Modeling and optimisation of energy systems

The 2025 version

Prof. François Marechal
EPFL

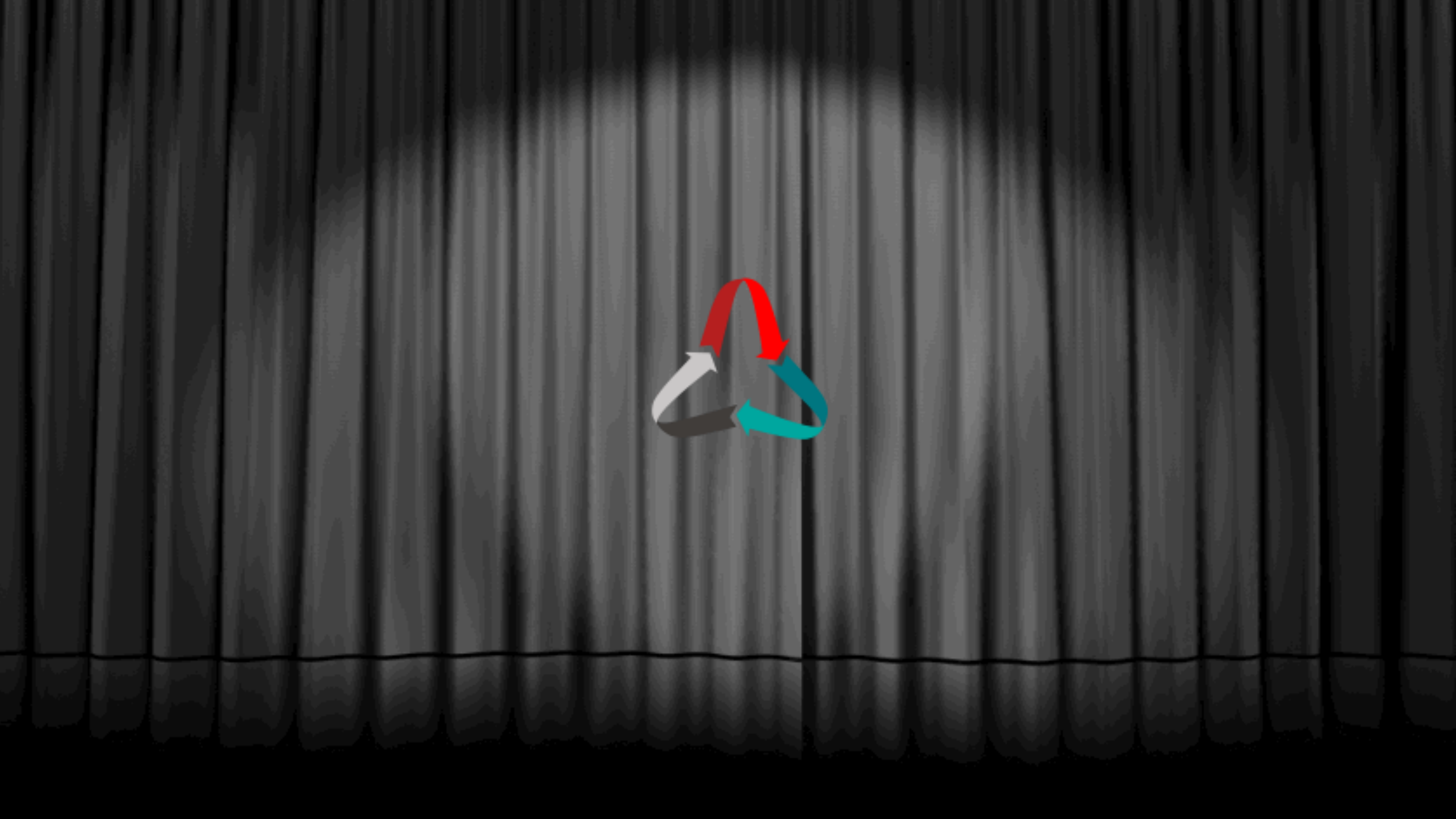
IPESE
Industrial Process
and Energy Systems
Engineering

Prof. François Marechal
Industrial Process and Energy Systems Engineering
EPFL Valais-Wallis, Energypolis, Sion

Chemical engineering …
Maried, 3 enfants

STI - Sciences et Techniques de l'Ingénieur
GM - Section Génie Mécanique

- Orientation Energie
- Minor Energie



ME-454 : Modeling and optimisation of Energy Systems

- Prof François Marechal
    - http://people.epfl.ch/francois.marechal, @francoismarechal.bsky.social
- Industrial Process and Energy Systems Engineering
    - http://ipese.epfl.ch - https://www.linkedin.com/company/ipese-epfl
    - IPESE—IGM-STI-EPFL
    - Ecole Polytechnique Federale de Lausanne
    - EPFL Valais-Wallis
    - CH-1951 Sion
- Assistants :
    - **Sai Sudharshan Ravi, Luc Giradin, Arthur Waeber**
    - **Student Assistants : Michele Poli**

The schedule of today

- Introduction to the course: Prof. F. Maréchal
  - Teaching concepts and organisation
  - Computational thinking …
- Project based learning concept
  - Introduction to the project chalenges
  - How it will be realised
- Project : Introduction of the project tools
  - how do we proceed ? what will be the tools used ?

What is an energy system ?

Our chalenge : Engineering the Efficiency for a Net-Zero future

Fossil resources
From where-When-How much - At which cost ?

Renewable resources
Where-When-How much ?

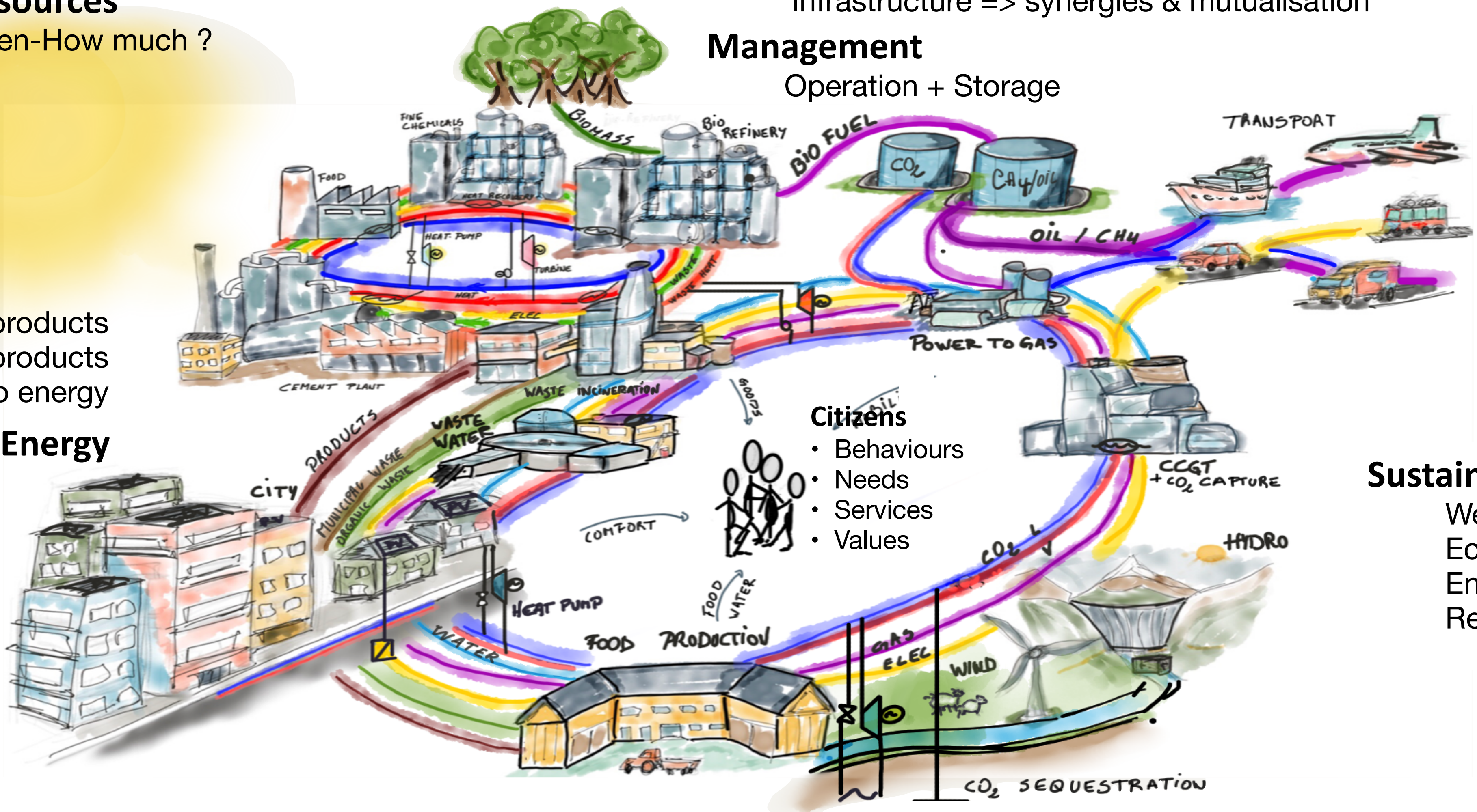
Investments
(**New**) Technologies
sizes : conversion and storage
Infrastructure => synergies & mutualisation

Management
Operation + Storage

Demand
Products
Services
Security of supply

Circularity
Waste to products
CO2 to products
Waste to energy

Waste-Water-Energy

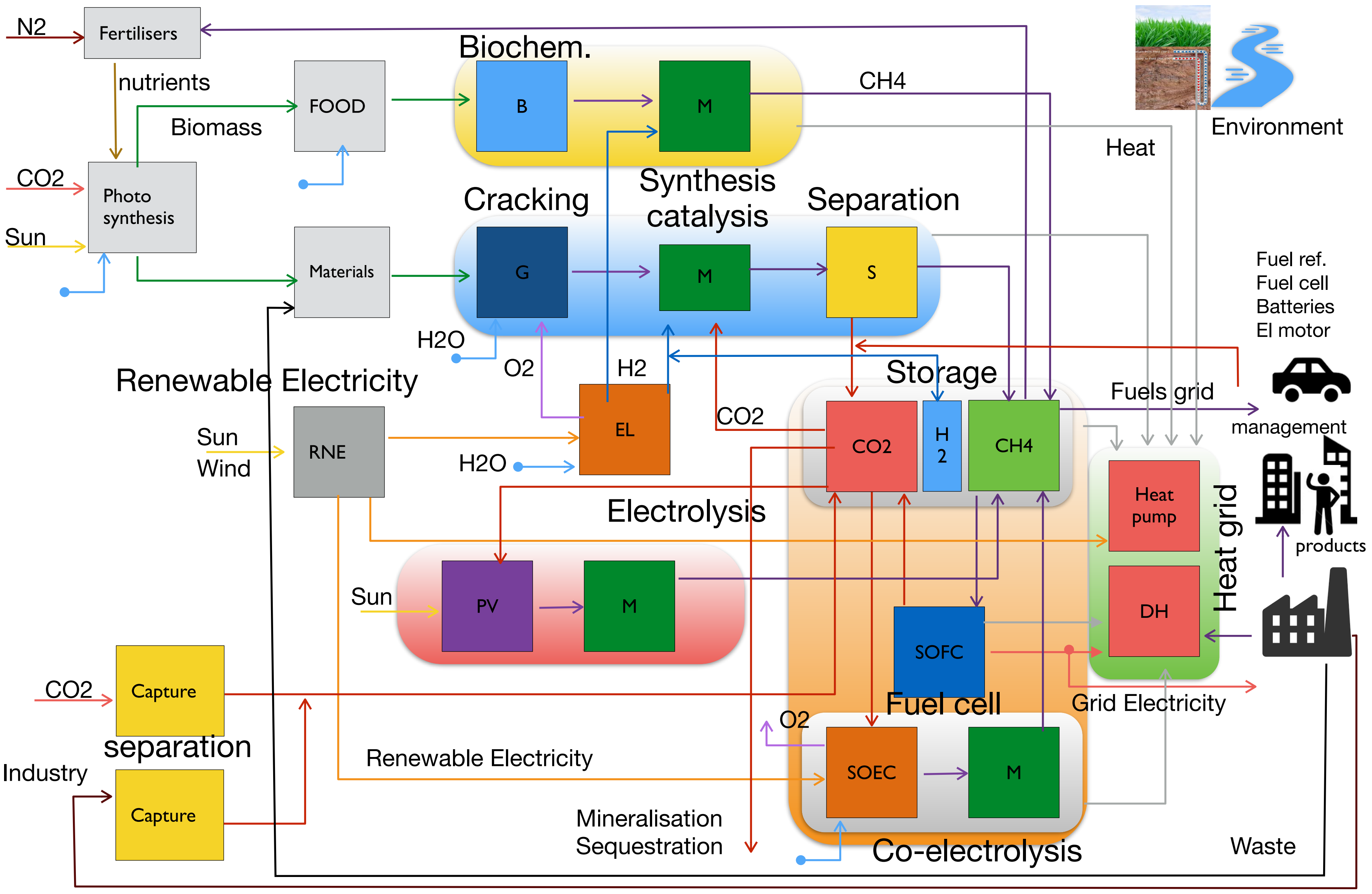


Citizens
- Behaviours
- Needs
- Services
- Values

Sustainability metrics
Wealth
Economic
Environment
Resiliency

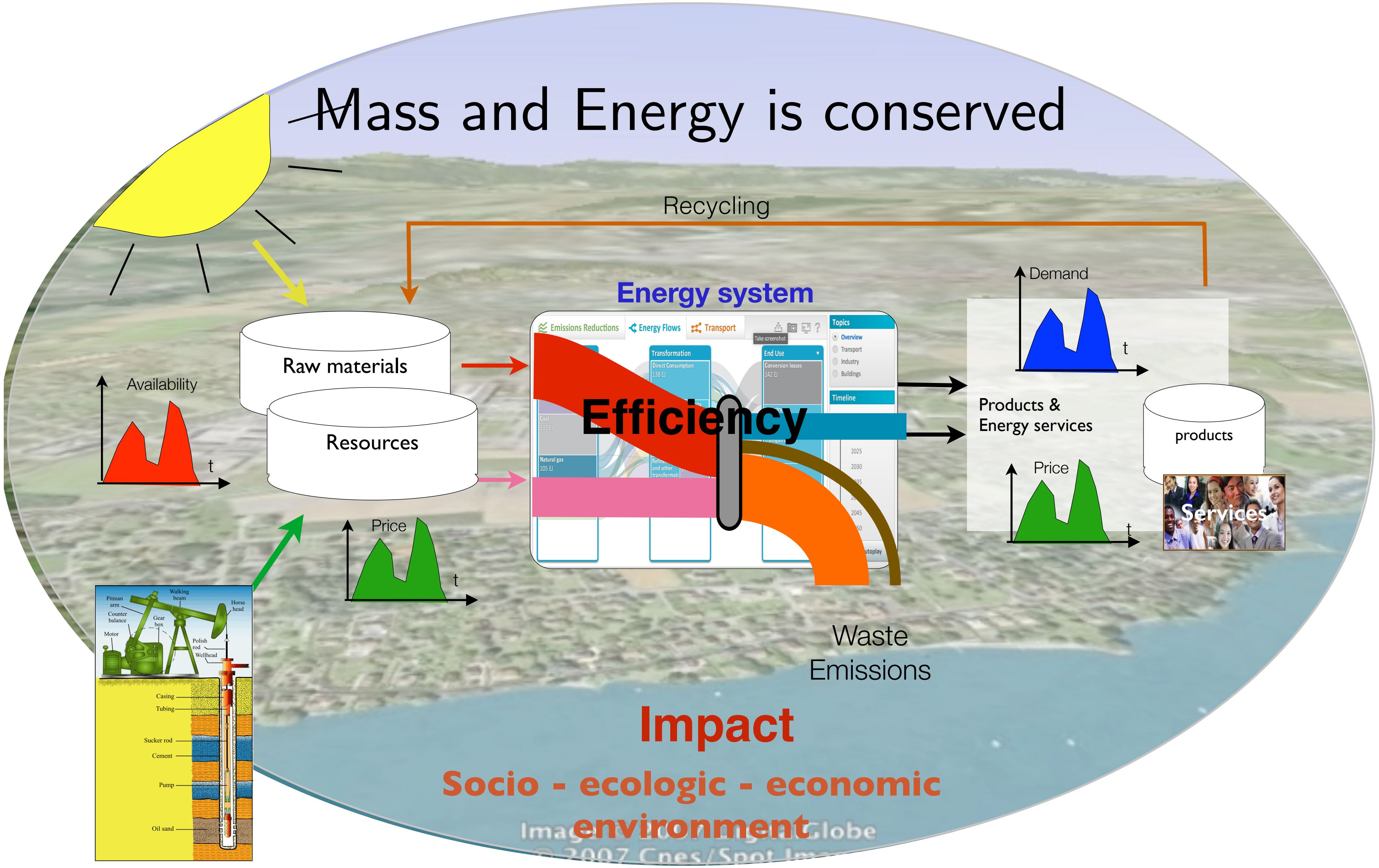
CO2 sequestration

EPFL The integated energy system

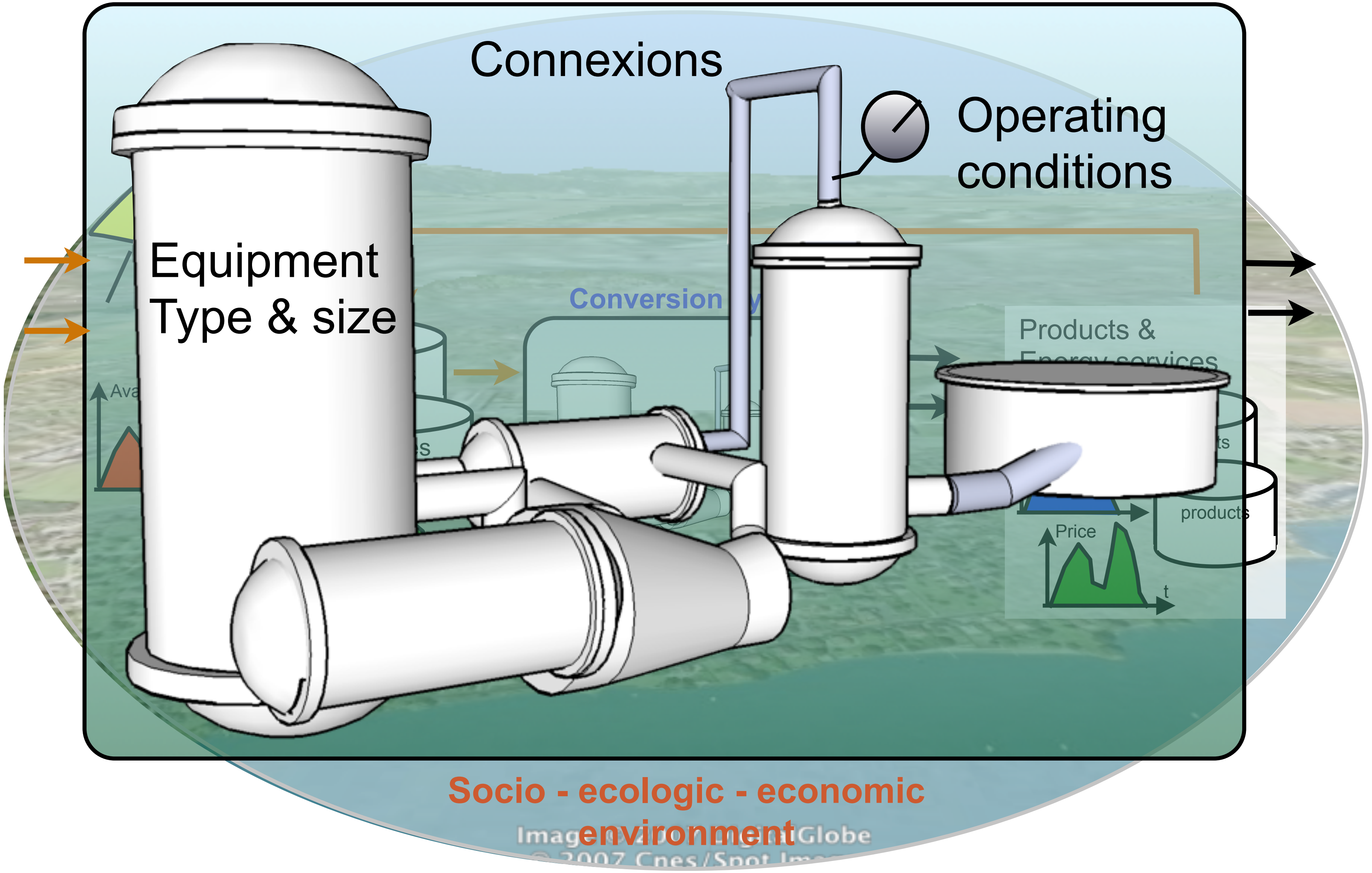


Resources → Technologies → Distribution → Supply chain → Seasonal storage → Daily storage

Efficiency of an energy system



Engineering decisions in energy systems



- Modeling of an energy system ?

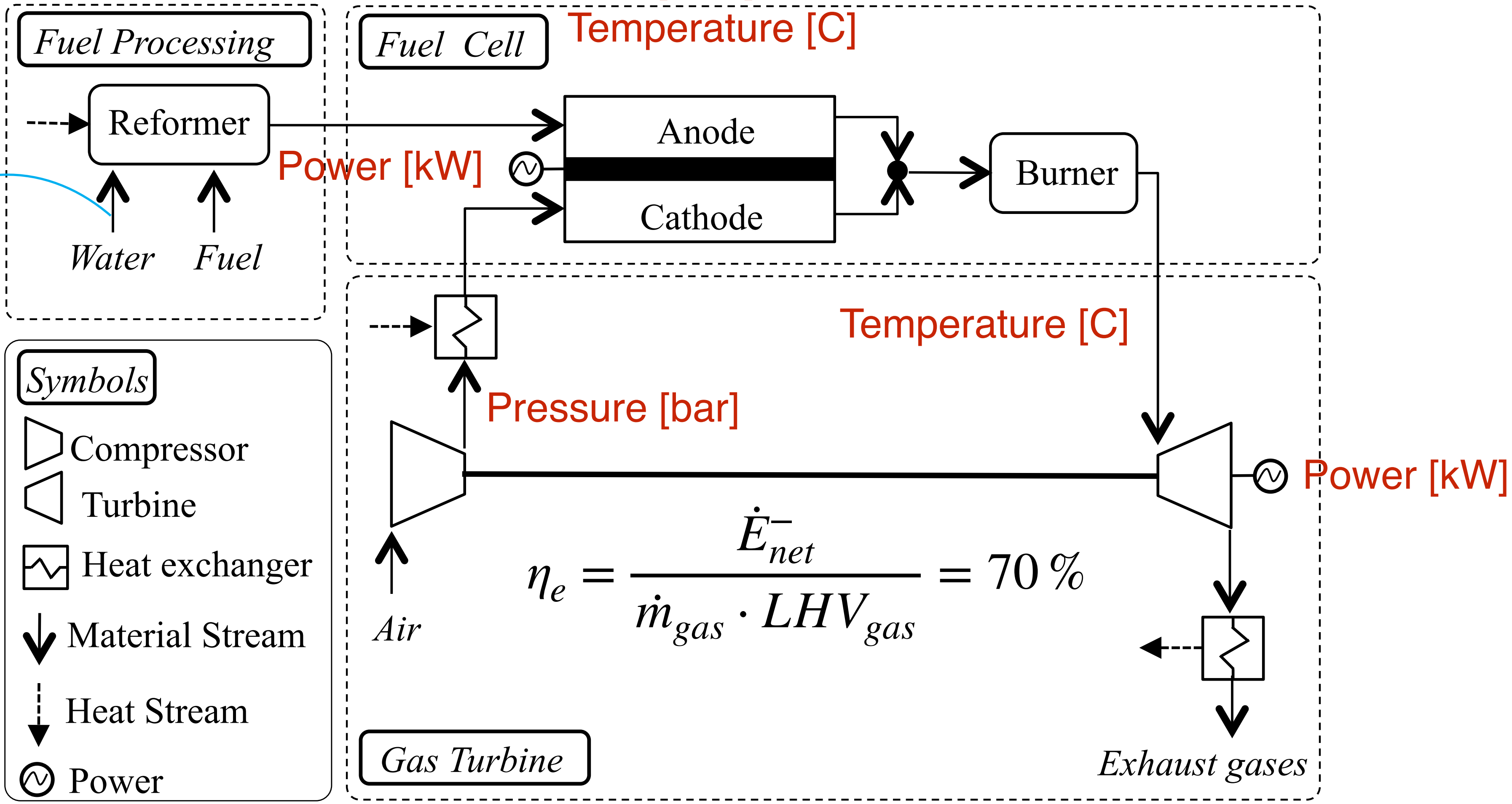
Flowsheet : flows in process units interconnected by pipes and wires

Streams that transport mass and/or energy

Flow [kg/s]
Temperature [C]
Pressure [Bar]
Composition[%]

Process units: equipments that convert mass and energy

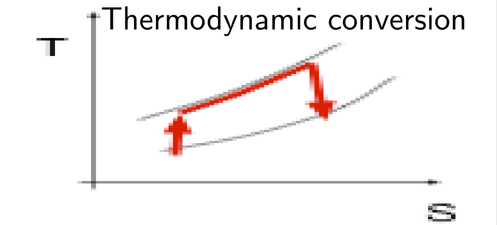
Size [m^2]
Temperature [C]



Flow [kg/s]
CO2 [%vol]

Thermo-economic modelling of Energy system

System model



Thermodynamical state

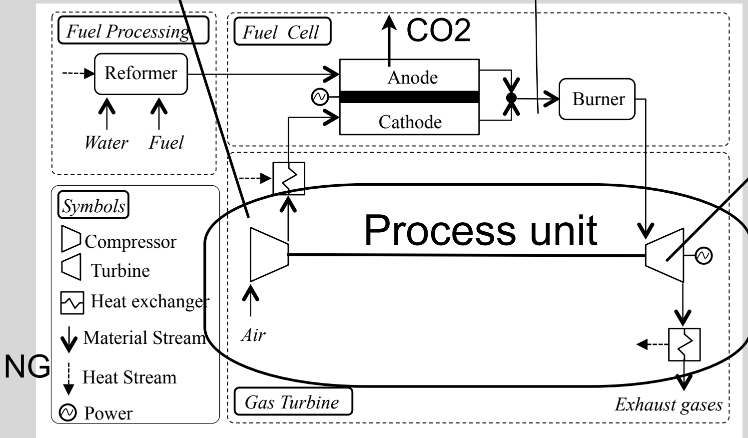
Flows => System States

$$\dot{M}_{fe,t}, \dot{E}_{fe,t}, T_{fe,t}, P_{fe,t}, X_{fe,t}$$

Economic investment

Equipment => Size or capacity installed

$$Size_e = \phi_{ce}(\pi_e, \dot{M}_{fe,t}, \dot{E}_{fe,t}, T_{fe,t}, P_{fe,t}, X_{fe,t})$$



Process flowsheet

System performance metric

Key Performance Indicator

$$KPI_p = \int_{t=0}^{lifetime} \left(\sum_f c_{p,f,t} \cdot \dot{M}^+_{f,t} \right) \cdot dt + \sum_e \phi_c(c_{p,e}, Size_e)$$

e : equipment

t : time of operation

f : flows

KPI_p : performance indicator

$\dot{M}^+_{f,t}$: flow of f in time t of life time

$c_{p,f,t}$: value associated to flow f in time t

$Size_e$: installed capacity of equipment e

$\phi_c(c_{p,e}, Size_e)$: value function of installed capacity of equipment e in performance indicator p

Performances of an energy system : interpret the results

Capital expenditure [CHF/year]

$$CapEx = \frac{1}{\tau}\sum_i I_i$$

Investment [CHF/year]

Operating expenditure [CHF/year]

Inc. management strategy

$$OpEx = \int_{year} (\dot{M}^{+}_{NG} c^{+}_{NG} + \dot{M}^{-}_{CO_2} c^{-}_{CO_2} - (\sum_i \dot{E}^{-}_i) c^{-}_e) dt$$

Total Cost [CHF/year]

$$TotEx = CapEx + OpEx$$

Performance : Specific Cost [CHF/kJ]

$$LevelisedCost_{el} = \frac{\int_{year} (\dot{M}^{+}_{NG} c^{+}_{NG} + \dot{M}^{-}_{CO_2} c^{-}_{CO_2}) dt + \frac{1}{\tau}\sum_i I_i}{\int_{year} (\sum_i \dot{E}^{-}_i) dt}$$

- Optimisation of an energy system ?

Optimisation of an energy system

- Fix the degrees of freedom of the system by minimizing an objective
  - **Decision variables** (Degrees of freedom)
    - Existence and Size of units + Operating conditions
  - **Objective** : Conditions under which we will take decisions : e.g. cheapest cost considering the present price of the energy flows
- When fixing the degrees of freedom, the different **states** the system will see over its **lifetime** can be calculated and the system performances can be calculated
  - Flows are known for every system's states and for given equipment capacities
  - Performances metrics are known
    - Economic (under given economic market assumption : Energy+Investment)
    - Environmental

Energy system engineering : taking decisions

- Binary choices
  - Choose technologies
  - Define the interconnections (pipes)
- Continuous choices
  - Define the sizes of equipment
  - Define the size of equipment for energy management : storage tanks, batteries
  - Define strategy of operation (flows, conditions, time)
- Decision criteria
  - Maximise profit
  - Minimise environmental impact
  - Minimise global warming impact
  - Integrate renewable energy sources
  - Trade-off between different objectives

Modeling and optimisation of energy systems

- Objectives of the lecture

At the end of the lecture , you will be able to :

- State a **energy system design** problem
  - Establish and develop flowsheets
  - Model the key performance of a system over its life time
  - Choose the criteria to be used to choose the system design
  - Define the size of the equipments in the system and how they will be operated
- Establish an energy conversion system simulation **model**
  - Make a degree of freedom analysis
  - Define the models and the level of details
  - Choose the solving method to solve a flowsheet
- State and solve an **optimisation** problem
  - Use models to define the demands
  - Use models to calculate the objective function
  - Identify and define the decision variables
  - Choose and implement a solving methods and the solving algorithms
- **Apply** optimisation methods to solve energy conversion system design problems
  - State the problem & make the necessary assumptions - Collect the data - Develop models - Solve optimisation problems
  - Interpret the results
  - Present and report your decisions
- **Propose** and **compare** energy system designs

Teaching concept

- **Project-oriented teaching**: you realise a guided project on modelling and optimization of the energy system of EPFL's buildings and the campus. This project covers the whole duration of this course, and will help you better understand the theory concepts and their application.
- **Theory - Application**: Theory is first presented and put in perspective of the project realisation.
  - **Lectures** by professor : **in class** + slides + lecture notes + videos
  - **Application** by applying theory in the project : a project report template with suggestions on how to solve the problems and FAQ is made available to support the project realisation. A quizz will test the use of the tools.
  - **Prospective** use of the models to answer more detailed questions.

Groups for project based learning

- Groups
  - 3 students

- Interaction time
  - Monday at time of the project see planning on moodle
  - Thursday : office hours 12:00-14:00 upon request via moddle forum => your TA

Schedule : see on moodle

Week	Date	Theory covered	Project goals
1	08.09.2025	computational thinking AGIR	Task1 : building energy demand (heating and cooling) and energy bill, imp change
2	15.09.2025	T 1: Energy demand analysis: building modeling T 2: Equations and solving methods	Task 1 : prospectives : Comfort T, CO2 control, adding insulation, CO2 im
3	22.09.2025	Holiday	Task 1 : prospectives : Comfort T, CO2 control, adding insulation, CO2 im
4	29.09.2025	T 3: Key Performance Indicators T 4: Estimating the investment	Task 1 : prospectives : Comfort T, CO2 control, adding insulation, CO2 im
5	06.10.2025	T 5.1: Flowsheet simulation and DOF T 7: Constitutive equations	Task2 : simulation energy system : heat recovery on the ventilation systen
6	13.10.2025	T 8: Resolution sequence definition	Task 2: simulation energy system, heat pump integration, data center inte recovery from electrical appliances, adding insulation, using lake, geother pump
7	20.10.2025	Break	Task 2
8	27.10.2025	T 5.2: Stating optimisation problem and solving strategies	Task 2: simulation energy system, heat pump integration, data center inte recovery from electrical appliances, adding insulation, using lake, geother pump
9	03.11.2025	T 6: Solving optimization problem	Task 3 : optimizing investment (NLP) + Fluid selection
10	10.11.2025	T 9: Data reconciliation and parameter identification	Task 3
11	17.11.2025		Task 3
12	24.11.2025	T 10: MILP optimization methodology	Task 4: system integration : choosing among options
13	01.12.2025	T 11: Techno-economic analysis by MILP optimization T 12: Multi-objective optimization	Task 4
14	08.12.2025		Task 4
15	15.12.2025		Task 4

Theory in the course

For realising those tasks, you will activate knowledge and theory and apply the concepts to your project.

1. The **theory** will be delivered as in class lectures (+ streaming) that explain the theoretical background of the tools and methods to be applied. The list of topics is given below with associated lectures and support materials.
2. A discussion **forum** is proposed for the theory topics.
   Questions will be discussed in an interactive session with the professor.
3. The **teaching assistants** have prepared the supporting materials and the necessary data to realise the tasks.
4. They will also present examples on how they have solved the different tasks in other projects.

At the end of the semester, you will have to deliver a **final report.**

Theory topics : list on moodle

- 1. Energy demand models: building modelling
- 2. Methods for solving a set of equations
- 3. Clustering : what are the most probable states to be realised by the energy system over its lifetime
- 4. Flowsheets and energy systems models
- 5. Key performance models of an energy system
- 6. Techno-economic optimisation of an energy system
- 7. Solving optimisation problems
- 8. Constitutive equations and thermodynamic properties of flows in flowsheets
- 9. Process units models
- 10. FlowSheet simulation
- 11. Data reconciliation and parameter identification
- 12. Energy system modelling with Linear programming techniques
- 13. Multi-objective optimization for energy system design

Lecture notes and teaching materials

- Slides and project data
  - on http://moodle.epfl.ch
  - Instructions : http://moodle.epfl.ch/
- Lecture notes
  - pdf and slides available on moodle
  - video of the previous year also available (updated as recorded video are available)
  - lecture notes are available as bookdown web or pdf.
- Support materials (e.g. writing reports)
  - http://ipese.epfl.ch -> teaching
- Reference books
  - Biegler, L. T., Grossmann, I. E., and Westerberg, A. W. (1997). Systematic Methods of Chemical Process Design, , (ISBN 01334924223),
  - Turton, R., Whiting, W., and Shaeiwitz, J. (1998). Analysis, Synthesis and Design of chemical processes, , (ISBN:130647926),

- computational thinking

The project

EPFL is not anymore the World #1 in sustainable campus.

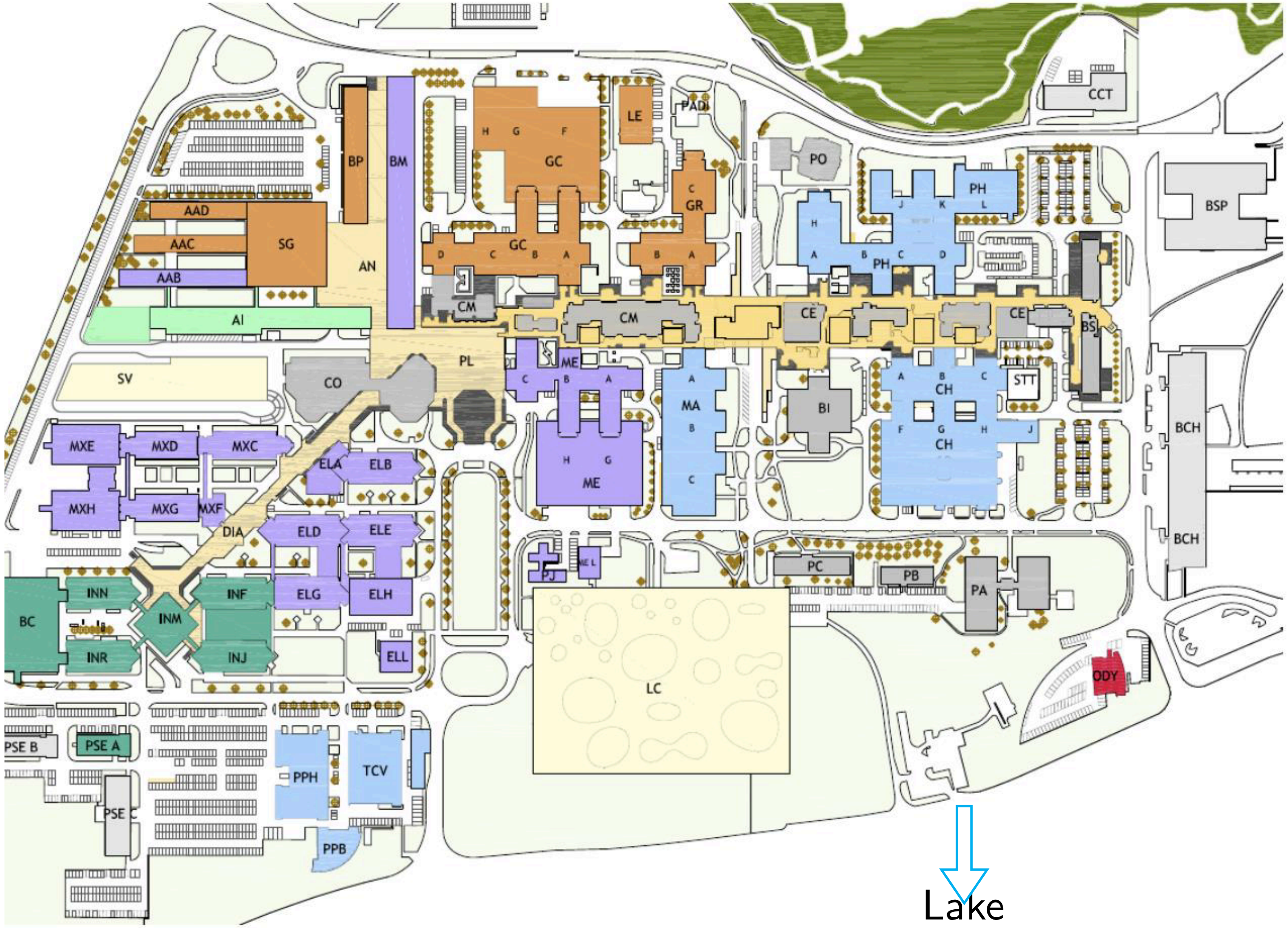
The president has decided to develop a sustainable development plan for his campus, the President is asking you to prepare a comparative study for different options for the future energy system of EPFL. Your results will be used to prepare a call for tender.

Ecole Polytechnique Fédérale de Lausanne EPFL

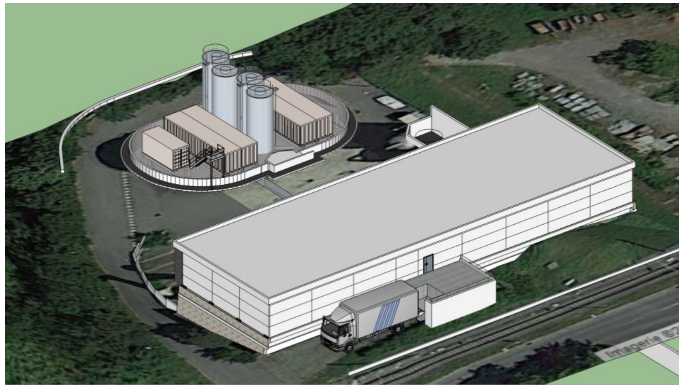
Renouvellement des infrastructures thermiques

Etienne Marclay VPRHO | 02.2017

The campus



- For each building
  - Electricity including lab consumptions
  - Comfort
    - Heating
    - Cooling
- For the campus
  - Central district heating plant
  - Data center
- Resources
  - PV on the roofs
  - Lake that feeds the heat pump
    - Problems with quagga mussels



The past energy system

http://dii-e.epfl.ch/fichiers/CCT.pdf

Capacités

Pompage eau du lac à 7°	1150 litres/s (EPFL&UNIL)
2x PAC NH3	9 MW therm
2x CCF mazout	10 MW therm + 6 MW élec
4x pompes réseau froid	600 litres/s

Performances moyennes

Chauffage: 73% PAC + 27% turbines CCF mazout

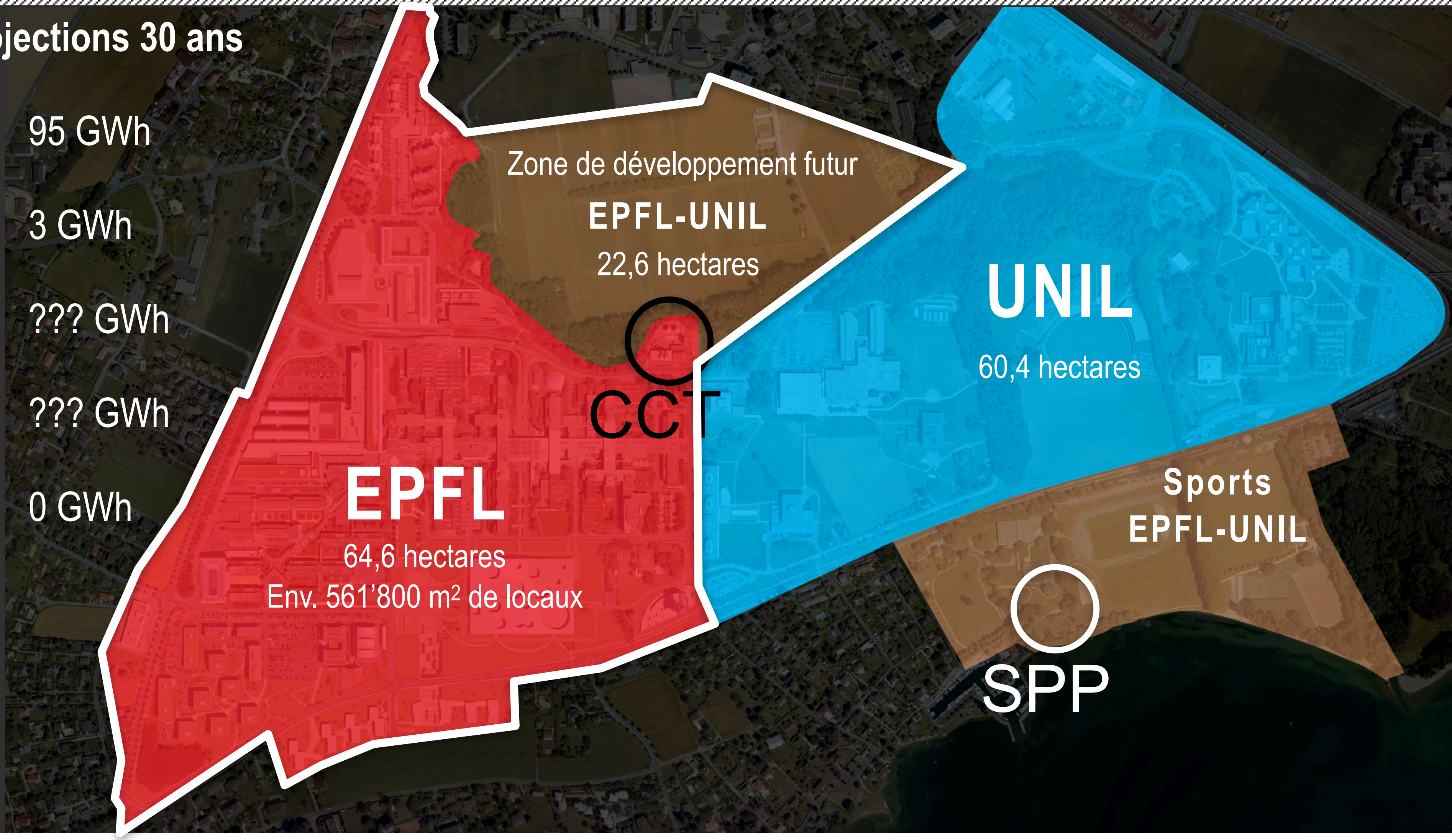
PAC: COP moyen annuel système 3.45
CCF: 37% chaleur + 24% élec + 39% pertes

Refroidissement: 95% eau du lac + 5% électricité

Info: achat électricité 97% hydro + 3% PV

Future demands

EPFL bilan 2016		Projections 30 ans
• 78 GWh élec hydro	→	95 GWh
• 2 GWh élec PV	→	3 GWh
• 55 GWh Water lake	→	??? GWh
• 12 GWh gaz	→	??? GWh
• 3 GWh mazout	→	0 GWh



Data center

«Datacenter on Demand»

Flexible data center to be installed

- Area 970 m2
- 1 à 9 Electricity supply transformers
- 4 MW IT => 5.5 MWe

Imagine you are an engineer ask to …

- Compare centralised and decentralised heating strategy.
- Anergy loop : low temperature heat distribution for heating and cooling
  - heat pumps
  - heat recovery
  - storage
  - Heat distribution by water from 14 to 10C or by CO2 heat transfer fluid (exergo)
- New constraints
  - EPFL innovation in PV cells (CSEM, Nazeerudin)
  - Building PV integration (facades)
  - Data production needs : Apertus (LLM)/heating bits

As a group of engineer you are therefore asked to assess the sustainability impact of the integration of decentralised solutions to renovate the EPFL campus.

The direction would like to receive a comparison of the options identified considering the sustainability aspects : i.e. economic, environmental impact, and impact on the EPFL operation, it particular it would like to know what will be the investments associated.

Steps in the course

The goal is to design the energy system of an international university campus with the goal of minimising its environmental impact.

- **Task 1 : Defining the energy demand of a campus building**
  - What are the heat loads to be supplied to each building
  - Define the temperature levels of the demand
  - Define the energy bill
- **Task 2 : Model the building energy system and heat recovery options**
  - Define the building energy system flowsheet
  - Calculate the system configuration states
  - Estimate the related investment
- **Task 3 : Optimise the investment of heat recovery options for a building**
  - define the size of the investments on an objective function
  - model heat pumps and to choose the best working fluids and operating conditions of heat pumping cycles
  - Integrate the data center heat recovery
  - generate building's retrofit options
- **Task 4 : Propose and compare options for a more sustainable campus energy system**
  - integrate the buildings in the campus district heating and cooling system
  - define sustainability metrics for the decision support
  - Compare decentralised and centralised options with pro and cons for different options of the system design

Project based learning : transversal skills

Team work

Tasks are realized by a team; it is important to distribute the work and the responsibilities when realizing the mission. A good team work implements the AGIR steps in a coordinated fashion to be efficient in the task realization :

- **Coordination** : description of the tasks, validation of the assumptions, work allocation, synthesis of the results and their interpretation
- **Communication** : who is doing what, "what" meaning a sub task with boundary conditions and expected results defined.
- **Validation** : team work allows easy validation mechanism, when someone is realizing a task, it makes sense to have another teammate making a critical review of the work done.
- **Exchanges :** discussion, critics, validation, support. A team is focused on the results generation and on their quality. It is therefore important to have a place to exchange, be open to ideas, welcome remarks and critics of the others.

- Define your work as sub-tasks and distribute the work among the team mates : (recommendation 2 people/sub-tasks)
  - **Analyse** the sub-tasks => what do you have, what do you need, what do you want ?
  - **Generate** the results => make calculations
  - **Interpret** the results => prepare a report and review your work before results transmission
  - **Report** => share your results with the other team mates and ask for an external review

Collaboration platform

- **Moodle: agenda**
- **Moodle: forums**
- **Quarto: report template**
- **Website**

Course grading

- Due to the large number of students, this course will be evaluated in a hybrid mode, combining continuous evaluation, group project report evaluation and a written exam.
- Here is the grading strategy:
  - **50%** : for the group report based on the resolution of the 3 parts of the project as a whole. The report grade will be "weighted" by an anonymous peer-self-evaluation (each member will declare how much they contributed to the report). Note that you are supposed to know what is in the report as you have signed it.
  - **5%**: your results to the quizzes during the semester. Quizzes are set-up to
  - **15%**: your peer review of the report of an other group. At the end of the semester you will receive one report from another group to be reviewed. As an assignment to be delivered at the start of the exam period you will have to deliver a review of the report
  - **30%**: your answer to the review. For the written exam, you will receive a 4 reviews concerning your report: one from an assistant and 3 from your peers. The written exam will consist in commenting the reviews and explaining what you will do to answer the remarks and suggestions of the reviewers.

Deliverables

- Quizzes
- 19.12.2025 : **Final report : group report**
  - **with the 4 tasks**
- 12.01.2026: **Individual review report**
- Exam day: **Written exam**

Comments on the course organisation

- **My slides**
  - are not lecture notes but a support to my talk (do not complain if the printed slides are messy !)
  - Just in time updates possible
  - Lecture notes and previous years lectures are available on video (see on moodle.epfl.ch)
- **The lecture**
  - Do not hesitate to ask questions
  - Ask questions wrt project (read the projects objectives and ask questions)
- **Project based learning using a case study**
  - Theory is associated with the tasks to be realised : the project template report includes a lot of hints concerning the structure of the work to be done. Do not hesitate to read the template again : this is a nice synthesis exercice.
  - Learning by doing => you will struggle with numerical problems or software problems : does not always converge : this is real life !
  - Discussions => I will come and discuss with you during the project, do not hesitate to ask questions.
  - Report => visible part of your work (not only in this lecture) !
    - pay attention to reports, tables, graphs…
    - You sign the report, you are supposed to sign what is in the report

Comments on the projet organisation

- **Number of students**
  - we will do our best
- **Assistants (limited numbers: sorry)**
  - They are available to help
  - They have a limited time available
    - “they are allowed to not answer if they consider that you can find the answer by yourself”.
    - Office hour on Thursday 12:00- 14:00 : reserve your time slots and prepare the discussion
- **Case study formulation and group work**
  - The case study is like a real problem
    - Distribute the work among yourself
    - Thinks might be missing : Make assumptions
    - Justify and report (journal)
    - Decide (negociation in the group)
    - http://te.epfl.ch (group organisation)
- **Double Deck** : noise !!!

Hope that we will have a lot of fun !