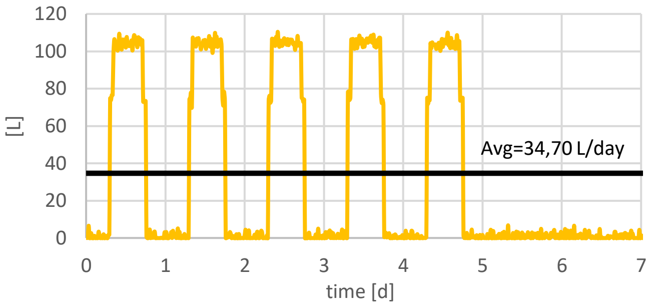


Process for recycling yellow water for cultivation of microalgae on a building facade

<u>Simulation conditions</u>:

- 1000 m^2 office building (AFNOR 100 people), yellow water collected at 100% without dilution with flush water
- 350m^2 biofacade: alternating PBRs and windows (67 100L PBRs)
- PBRs operated at constant light q=270 µmole$_{hv}$.m^{-2}.s^{-1} (annual average in Nantes, France)

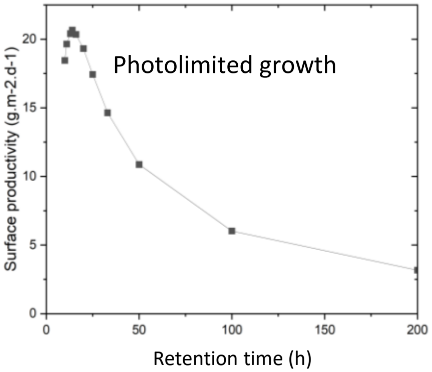


Yellow water production of a 1000 m^2 office building and average weekly flow

Objective: maximal purification efficiency and biomass productivity

EFFLUENT RECYCLING MODEL: RESULTS

Biomass productivity



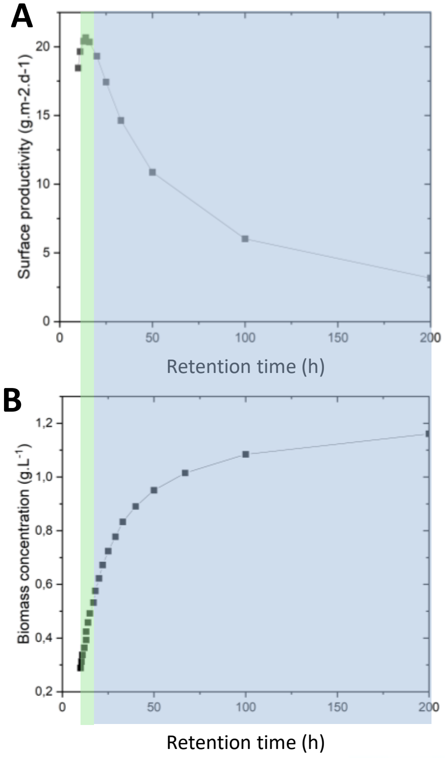
Purification efficiency

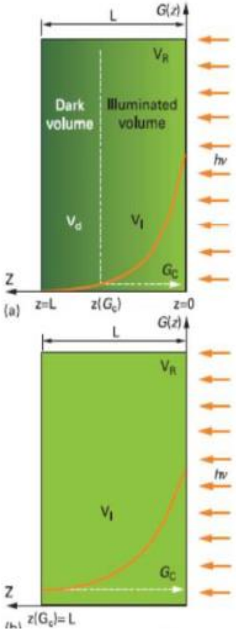
Environmental impact

EFFLUENT RECYCLING MODEL: RESULTS

Biomass productivity

The shorter the retention time, the lower the biomasse concentration hence the lower the dark volume in the reactor





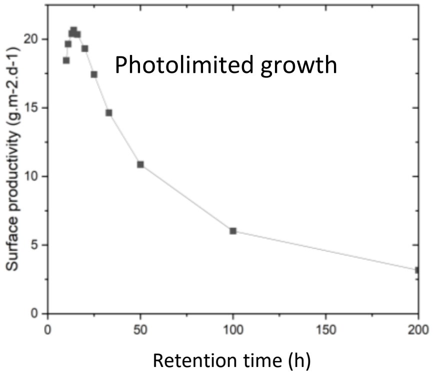
Photolimited

Luminostat

Theoretical A) surface productivity and B) biomass concentration of Chlorella vulgaris as a function of retention time for a 3,8 cm deep PBR operating at q=270 µmole$_{hv}$.m^{-2}.s^{-1}

EFFLUENT RECYCLING MODEL: RESULTS

Biomass productivity



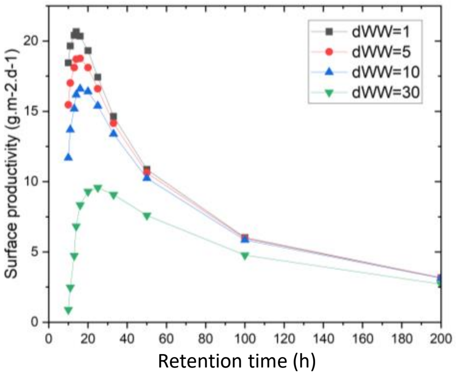
Purification efficiency

Environmental impact

EFFLUENT RECYCLING MODEL: RESULTS

Biomass productivity

The more diluted the yellow water, the lower the biomass productivity ➔ nutrient limited growth



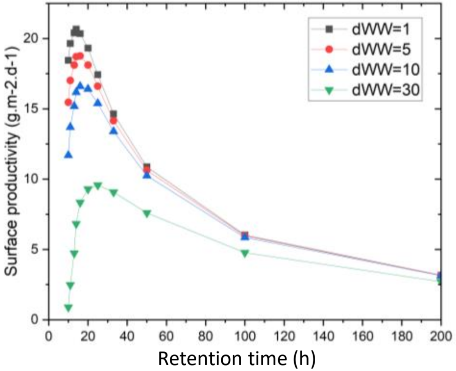
Purification efficiency

Environmental impact

EFFLUENT RECYCLING MODEL: RESULTS

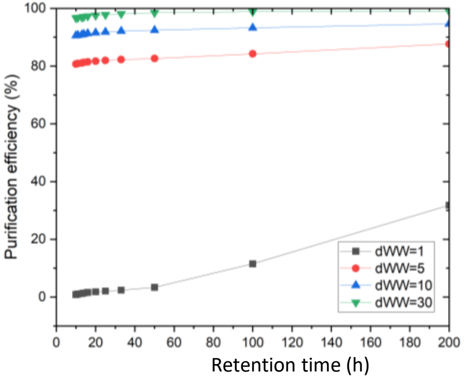
Biomass productivity

The more diluted the yellow water, the lower the biomass productivity ➔ nutrient limited growth



Purification efficiency

The more diluted the yellow water, the higher the purification efficiency



Environmental impact

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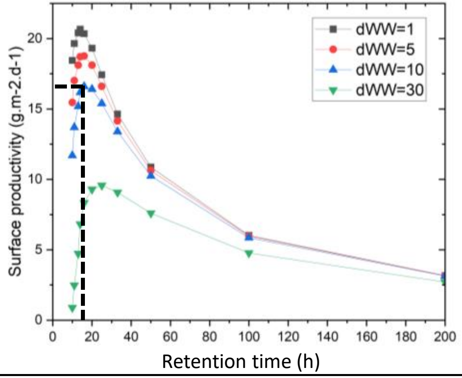

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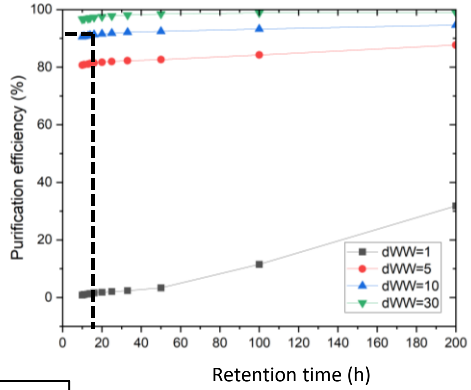


Trade-off between purification efficiency and biomass productivity

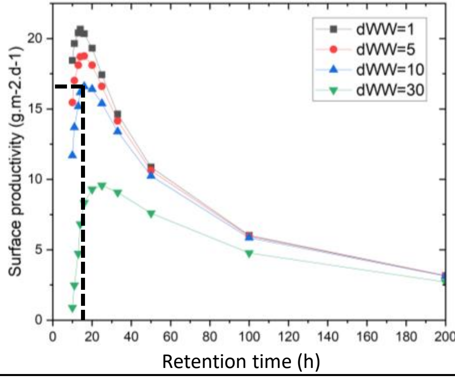
τ=16 h, dWW= 10 → biomass productivity about 15g.m^{-2}.d^{-1}, yellow water purification efficiency about 90%

Environmental impact

EFFLUENT RECYCLING MODEL: RESULTS

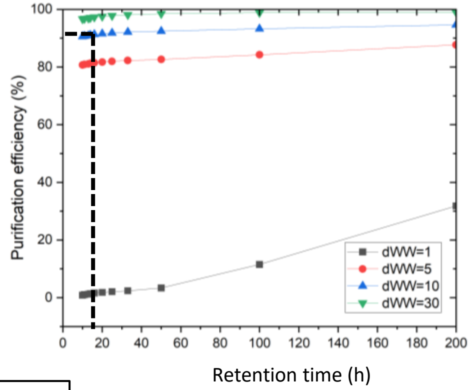
Biomass productivity

The more diluted the yellow water, the lower the biomass productivity ➔ nutrient limited growth



Purification efficiency

The more diluted the yellow water, the higher purification efficiency



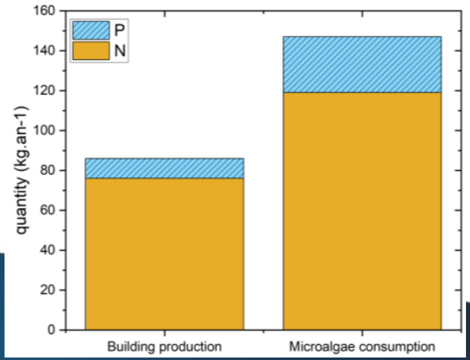
Trade-off between purification efficiency and biomass productivity

τ=16 h, dWW= 10 → biomass productivity about 15g.m^{-2}.d^{-1}, yellow water purification efficiency about 90%

Environmental impact

With 90% yellow water purification: 60% of the annual nitrogen and 40% of phosphorus is recovered for biomass production

➔ Reduce the need for synthetic nutrients



Annual nutrient production of the building annual nutrient consumption of the microalgae

Conclusion

System model calculates:

- Energy consumption for building and PBRs thermal regulation
- Optimal operating parameters to maximize biomass productivity and yellow water purification

Promising terrestrial application of the MELiSSA process to develop sustainable buildings and microalgae cultivation systems

Perspectives

Use the system model for:

- PBRs optimization (passive cooling and mixing)
- Simulating building flue gas as a source of inorganic carbon for microalgae culture

MELiSSA

MICRO-ECOLOGICAL
LIFE SUPPORT SYSTEM
ALTERNATIVE

THANK YOU.

Flora GIRARD

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Unil
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vito

BIOFACADE: PROJECTS

Renovation: **SymBIO2** (2019)
CSTB Champ sur Marne

Pilot : 200 m^2 biofacade

Construction: **ALGUESENS** (2023)
Paris 13

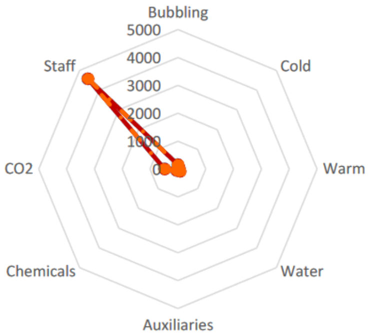
17 450 m^2 building
(housing and laboratories)
500 m^2 biofacade

SymBIO$_2$ consortium: XTU, VIRY FAYAT GROUP, OASIIS EXPERT EN PERFORMANCE ENVIRONNEMENTALE, Séché environnement Séché global solutions, GEPEA UMR CNRS 6144, AlgoSource microalgae for health, KALITEC GÉNIE CLIMATIQUE

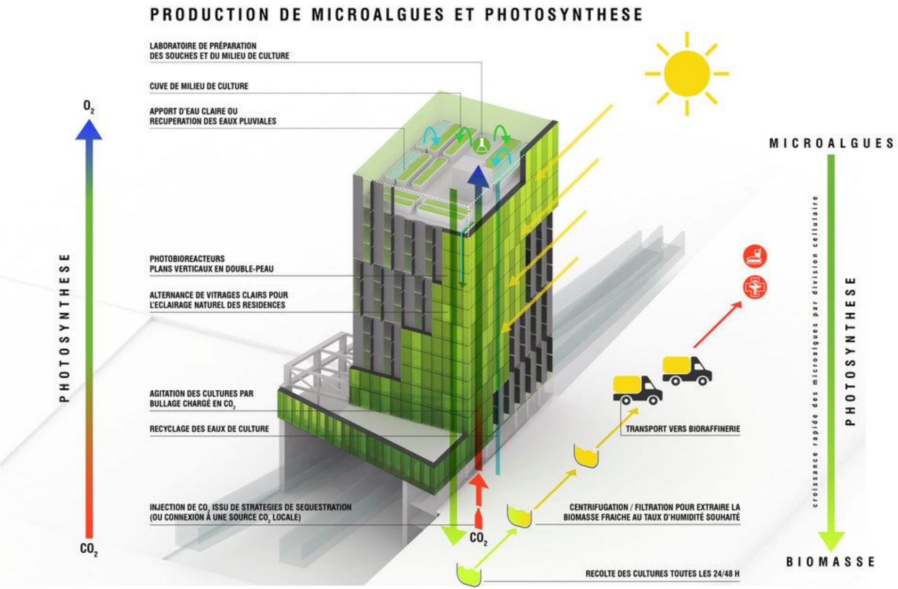
BIOFACADE: USE

Prices:
- Biofacade: 2000-3000 €/m^2
- Technical room: 50 K€-500 K€
- Biomass sales price: 450 (dry) -10000 (molecules of interest) €/kg

Maintenance: automation
+ 1 technician



Repartition of OPEX per PBR over a year (€)



Equation-based and object-oriented system modeling language

Objective: unify the object-oriented language by designing a new language for the representation of system models

[Mattsson, Sven Erik, et Hilding Elmqvist. (1997)]

BENEFITS

Multi-physics

- Thermal
- Electrical
- Mechanical
- Biology

Libraries of standard or new components

Interoperability
(FMI standard)

Solver: Integration algorithm types

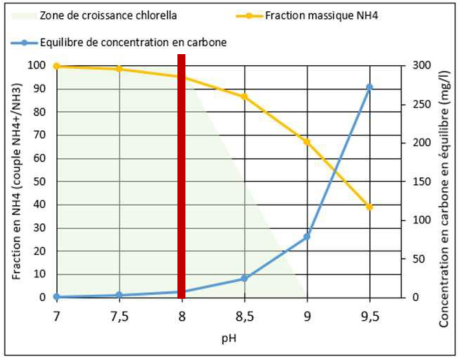
Euler
DASSL: Runge Kutta
Dopri45: Backward Differentiation Formulas
etc.

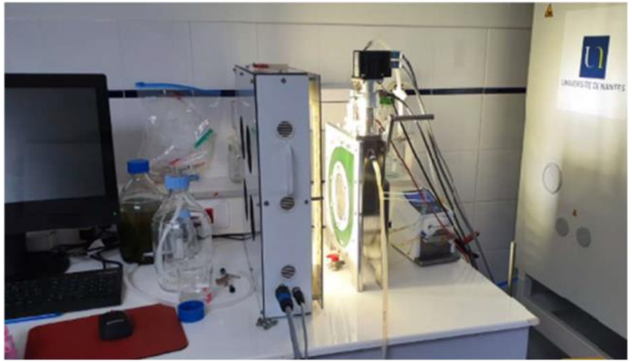
Fixed step

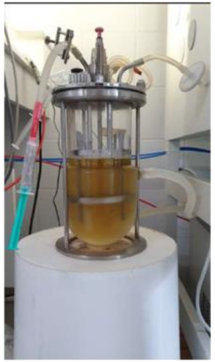
Variable step

YELLOW WATER FOR MICROALGAE CULTURE

$$CO(NH_2)_2 + 2H_2O \rightarrow NH_3 + NH_4^+ + HCO_3^-$$



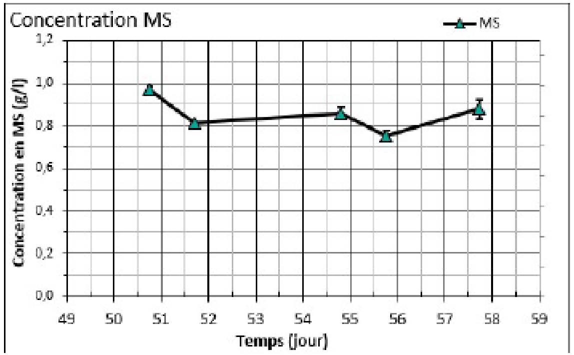


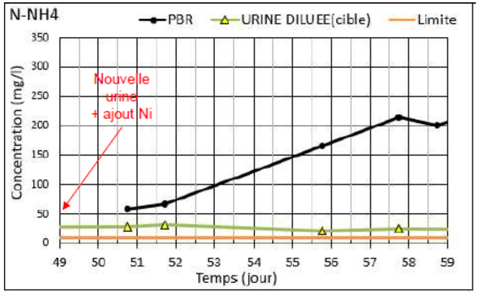


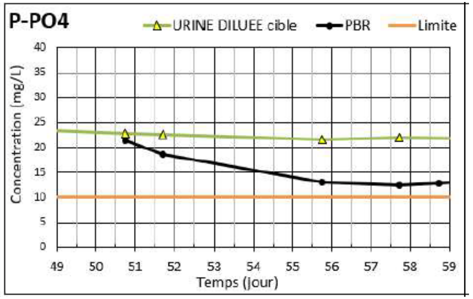
Microalgae culture at pH=8, T=23°C and q=270 µmole$_{hv}$.m^{-2}.s^{-1} with stabilized urine

Urine storage at 4°C

10 fold dilution
+ acid
+ Mg
+ Ni







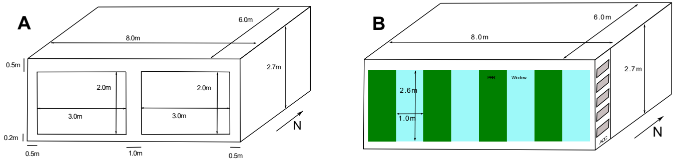
Biomass productivity = 11 g.m^{-2}.d^{-1}
With microalgae on good physiological state

Litterature :
Tuantet et al. (2013, 2014, 2019)

PASSIVE COOLING POTENTIAL OF THE ACC

Simulation conditions :

- 48m^2 standard heavy weight building with thermal regulation 20°C-27°C
- 8m^2 microalgae biofacade (alternating windows and PBRs) with thermal regulation 15°C-35 °C
- Locations : Nantes (France) and Los-Angeles (USA)



A) Standard building B) building with a microalgae-based biofacade

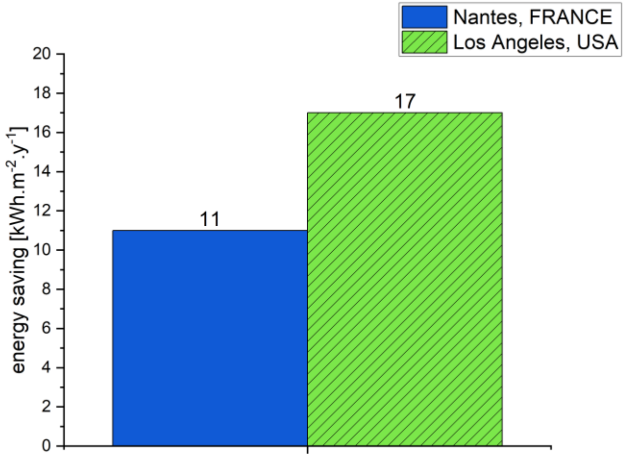
Thermal balance on ACC

$$m \times Cp \times \frac{dT_{ACC}}{dt} = \dot{Q}conv_{building} + \dot{Q}conv_{PBR} + \dot{Q}wind$$

$$\dot{Q}wind = d_{Air} \times A_{shutters} \times Cp \times Uwind_{ext} \times F_{wind} \times (T_{ACC} - T_{ext})$$

with dAir air density [kg.m^{-3}], $A_{shutter}$ shutter area of the ACC [m^2], $Uwind_{ext}$ outdoor wind speed [m.s^{-1}], F_{wind} = 0.025 empiric adjustment factor measured on the Symbio2BOX pilot

$$ACC\ energy\ saving = \int_{t=0}^{t=i} \left|\dot{Q}wind\right|$$



Annual energy savings by natural ventilation in the ACC, in Nantes and in Los Angeles

In that case, the passive cooling effect provided by the ACC represents 16% of the system cooling energy consumption in Nantes and 9% in Los Angeles

CO$_2$ FROM FLUE GAS AS A CARBON SOURCE FOR MICROALGAE CULTURE

- **Carbon :**

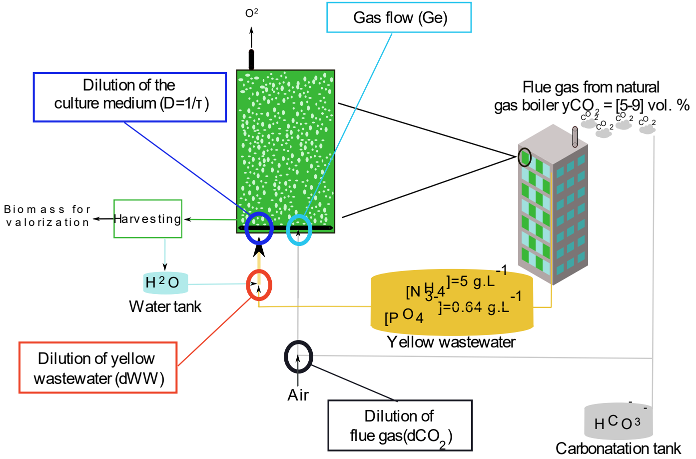
Gaz liquid transfer **Microalgae consumption** **Supply**

Balance on liquid phase $\frac{dC_T}{dt} = \boxed{k_L a \times (\frac{y_{CO2}^{out} \times p_{CO_2}}{H_{CO_2}} - \frac{C_T}{K})} - \boxed{Y_{CO_2/X} \times < r_x >} + \boxed{D \times (C_{total}^{in} - C_{total}^{out})}$

With $K = 1 + \frac{K_1}{C_H^+} + \frac{K_1 K_2}{C_{H+}^2}$ chemical equilibrium constant of carbon

Balance on gaseous phase $\frac{dC_{CO2}}{dt} = \boxed{-k_L a \times \left(\frac{y_{CO2}^{out} \times p_{CO_2}}{H_{CO_2}} - \frac{C_T}{K}\right)} + \boxed{\frac{Ge}{Vl} \times \Delta y_{CO2}}$

With $\Delta y_{CO2} = y_{CO2}^{in} - y_{CO2}^{out}$ and $y_{CO2}^{in} = \frac{y_{CO2}}{dCO_2}$, Ge gaz flow and Vl liquid volume of the PBR



Calculation of the boiler flue gas flow as a function of the heating demand to regulate the temperature of the building and the culture medium

Methodology : *EN 12952-15*

Hypothesis :

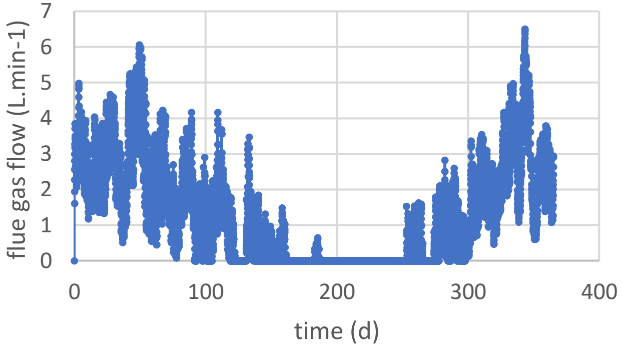
- 48m^2 standard heavy weight building with thermal regulation 20°C-27°C
- 8m^2 microalgae biofacade (alterning window and PBR) with thermal regulation 15°C-35 °C

Calculation :

Stoichiometric flue gas flow (m3.s^{-1}) = S x P$_{th}$

With S=0,240 m3.MJ^{-1} for natural gas and 0% O$_2$ dry 273.15K & 101.325kPa

And P$_{th}$ (MW) is the process heat release calculated with the thermal model of a building equipped with a biofacade



Stoechiometric flue gas flow produced by a natural gas boiler for heating a building and its biofacade over a year in Nantes