

Modeling and optimisation of energy systems

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- Introduction to the course: Prof. F. Maréchal
 - Teaching concepts and organisation
- Projects
 - Introduction to the project challenges
 - 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 challenge : Engineering the Efficiency for a Net-Zero future

Fossil resources

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

Renewable resources

Where-When-How much ?

Circularity

Waste to products
CO₂ to products
Waste to energy

Waste-Water-Energy

Investments

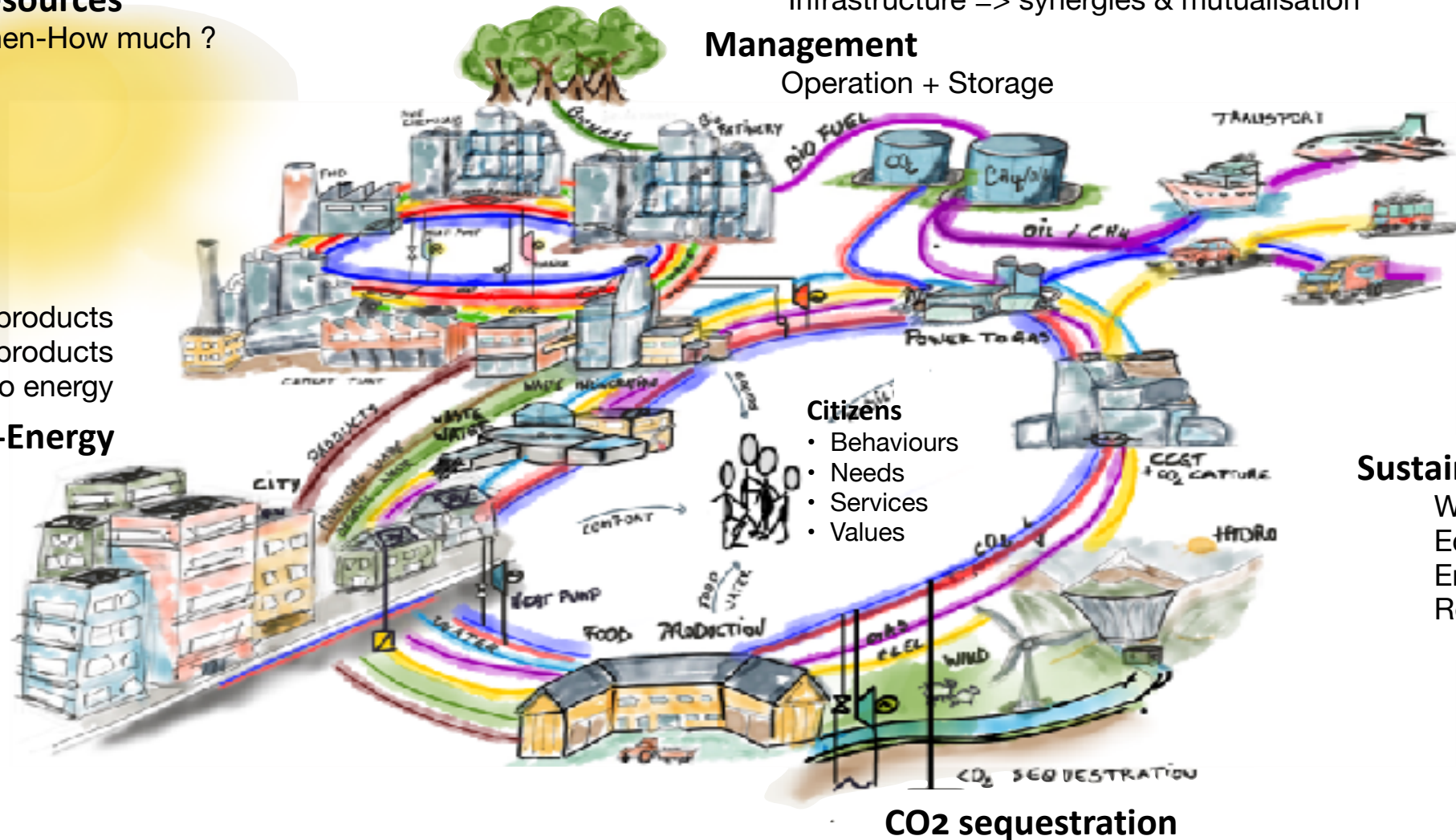
(New) Technologies
sizes : conversion and storage
Infrastructure => synergies & mutualisation

Management

Operation + Storage

Demand

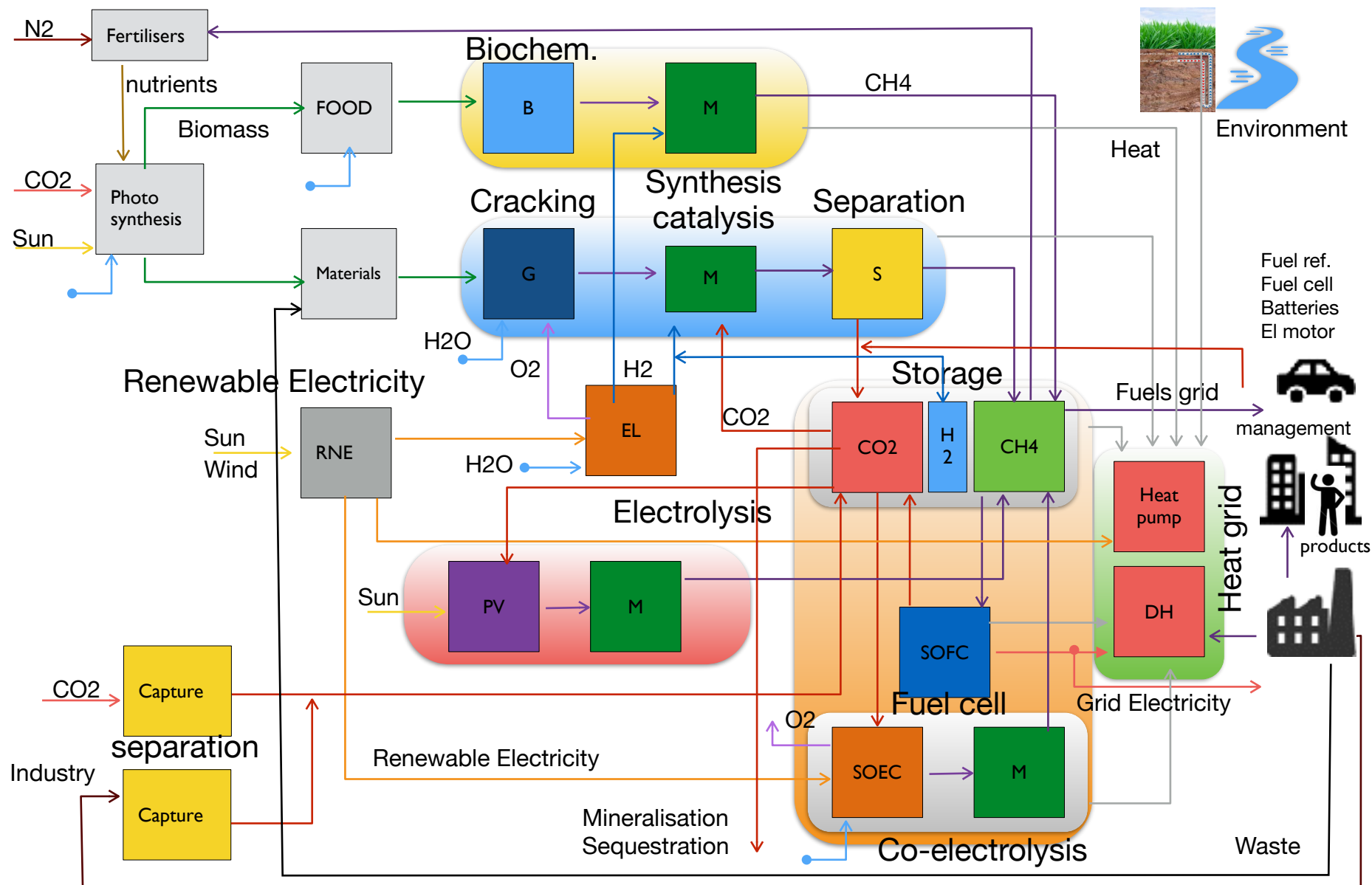
Products
Services
Security of supply

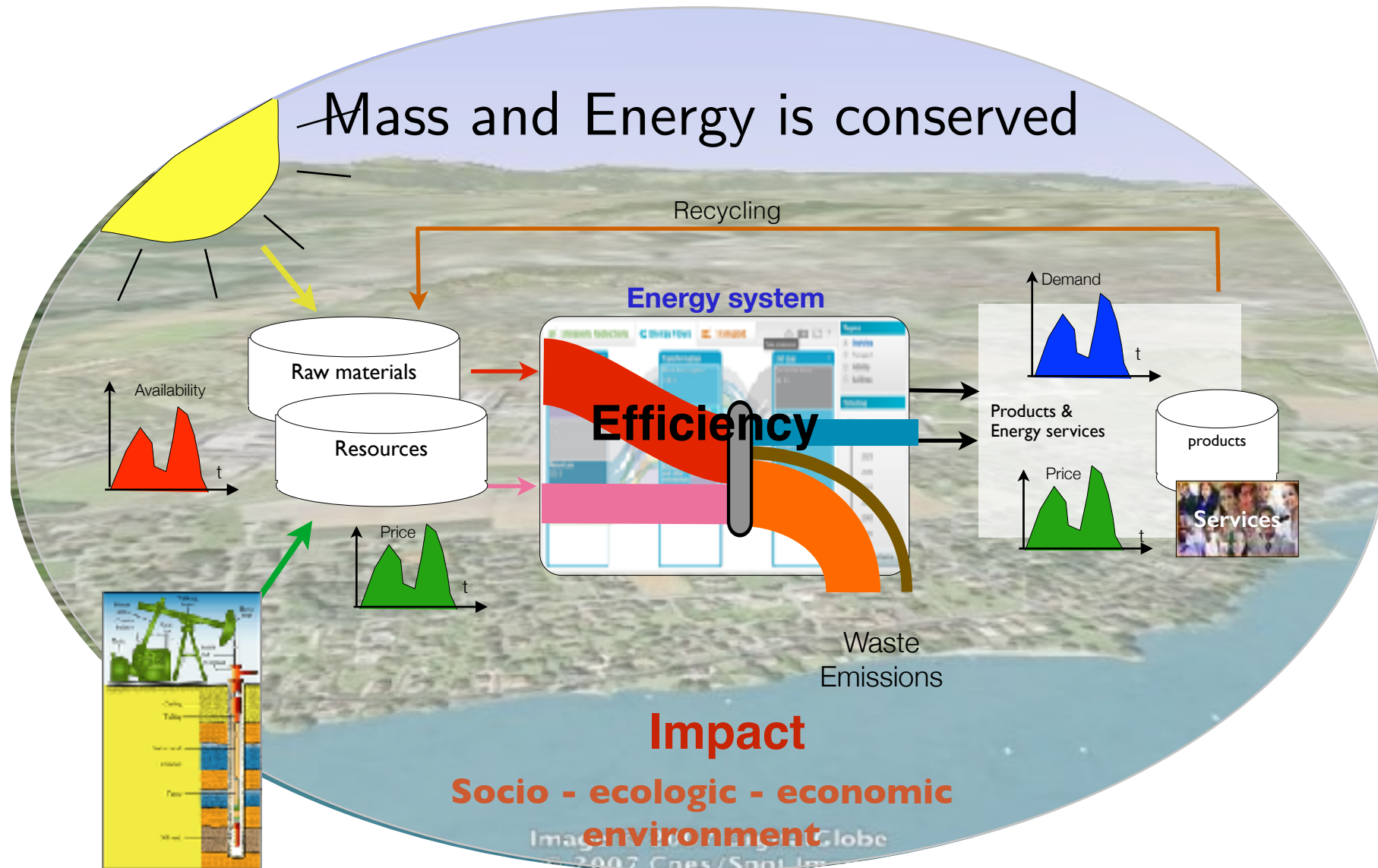


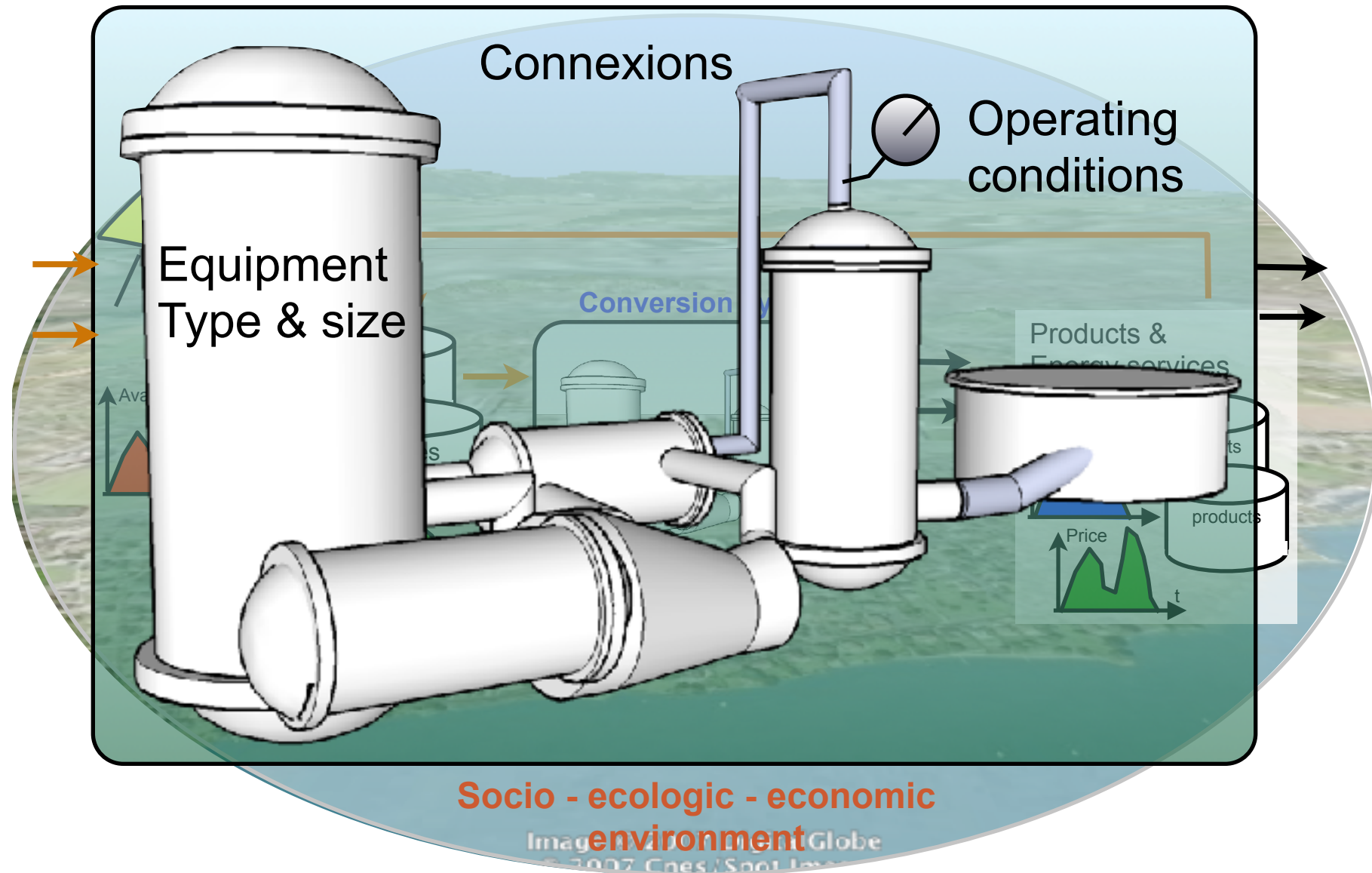
Sustainability metrics

Wealth
Economic
Environment
Resiliency









■ Modeling of an energy system ?

Flowsheet : process units interconnected by streams

Streams

Flow [kg/s]

Temperature [C]

Pressure [Bar]

Composition[%]

Symbols

Compressor

Turbine

Heat exchanger

Material Stream

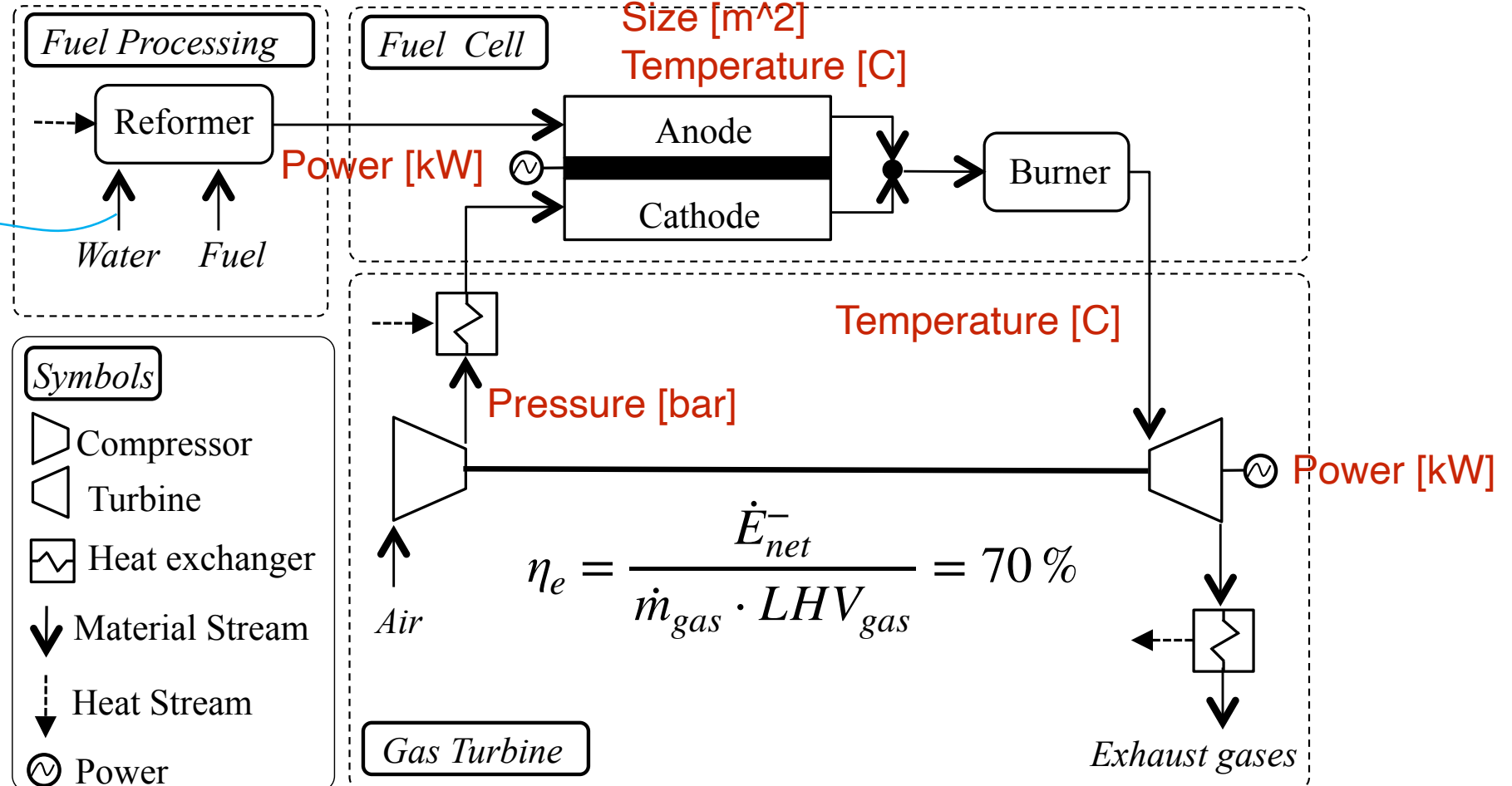
Heat Stream

Power

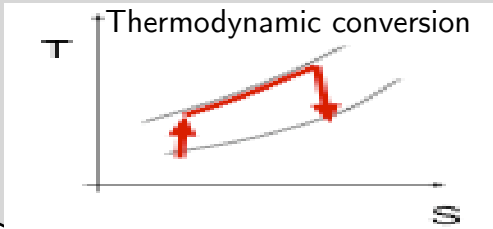
Process unit

Size [m²]

Temperature [C]



System model

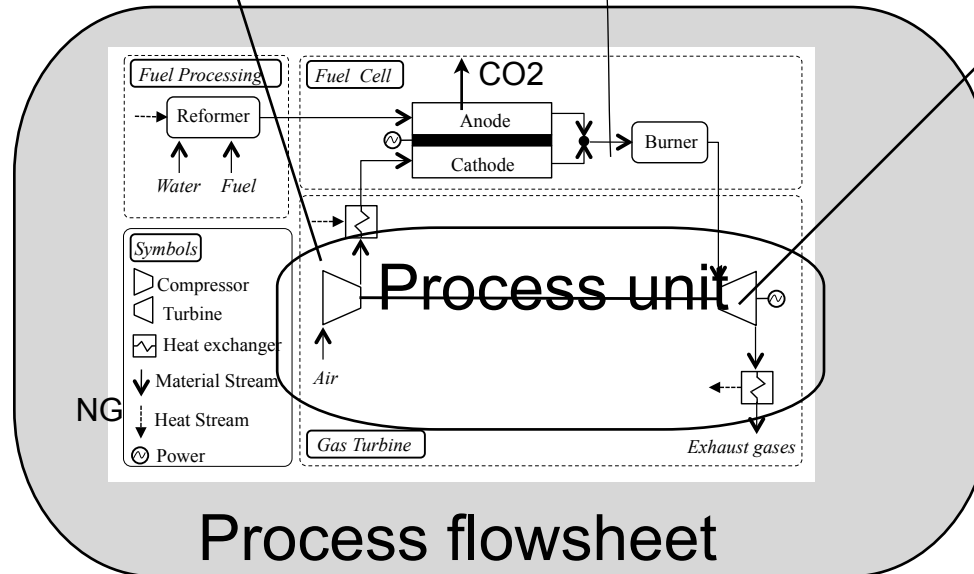


Flows => System States

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

Equipment => Size or capacity installed

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



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

System investment [CHF/year]

$$CapEx = \frac{1}{\tau} \sum_i I_i \quad \text{Capital expenditure [CHF/year]}$$

Operating cost [CHF/year]

Inc. management strategy

$$OpEx_{el} = \int_{year} (\dot{M}_{NG}^+ c_{NG}^+ + \dot{M}_{CO_2}^- c_{CO_2}^- - (\sum_i \dot{E}_i^-) c_e^-) dt$$

Total Cost (e.g. levelized cost of EI production) [CHF/year]

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

■ Optimisation of an energy system ?

- Fix the degrees of freedom of the system with an objective
 - **Decision variables** (Degrees of freedom)
 - Existence and Size + 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
 - Performances metrics are known
 - Economic (under given economic market assumption : Energy+Investment)
 - Environmental

- 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

- Objectives of the lecture

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

17

- 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

- **Project-oriented teaching:** you realise a guided project on modelling and optimization of the energy system of EPFL. This project covers the whole duration of this course, and will help you better understand the theory concepts.
- **Theory - Application - Flip class :** 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.
 - **Flip Class :** Typical questions of the exam prepared and illustrated by students on Miro boards : “ The theory and how it was applied in your project “ + feedback discussion by professor.

- Groups
 - 6 students
 - 1 TA + 1 Backup
- Interaction time
 - Monday at time of the project see planning on moodle
 - Thursday : office hours 12:00-14:00 upon request => your TA

- Organisation on moodle
- Materials on moodle

Week	Date	Agenda class	Theory covered	Project work	Video lecture	Submissions
1	09.09.2024	Course introduction Introduction to Part 1		Project overview + Task 1	1. Introduction to course and project MOES 2. Building demands	
2	16.09.2024	Holiday		Task 1		
3	23.09.2024	Lectures T1, T2 Introduction to Part 1 NR	T 1: Energy demand analysis: building modeling T 2: Equations and solving methods	Task 1	3. Solving non linear equations	
4	30.09.2024	Lectures T3, T4 Work on Part 1 Introduction to Part 2	T 3: Key Performance Indicators T 4: Estimating the investment	Task 1+2	4. KPIs 5. Investment estimation	
5	07.10.2024	Lecture T5	T 5.1: Flowsheet simulation and DOF T 5.2: Stating optimisation problem and solving strategies	Task 2	6. DOF process units and flowsheets 7. Solving strategies for an optimization problem	
6	14.10.2024	Lecture T6 Work on Parts 2	T 6: Solving optimization problem	Task 2	8. Solving linear optimization problem 9. Solving non-linear optimization problems	
7	21.10.2024	Holiday				
8	28.10.2024	Lectures T10, T11 Introduction to Part 3	T 10: MILP optimization methodology T 11: Techno-economic analysis by MILP optimization	Task 3		
9	04.11.2024			Task 3		
10	11.11.2024	Lecture T7, T8 Work on Part 3	T 7: Constitutive equations T 8: Resolution sequence definition	Task 3		
11	18.11.2024	Lecture T9 Work on Part 3 Introduction to Part 4	T 9: Data reconciliation and parameter identification	Task 4		Submit Preliminary Report
12	25.11.2024	Flip class		Task 4		
13	02.12.2024	Work on Part 4		Task 4		Submit Review
14	09.12.2024	Lecture T12	T 12: Multi-objective optimization	wrap up		
15	16.12.2024	Project presentation and feedback		wrap up		

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. Team of two students will be asked to prepare an illustration of the **application of the theory** to realise the task. The following discussion will be the occasion of experimenting the oral exam.
4. The **teaching assistants** have prepared the supporting materials and the necessary data to realise the tasks.
5. 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** and **present** your results.

- 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

- 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

EPFL is not anymore the #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

The campus



- For each building
 - Electricity
 - Comfort
 - Heating
 - Cooling
- For the campus
 - Central district heating plant
 - Data center
- Resources
 - PV on the roofs
 - Lake



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

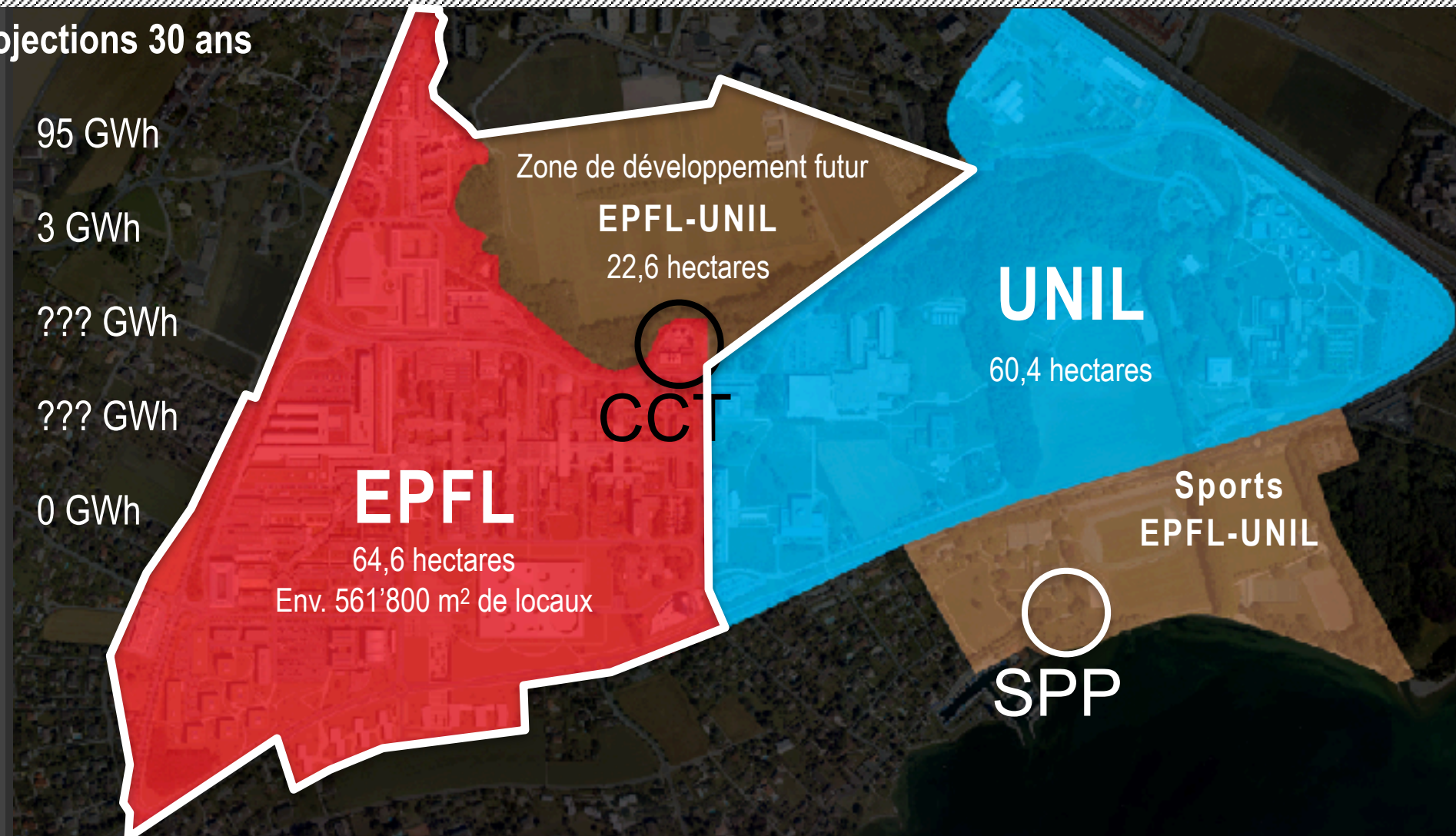
Future demands

EPFL bilan 2016

- 78 GWh élec hydro
- 2 GWh élec PV
- 55 GWh Water lake
- 12 GWh gaz
- 3 GWh mazout

Projections 30 ans

- 95 GWh
- 3 GWh
- ??? GWh
- ??? GWh
- 0 GWh



«Datacenter on Demand»

Flexible data center to be installed

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



As a team, you will have to :

Propose the system configuration

Estimate the investment

Estimate the operating cost

Prepare a report on the solutions proposed

Present the solutions

EPFL Your turn what are you doing ?

32

- The president has first asked his colleagues to make some suggestions of the options :
 - Prof of Architecture : you have to refurbish the buidlings
 - Prof of Heat exchangers : recover the heat of the data centers and the hot air in buildings
 - Prof of Compressor : use multi-level heat pumps, choose the right fluid
 - Prof of Photovoltaic : use PV panels
 - Prof of Fuel cells : use a solid oxide fuel cell
 - Prof of Bio-engineering : use biomethane
 - Prof of Geology : use deep geothermal sources
 - Prof of Water Treatment : use of the heat of the waste water
 - Prof of Energy system : look at the system integration
 - Prof of power systems : use my battery
 - Prof of Climate and economics : take into account the global warming
 - Vice-president finance : I do not have money for that
 - ETH board : demonstrate the sustainability
 - Market : sorry but no more cheap electricity : from 5 to 50 cts/kWh

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**
 - What are the heat loads to be supplied to each building
 - Define the temperature levels of the demand
 - Bonus : define ways to reduce the demand
- **Task 2 : Optimising heat recovery and building's energy system**
 - Invest in renovation, heat recovery, decentralised heat pumps, recover heat sources
 - Define economic conditions of the options
- **Task 3 : Choosing fluids for the campus heat pumping system**
 - model heat pumps to choose the best working fluids and operating conditions of heat pumping cycles
 - What is the best heat-pumping system configuration
 - Bonus : integrate the data center on demand
- **Task 4 : Propose and compare options for a more sustainable campus energy system**
 - Convert resources in energy services : heat pumps, cogeneration, boilers
 - Compare options with pro and cons for different options of the system design
 - Bonus : propose options for maximising the use of renewable energy

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
- **Bonus** : two students will be in charge of assessing advanced options (not proposed in the project scenario)

- Intermediate report : end week 10
 - Groups deliver preliminary report after 60% of the work
- Individual review report
 - Student deliver individual review of the report of one other group
 - Reviews are graded (**10 points to the final grade**)
 - Groups are supposed to integrate the comments in the final version of the report
- Final presentation
 - A dry run (individual meeting with prof. and assistant) is used to prepare the final presentation at the exam.
- Final report (**30 points to the final grade**) to be delivered 10 days before the exam

- **Project report required to be authorized to enter the exam room**
- **Oral exam based on an individual poster presentation of your project**
 - 3min poster presentation of the methods used for the project realisation (MIRO presentation)
 - 17 min exam : explain how the theory concepts have been or could have been applied
 - We try to cover as much as possible all theory topics
 - The project is used as a support to explain the theory
 - The flip-classes are used to prepare to the exam.

EPFL How to prepare the exam : list of the specific objectives

38

At the end of lecture, I can ..

Question number	T 1-3	Student
1.1	I can explain how to define demands, distribution and supply in an energy system I can explain how to define and characterize the demands and how it has been done in my project.	
1.2	I can explain the methods to solve a non linear equation in implicit and explicit form. I can explain how to test the convergence and I can elaborate on the necessary conditions and the possible difficulties of using such algorithms.	
	T 4-6	
2.2	I can explain how to calculate the operating cost of an energy system and explain how it has been done in the project. You can give an example with a heat pump and a boiler	
2.3	I can explain how to estimate the investment in an energy conversion system.	
2.4	I can explain how to calculate the key performance indicators of an energy system. I can explain how to calculate the thermo-economic performance, and how to consider the environmental and sustainability aspects.	
2.6	I can explain different strategies to state and solve an optimization problem. I can explain differences between black box, simultaneous, hybrid methods and explain pros and cons.	
2.7	I can explain the problem of parameter estimation and explain how the problem is stated. I can explain how to deal with uncertainties in values and assumptions of an energy system design problem	
2.8	I can explain how to solve an unconstrained (uni-variate and multi-variate) optimization problem.	
2.9	I can explain how to solve a multi-variable unconstrained optimization problem.	
2.11	I can explain how to solve a multi-variable constrained optimization problem.	
	T 7-9	

See questions in the [google docs](#)

■ 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 exercise.
- 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

EPFL Comments on the projet organisation

▪ Assistants

- They are available to help
- They will do their best to coach and organise the project
- 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
 - Things might be missing : Make assumptions
 - Justify and report (journal)
 - Decide (negociation in the group)
 - <http://te.epfl.ch> (group organisation)
- **You will have to state the problems for each step**
 - Analyse => literature search, assumptions, level of detail requested, expected results, ...
 - Generate => generate numerical solutions
 - Interpret => translate numbers into engineering decisions
 - Report => transfer your knowledge to the rest of the world

EPFL Hope that we will have a lot of fun !