Energy System Optimisation

TANDEM Summer school

2024 June, 27th

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Content

1. CEA & CONTEXT

CEA Organisation

DAM Military Applications	DRF Fundamental Research	DRT Technological Research	DES Energies

DES:
- LITEN
- DTCH
- SSETI
- LSET

Stéphanie Crevon,

Modelling engineer,
Software developer with background in energy systems

WP3 leader of TANDEM project
Also involved in NPHYCO project

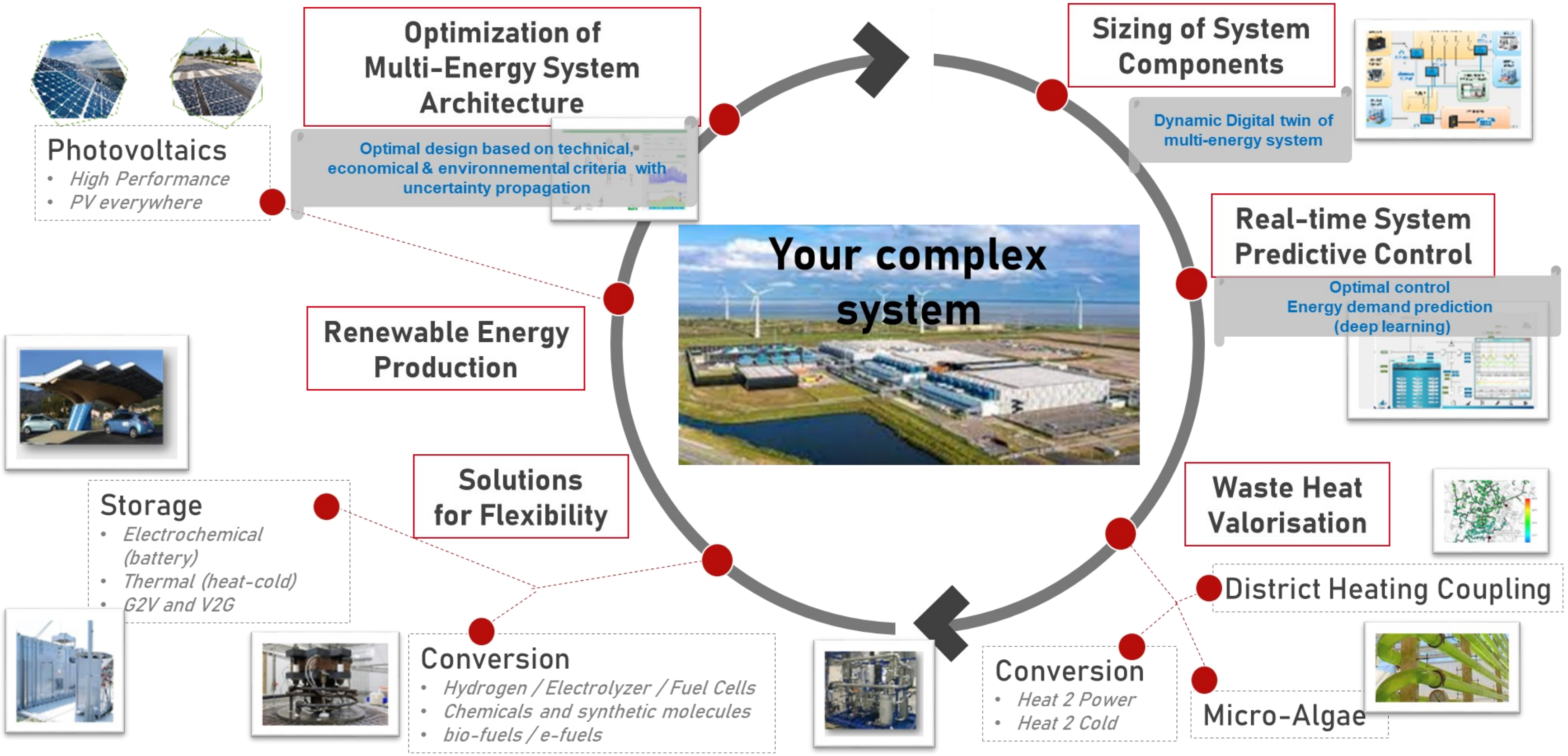
→ LSET

CEA is a **major player in research**, serving the French state, the economy and citizens. Based on **excellent fundamental research**, it provides concrete solutions to their needs in four main fields:

- **Low carbon energies (nuclear and renewable)**
- **Digital**
- **Technologies for the medecine of the future**
- **Defense and security**

CEA/DES develops hardware for energy bricks and systems

- Detailed knowledge of different technologies (H2, PV, Battery, Waste valorisation, Nuclear, …)
- Skills in integration of all these technologies at a system level

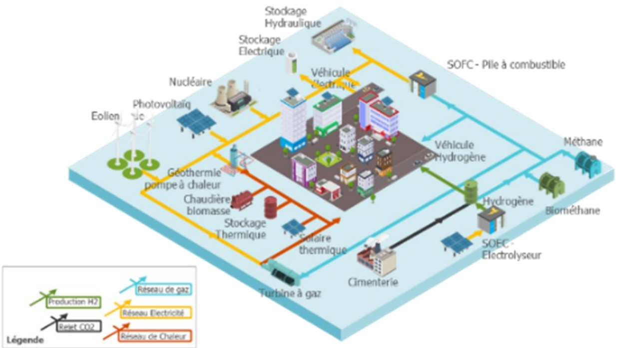


LSET: Laboratory specialized in optimization of energy systems

MODELING

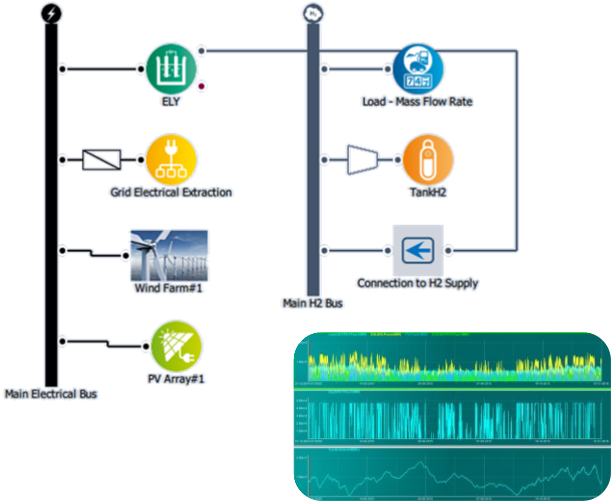
Heat & Cold Grid – Gas Grid, multi-energy – Hydrogen systems

Integration of new converters, tools for real-time control



OPTIMISATION

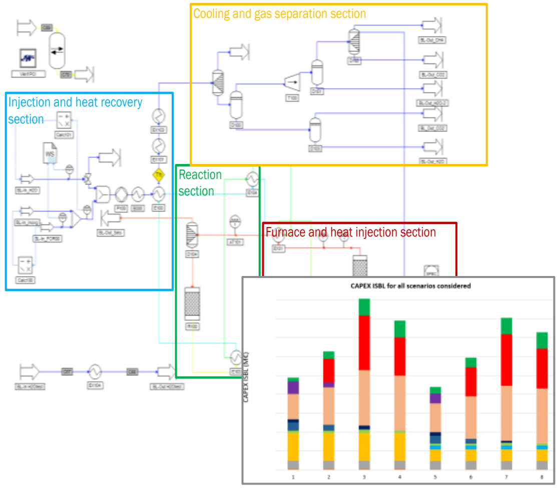
R&D methods &numerical tools applied to energy systems



EVALUATION

Techno-economic & environmental studies

Of new components and energy systems



A team of 30 engineers and PhDs: Experts in physical modelling, applied mathematic, software developers, physical modeling experts, operational research, project managers, process engineering, LCA, costing

From research to industry: creation of 2 start-ups

SEED ENERGY DistrictLab

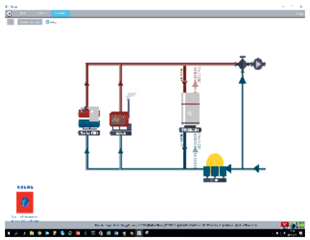
Pillars of LSET softwares

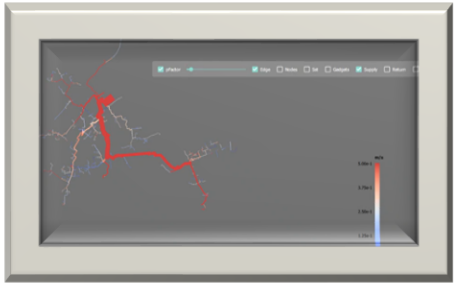
Opportunity study → Techno-economical feasibility → (Pre) Sizing → High level control conception → High level operating control → Operation, diagnostic, maintenance prediction

- Heat
- Electricity
- H_2
- Biogas
- Waste
- Environment
- Emissions
- Cogeneration
- Cold

Techno economic and environmental studies | **Fine technical studies in real environment**

From feasibility studies to real-time operation





Databases

- Technology
- Loads
- Renewable production

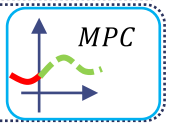
Component models

Verified, validated and documented

DEV C++ — MODELICA

Operation strategies

- Expert rules
- Predictive control



Optimisation method

- MILP /MINLP
- Meta-heuristics
- Robust optimisation
- Multi-criteria approach

2. Introduction to Energy System Optimisation

Needs for Energy System Modelling

- Energy systems are more and more complex (balancing of intermittencies, interdependencies between components)
- Energy systems are expensive to build and should last

→ Need tools in order to:

Simulate energy system	Optimize energy system	Operate energy system
To better understand technically how they work and find the best settings	To provide decision support for planning needs	To help operate them efficiently
MATLAB, MODELICA, ProSim	SEED ENERGY, TIMES (The Integrated MARKAL EFOM System), HOMER Energy, OSeMOSYS (Open Source Energy Modelling System), PERSEE, EnergyPLAN (Advanced energy system analysis computer model)	EnergyOptima 3, antares simulator

The list is not exhaustive and it may be difficult to fit the tools into a single box!

Focus on Energy System Optimisation to help decision makers

The investment-related problem can address various sub-questions:

- What technology to invest in?

If several technologies are in competition or can be used in symbiosis

- How much?

When one must decide the installed capacity of a technology

- Where to install it?

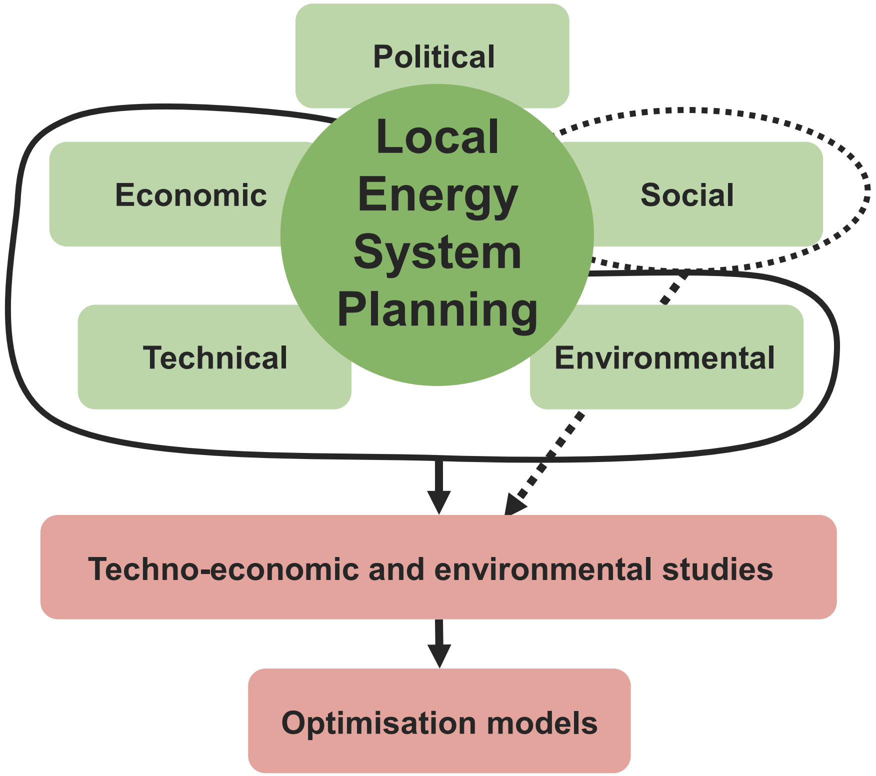
If a detailed spatial representationis used;

- When to install it?

When considering the system design evolution or in a Real Option (RO) thinking

The investment-related problem can have several criteria:

- Profitability
- Robustness
- Environmental impact
- …



A wide eco-system of tools for modelling, sizing and control optimization (1/2)

- **Feedback level: investment optimization**

What is the best architecture and when to invest in it?

  - Static case: a single investment decision stage is optimized
  - Myopic dynamic: several static investment optimizations are run iteratively
  - Anticipative dynamic: all investment decisions are optimized jointly

- **Tech-eco operational models**

How detailled are the models?

  - Linear / Include integers / Non-linear

- **Temporal model**

How accurate is the temporal model?

  - Aggregated data (yearly data for instance) / Full horizon

- **Operational decisions model**

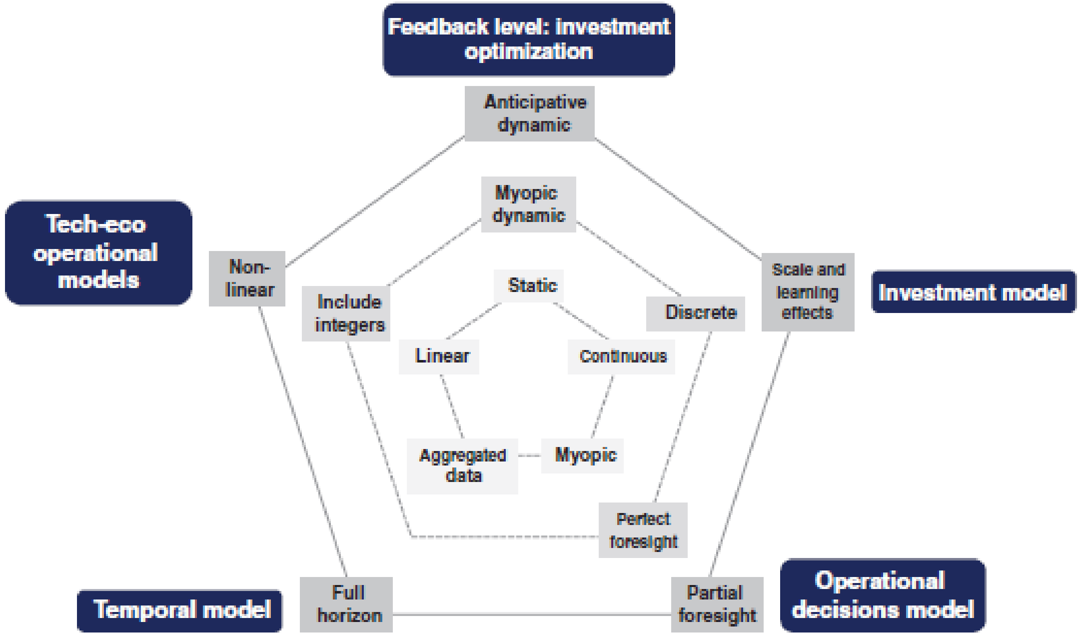
How forecasts are taken into account?

  - Myopic: the future is not known
  - Perfect foresight: the future is perfectly known and taken into account for the optimization as it is
  - Partial foresight: the future can be known but with uncertainties: for instance, the near future is known and trends are provided for the distant future

- **Investment model**

How realistic is the investment model?

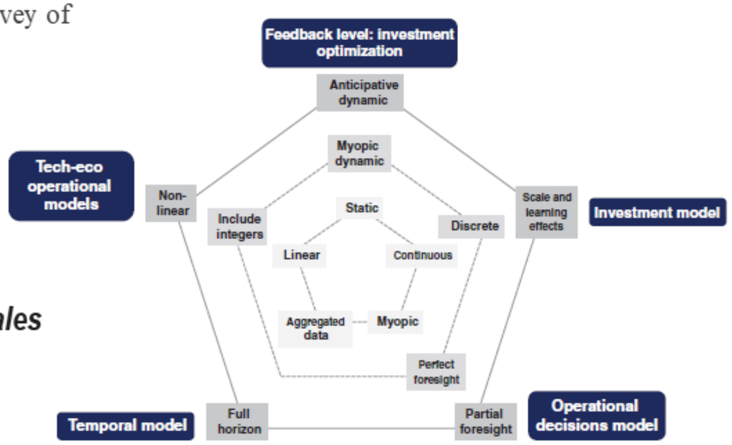
  - Continuous / Discrete / Scale and learning effect



E. Cuisinier, et al. , « Techno economic planning of local energy systems through optimization models: a survey of current methods », International Journey of Energy Research, vol 45, no. 4, pp. 4888-4931, 2021, doi: https://doi.org/10.1002/er.6208.

A wide eco-system of tools for modelling, sizing and control optimization (2/2)

E. Cuisinier, C. Bourasseau, A. Ruby, P. Lemaire, and B. Penz, 'Techno-economic planning of local energy systems through optimization models: a survey of current methods', *International Journal of Energy Research*, vol. 45, no. 4, pp. 4888–4931, 2021, doi: https://doi.org/10.1002/er.6208.



- Current tools and models
- Energy system planning studies with independent models (~ 60 papers)
- Methodological focuses, reviews, thesis etc. (~ 60 papers)

➡ *Definition of an analytical framework*

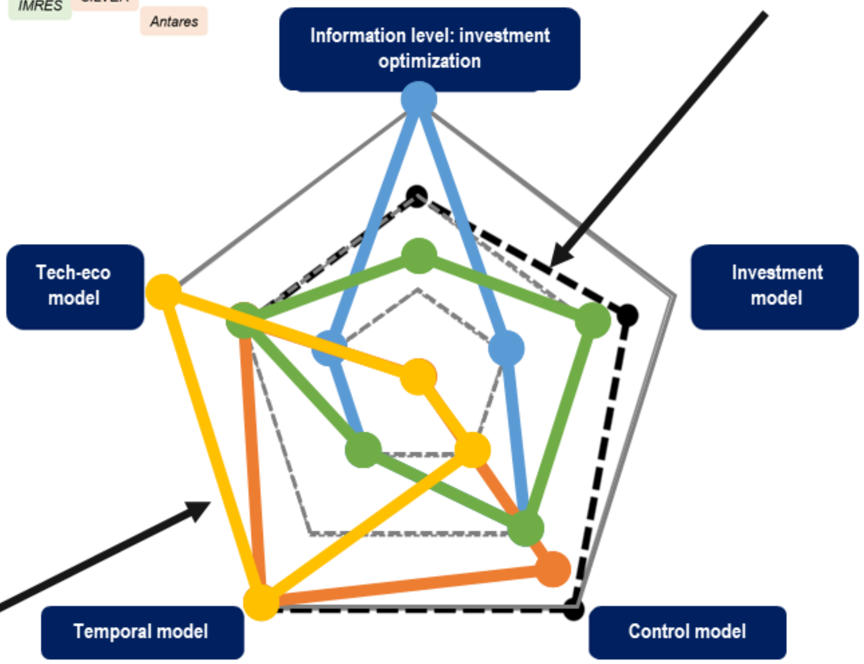
TIMES/MARKAL, ReEDS, OSeMOSYS, SWITCH, Energy Pro, HOMER, PERSEUS, PLEXOS, iHOGA, LUSYM, DER CAM, Energy Plan, Balmorel, Dispa-SET, Odyssey, IMRES, SILVER, Antares

Modelling approaches: some trends

LP + Typical Periods	TIMES, OSeMOSYS
Operational MILP (+ Rolling Horizon)	PLEXOS, LUSYM ~ANTARES
MILP + Typical Periods	IMRES, DER CAM
Simulation Model + Control Rules (+ Metaheuristic)	iHOGA, HOMER, Energy Pro Energy Plan

PERSEE

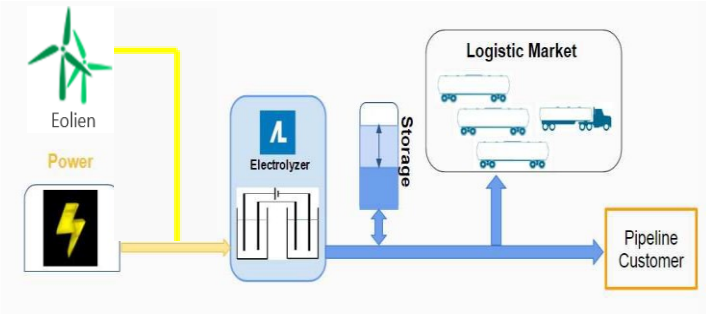
Multi-carrier
Multi-horizons
Several space scales

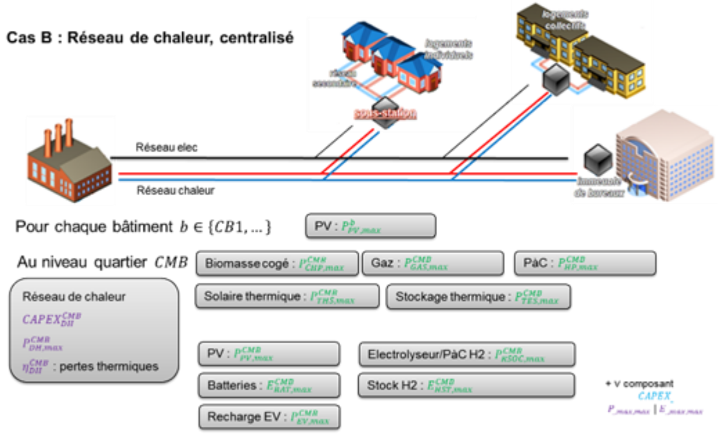


SEED ENERGY 2019

5th International Conference on Smart Energy Systems
Copenhagen, 10-11 September 2019
#SESAAU2019

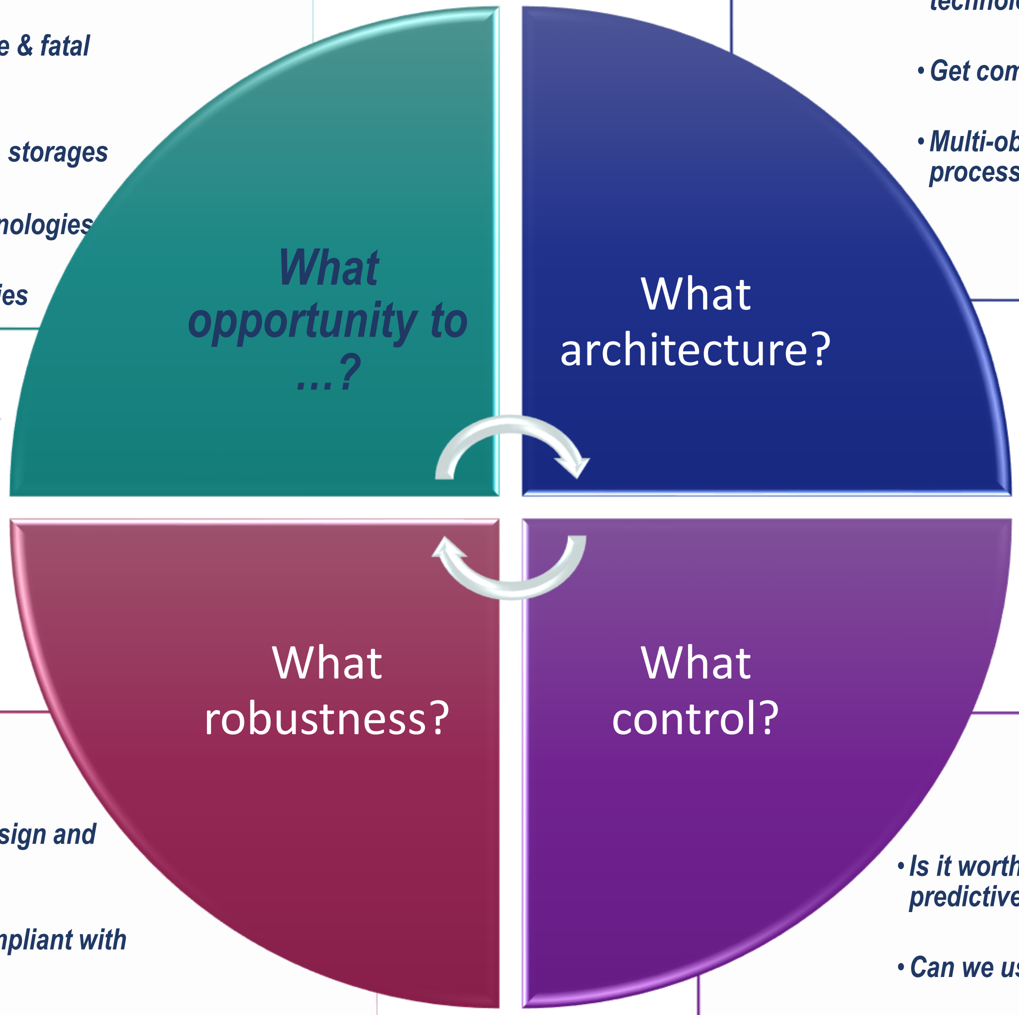
Typical questions that can be answered with PERSEE

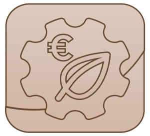




- Reduce environmental impact
- Integrate renewable & fatal energy sources
- Limit curtailment & storages
- Integrate new technologies
- Use carrier synergies

- Choose between possible technologies and designs
- Get component optimal sizes
- Multi-objective selection process: cost / environment





Techno-economical and environmental approach

- How robust are design and control?
- Is optimal size compliant with uncertainties?
- Handle uncertainties by control

- Is it worth using model predictive control ?
- Can we use predictive control?
- Is linear control sufficient?

3. PERSEE

A progressive dive into PERSEE tool

PERSEE

DIFFERENCIATING PILLARS

COMPONENTS MODEL LIBRARY

- **Extandable range** of technologies,
- **Any energy carriers**
- **Various model complexities** for various development steps

OPERATING CONTROL

Various operating control:

- Perfect control,

- Predictive control with limited foresight

OPTIMISATION METHODS

- **Direct** MILP optimization
- **Multi-objective hierarchical optimization**

SENSITIVITY ANALYSIS

- Parametric or Global Sensitivity Analysis
- Robustness assessment
- **Robust design**

SW INTEGRATION

- CoSimulation ability
- Continuous use from design to demonstration steps
- **OpenSource and Proprietary layers**

Several years of CEA R&D combining
modelling, planning, LCA, simulation and control of energy systems
for District Heating, Heat storage, H2 production, RES - NPP integration studies

Timeline

Design	V0	V1	V2	V3		VOpen source
2018	2019	2020	2021	2022	2023	2024

Different uses of PERSEE

U1 - Optimal sizing under perfect long term optimal control
U2 - Optimal sizing under realistic optimal control
U3 - Optimal short term control of simulators or real systems

PERSEE (U1 → Techno-economical feasability) · PERSEE (U2 → (pre)sizing) · PERSEE (U3 → High Level Control conception)

Opportunity → Techno-economical feasability → (pre)sizing → High Level Control conception → High Level Operating control → Operation and Maintenance, diagnostic, maintenance prediction

Architecture scanning
Techno-economic and environmental studies

→ **Fine studies of real systems – Towards digital twin**

From feasibility to operation in real environment

As system architecture and size get more defined, needs for finer / more realistic models increase

Short term operation, Long term foresight

Planning Horizon	Time Space	[1 year with 1 hour timesteps] [region – city – district – industrial plants]	[1 week using 5 mn timesteps] [plant - component]
Modeling scale			
System determination			

More realistic and robust designs need short term forecast capabilities with seasonal / long term constraint

Assessment / robust design Accounting for uncertainties

Regulation: Fees, incentives
Model parameters: Tec, Eco, Env
Time series: Source load, Weather, Cost

An example of project:
Towards Zero EmISSION FACTORY

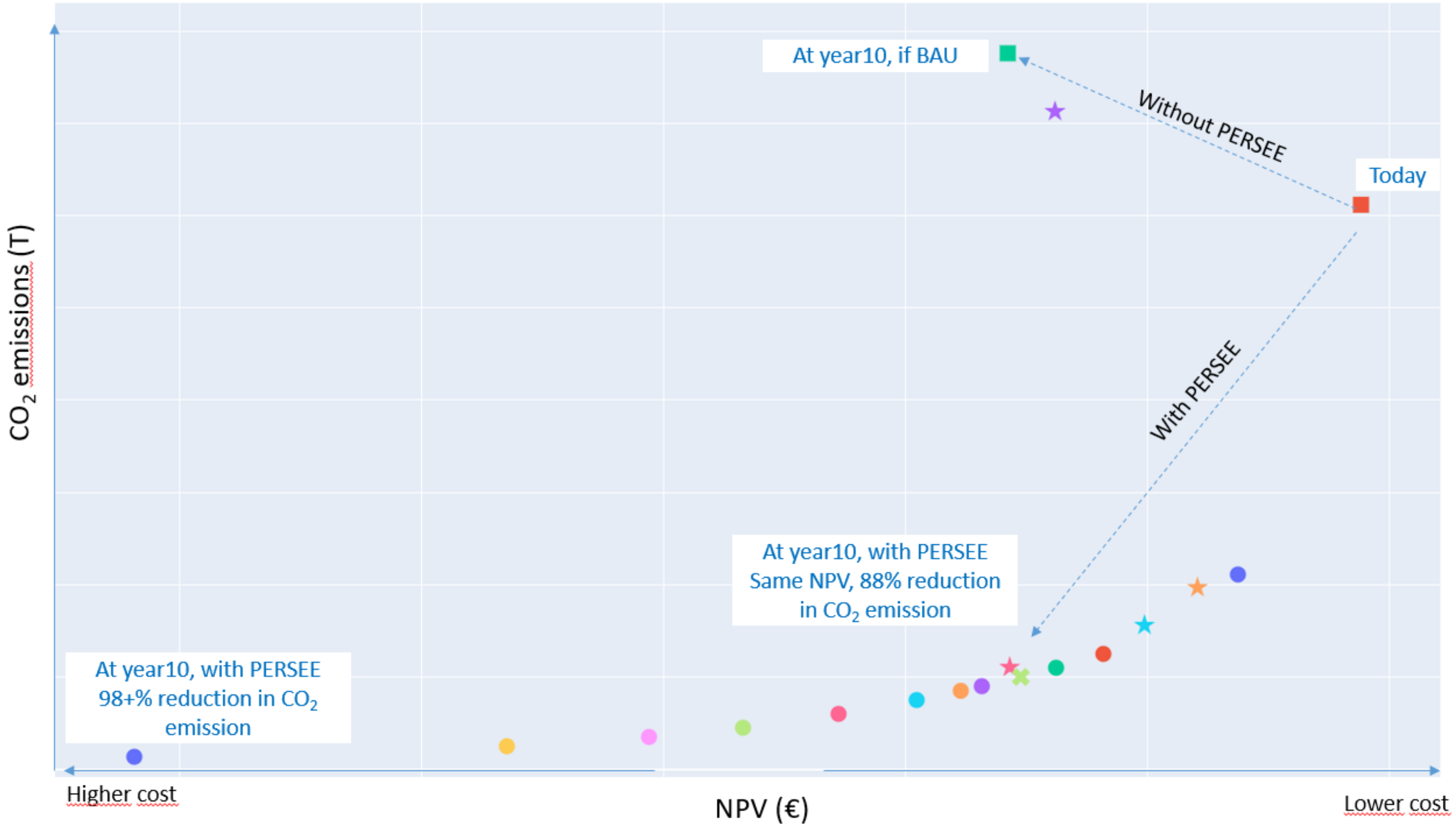
BUSINESS CASE

- **Partner :** a 1+B$; natural and organic cosmetics and well-being products
- **Partner's ambition :** Zero CO_2 factory within 10 years
- **Industrial caracteristics :** industrial site using electricity, heat, steam, cold & water treatment

OUTCOME

Without Persee (Business as Usual) : 36% CO_2 increase in 10 years (with increased production +40%)

With Persee :
- With similar NPV as BAU,
- 88% CO_2 reduction,
- 69% energy autonomy,
- With only 4 steps and limited capex (less than 0,3% of turnover) : PV, Heat pumps, cogeneration, storage…

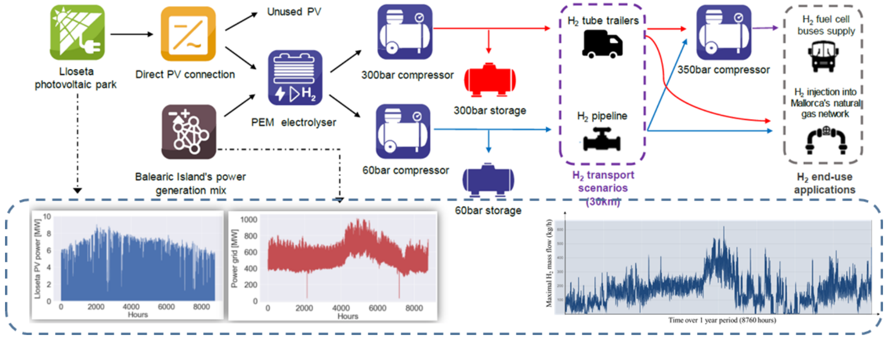


U1 - Optimal sizing under perfect long term optimal control

Principle of PERSEE

PERSEE

Build and **solve** a MILP optimization problem to **size** and **operate** an energy system



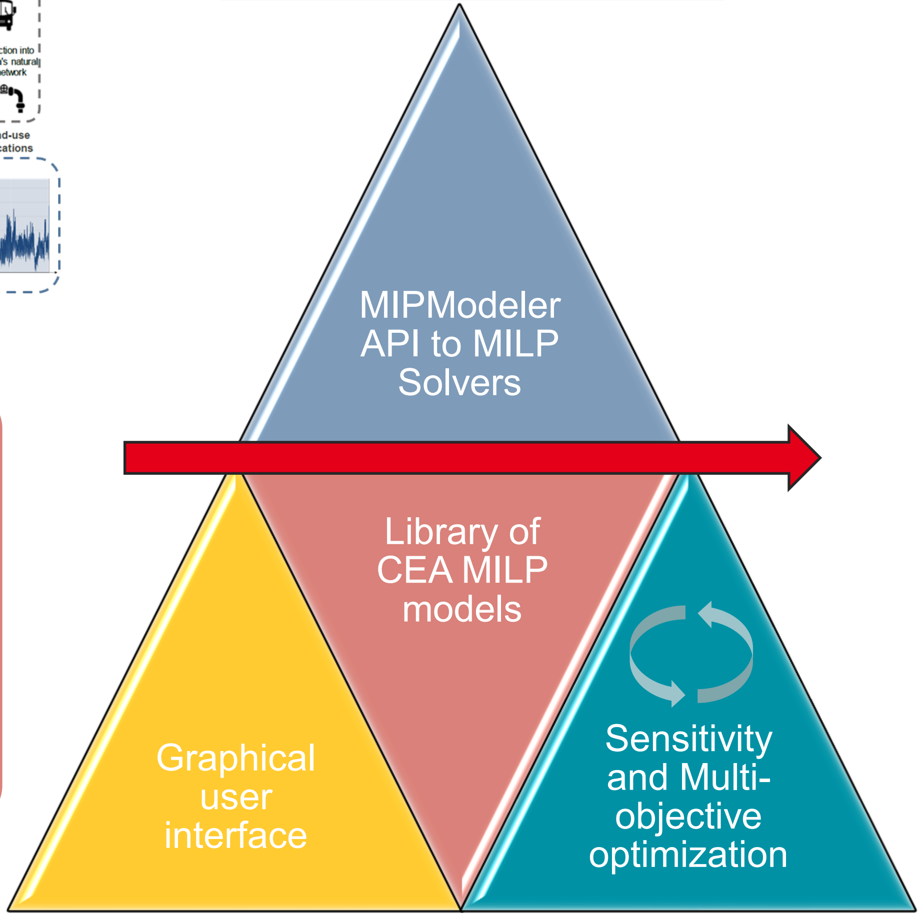
Objective function
NPV, IRR, CO2 emission

Components constraints models
Start-up, ramps…

System constraints models
Node laws, Equalities…

☺ All energy carriers
☺ System design in dynamic transients
☺ Predictive Control

C++
TULEAP, Jenkins
CEA License



Optimal sizing of the system and optimal operation

KPIs
- Total costs
- CO2 emissions
- Energy, power, number of operating hours

- Optimality of the solution is guaranteed

Sensitivity studies can be conducted easily (internally or with URANIE)

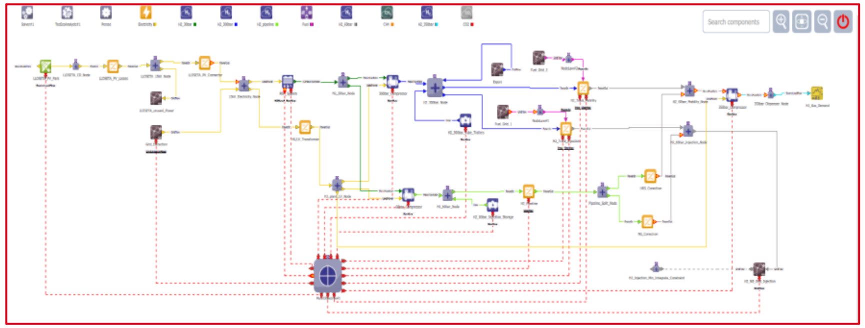
Principle of PERSEE

PERSEE

☺ All energy carriers
☺ System design in dynamic transients
☺ Predictive Control

C++
TULEAP, Jenkins
CEA License

Persee IHM to build the architecture



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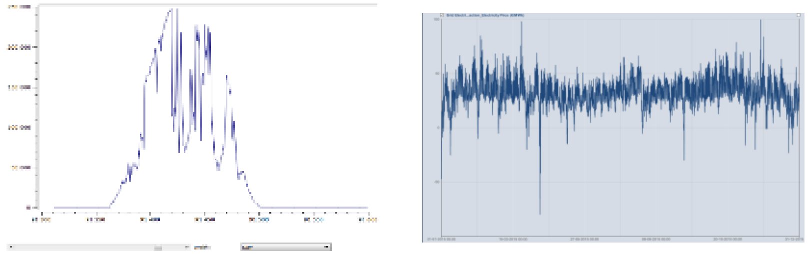
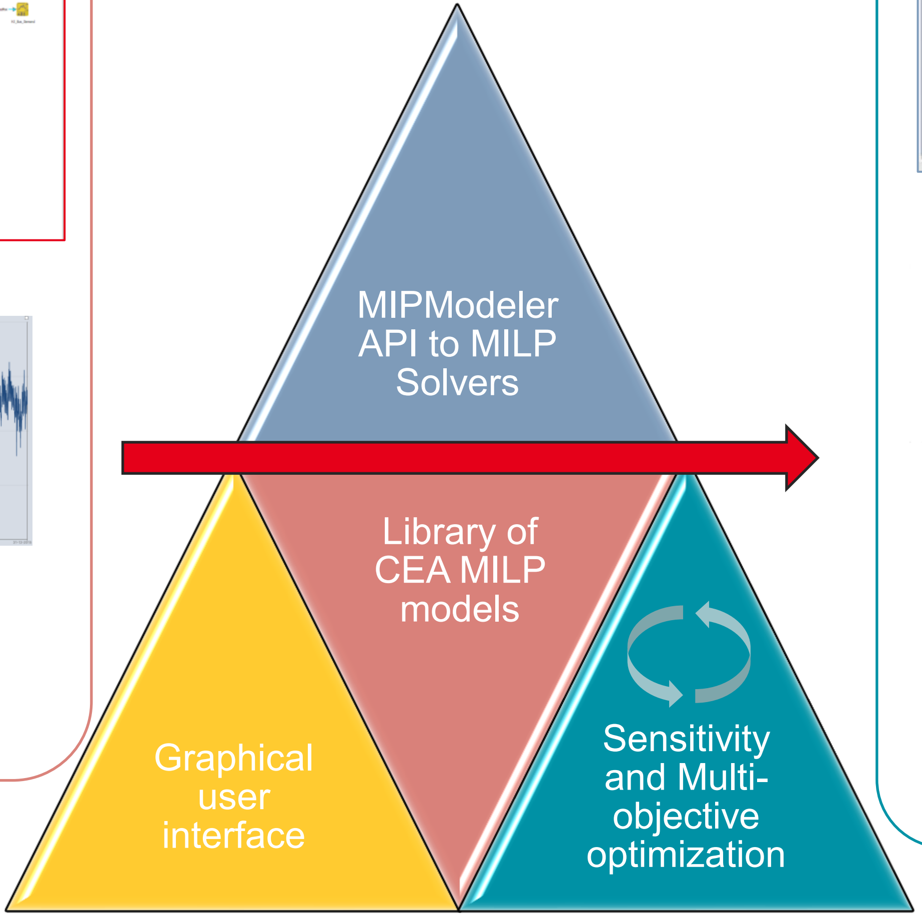
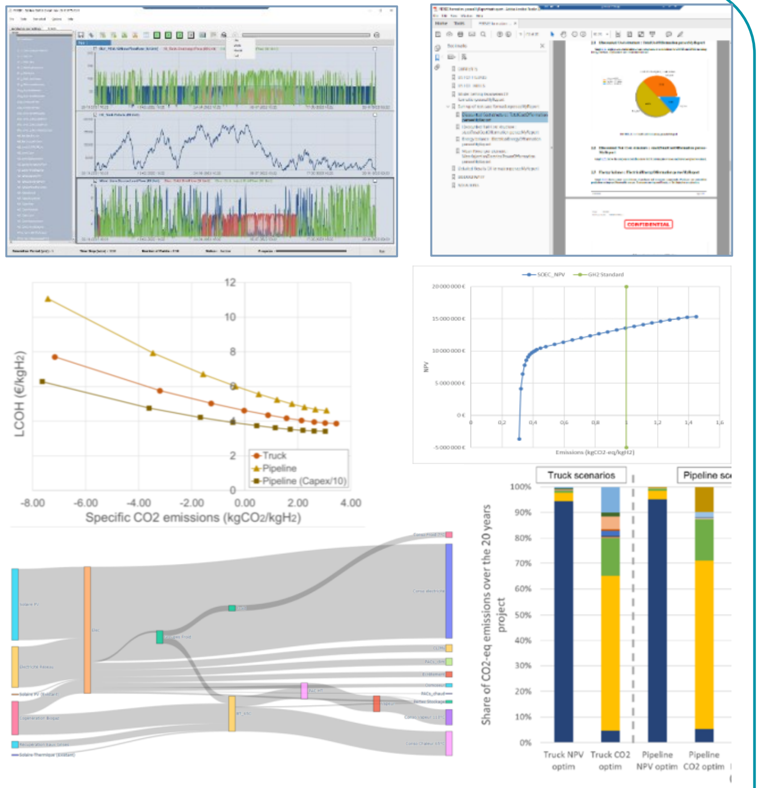


Load profile,
RE producible,
…

GAMS, COIN-OR, IBM ILOG CPLEX, GUROBI OPTIMIZATION





Temporal analysis, documentation,
« Pareto » front, Sankey diagram, …

The basics of economics: Investment decision (1/3)

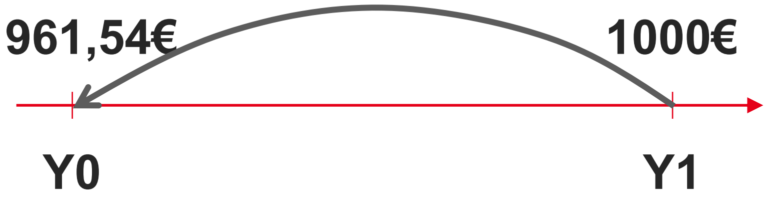
- Money value through time
  - Principle: the value of two amounts of money can be different if they are not available at the same time (e.g. inflation effect)
  - Levelization and capitalisation allow to compare two amounts of money available at different times

Levelization

- From future to today
- *Example:*
  - *I should receive 1000€ in 1 year but I need money today -> I loan money to a bank*
  - *How much money can I loan at 4%?*
    - ***S1** = S0 (1,04) = **1000€***

    *So **S0** = 1000/(1,04) = **961,54€***

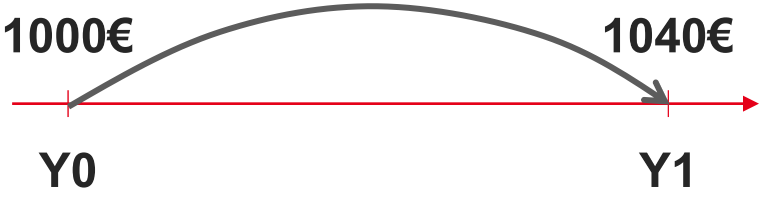
    S0 is called the levelized value of 1000€ in one year



Capitalisation

- From today to future
- *Example:*
  - *I have **1000€** to a bank*
  - *How much money will I have in one year at 4%?*
    - ***S1** = 1000 (1,04) = **1040€***

    After two years, S2 = S1 (1,04) = 1081,6€



The basics of economics: Investment decision (2/3)

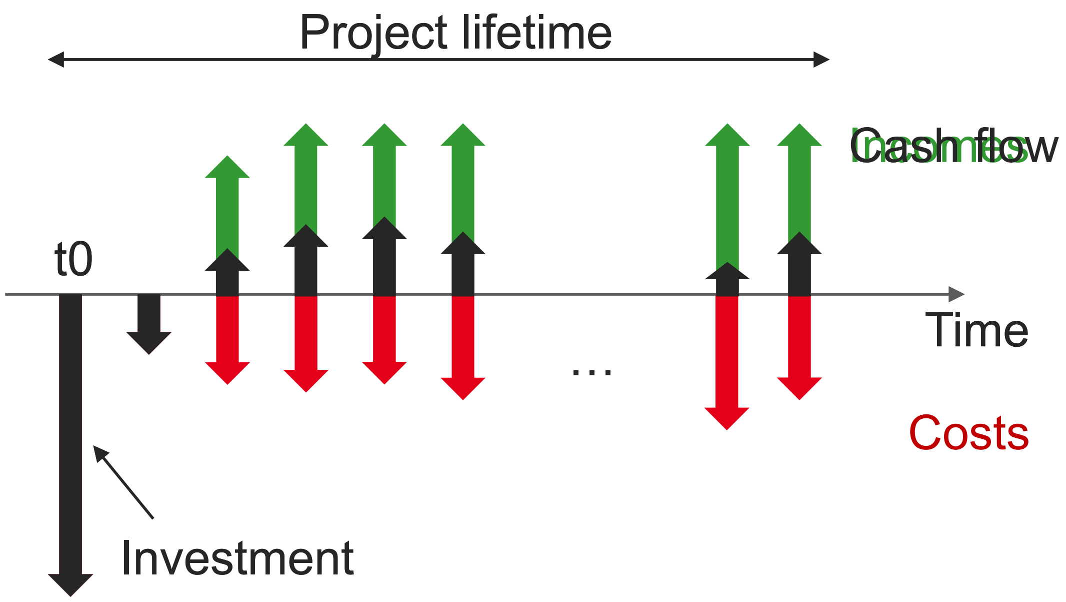
Investment | *Project lifetime*

CAPEX ←

→ OPEX

→ Taxes

← Incomes



- Cash flow = Cash inflow – Cash outflow
- All the cash flows must be levelized

$Discount\ rate$ is based on the cost of debt and the cost of equity. Depending on the risk of investing, the investment return could be more higher.

$$Discount\ rate\ r = 10\% \qquad Discount\ factor_i = \frac{1}{(1+k)^i}$$

Year	0	1	2	3	4	5	6	
Cash flow	0	20	30	50	50	50	50	Σ = 250
Discount factor year i	1.00	0.91	0.83	0.75	0.68	0.62	0.56	
Discounted cash flow	0	18	25	38	34	31	28	Σ = 174

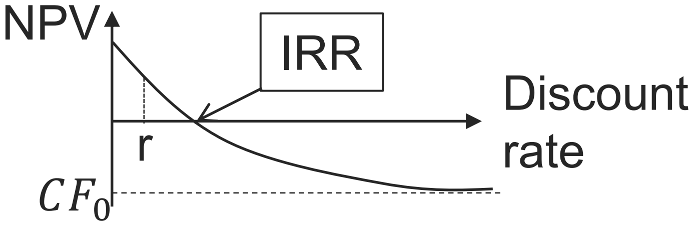
The basics of economics: Investment decision (3/3)

- Definition of ecomic criteria:
  - **NPV (Net Present Value)**
    Sum of the levelized cash flows
    NPV > 0 means that the project is profitable
    (incomes cover the expenses, the investment can be paid back, an excess profit is created)

$$\sum_{i=0}^{n} \frac{Cash\ Flow_i}{(1+r)^i}$$

  - **IRR (Internal Rate of Return)**
    Rate for which the cash flows pay back the investment (NPV=0)
    IRR > WACC (or discount rate) to be profitable
    WACC = Weighted Average Cost of Capital $WACC = \alpha e + (1-\alpha)c_p$

$e = loan\ rate, c_p = rate\ of\ return\ expected, \alpha = breakdown\ of\ loan\ and\ equity$



  - **LCOE (Levelized Cost Of Energy)**
    Cost for which energy must be sold to cancel the NPV (NPV=0)
    /!\ When multiple output products

$$LCOE = \frac{\sum_{i=0}^{n} \frac{CAPEX_i}{(1+r)^i}}{\sum_{i=0}^{n} \frac{Q_i}{(1+r)^i}} + \frac{\sum_{i=0}^{n} \frac{OPEX_i}{(1+r)^i}}{\sum_{i=0}^{n} \frac{Q_i}{(1+r)^i}}$$

The basics of environmental assessment (1/1)

- Definition of environmental criteria:
  - **CO_2 eq emissions**

    Grey/Indirect emissions: linked to the construction of the component in kg CO_2 eq /{Installed capacity unit}

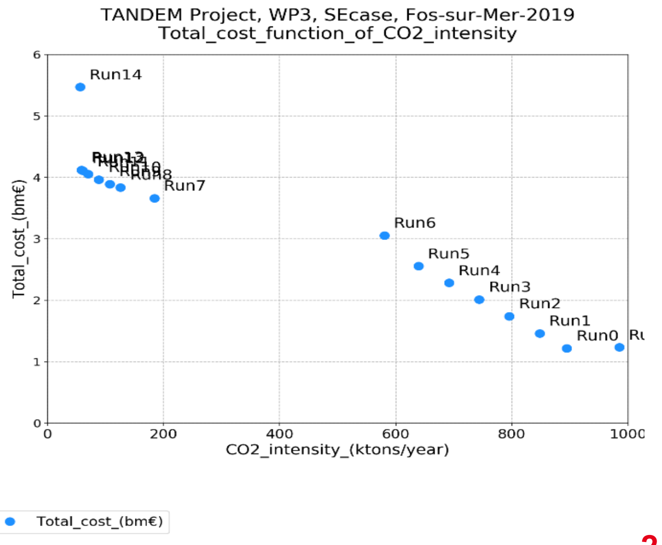
    Direct emissions: linked to the use of the component in kg CO_2 eq/{energy unit}
  - **Towards LCA criteria**

    16 categories of impacts defined in Environmental Footprint (EF) v3.0 method*

- Bi-criteria optimisation
  - Two objective functions

  e.g. minimize total costs and minimize total CO_2 eq emissions
  - Parametric study on one of the criteria

  e.g. total CO_2 eq emissions



*https://eplca.jrc.ec.europa.eu/LCDN/EF_archive.html

The basics of LP/MILP (1/3)
LP

- <u>Form of the problem</u>
  - Ω of n variables $(x_1, \ldots\ x_n) \in \mathbb{R}$
  - Linear constraints $a_{i1}x_1 + \ \ldots + a_{in}\ x_n \leq \mathrm{b}_i$
  - Linear objective function: $cx_1 + \ \ldots + c_n\ x_n$ to be minimized or maximized

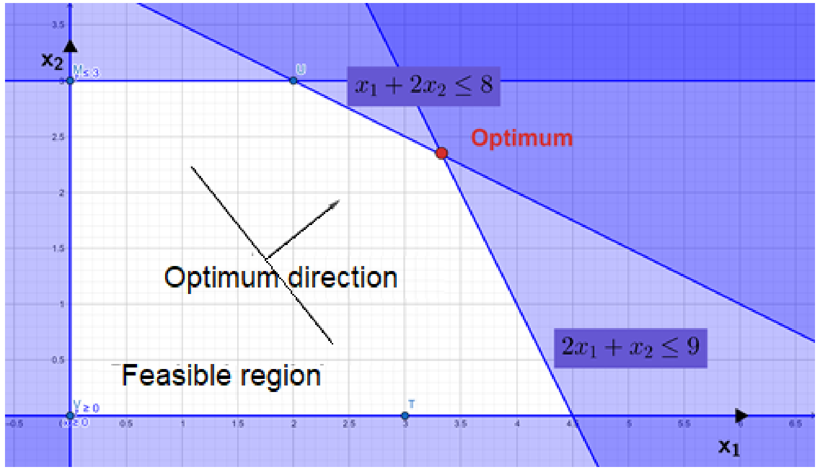
- <u>Problem solving</u>
  - *Simplex algorithm*: the solution is one of the vertice of the feasible region which is a polyhedron
  - *Interior-point method*: move through the interior of feasible region

- <u>Properties of the problem</u>
  - The problem is convex, there is **no local optimum**
  - The problem is found in **polynomial time** depending on the number of constraints and variables

<u>Example:</u>

$$\max \quad 4x_1 + 5\,x_2$$

$$\text{St} \quad \begin{cases} x_1 + 2\,x_2 \leq 8 \\ 2\,x_1 + x_2 \leq 9 \\ x_2 \leq 3 \\ x_1 \geq 0 \\ x_2 \geq 0 \\ x_1, x_2 \in \ \mathbb{R}^2 \end{cases}$$



The basics of LP/MILP (2/3)
MILP

- Form of the problem
  - Ω of n variables $(x_1, \ldots\ x_n) \in \mathbb{R}$ and Ω of m variables $(y_1, \ldots\ y_m) \in \mathbb{N}$
  - Linear constraints $a_{i1}x_1 + \ \ldots + a_{in}\ x_n + b_{i1}y_1 + \ \ldots + b_{im}\ y_m \leq c_i$
  - Linear objective function: $d_1 x_1 + \ \ldots + d_n\ x_n$ to be minimized or maximized

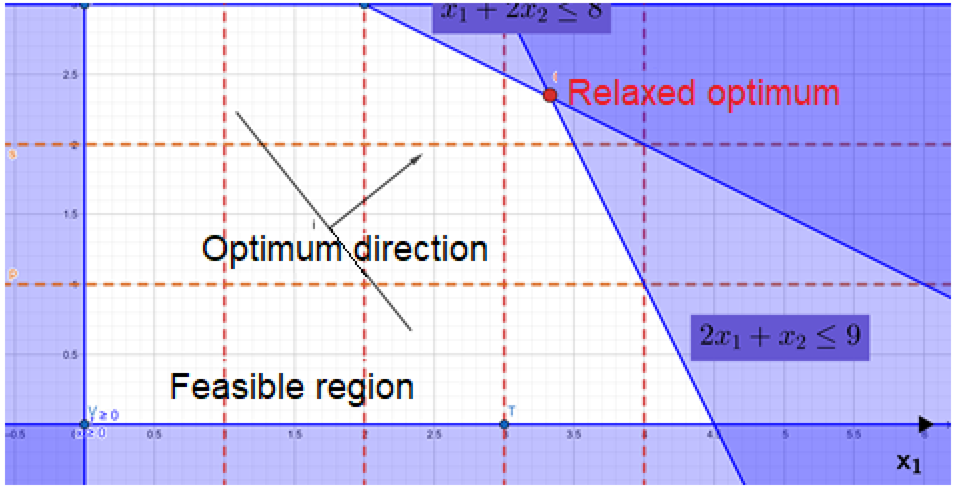
- Problem solving
  - *Branch-and-bound/Branch-and-cut*

- Properties of the problem
  - The problem is NP-hard meaning that it is possible to encounter a problem where testing all the combinations of integer variables is needed to find the optimum. In this case, the number of evaluations is exponential in function of the number of integer variables
  - Owing to branch-and-bound/branch-and-cut, it is possible to provide guarantees about the quality of a solution without having reached the optimum

Example:

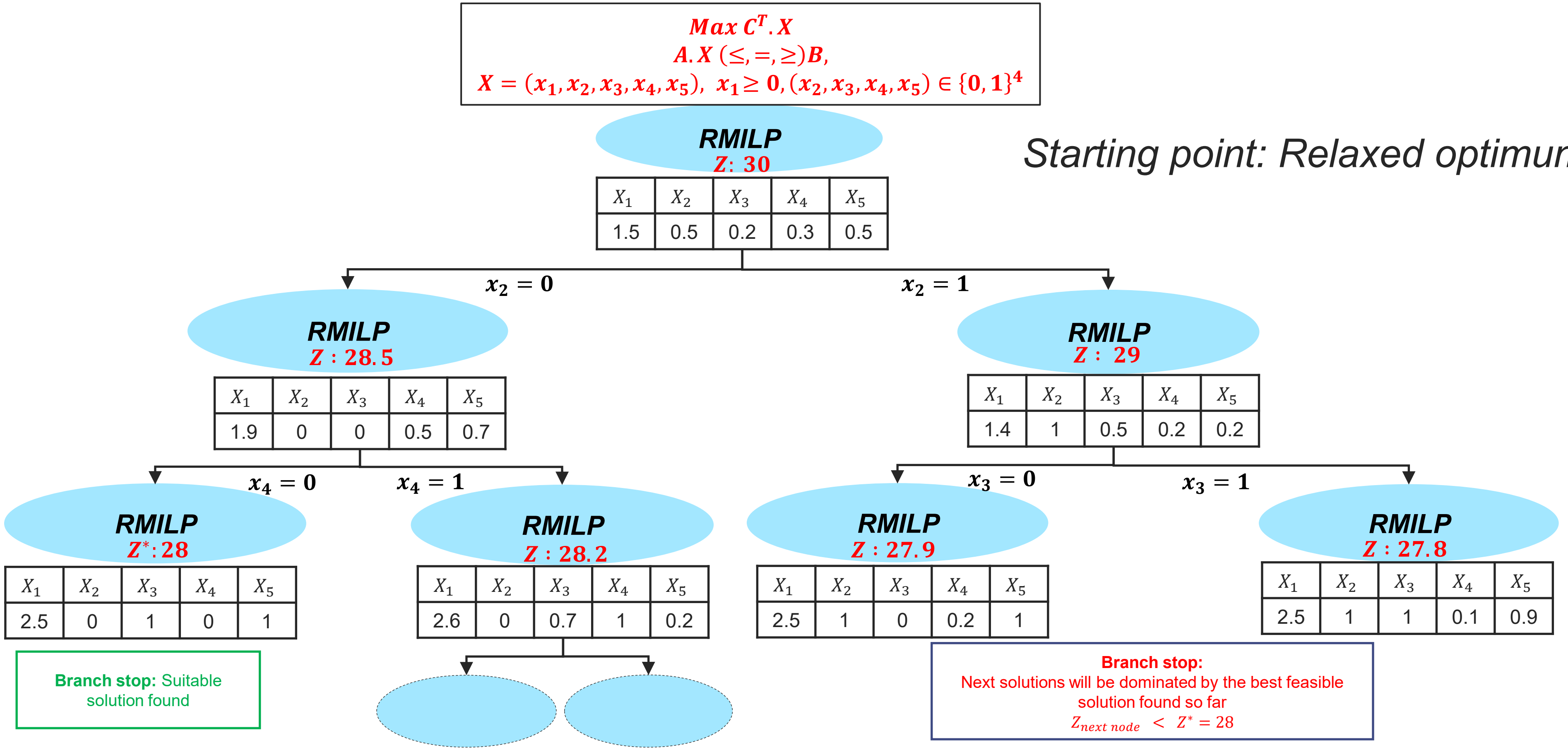
$$\max \quad 4x_1 + 5\,x_2$$

$$\text{St} \quad \begin{cases} x_1 + 2\,x_2 \leq 8 \\ 2\,x_1 + x_2 \leq 9 \\ x_2 \leq 3 \\ x_1 \geq 0 \\ x_2 \geq 0 \\ x_1, x_2 \in \mathbb{N}^2 \end{cases}$$



The basics of LP/MILP (3/3)
MILP

- Branch and bound method

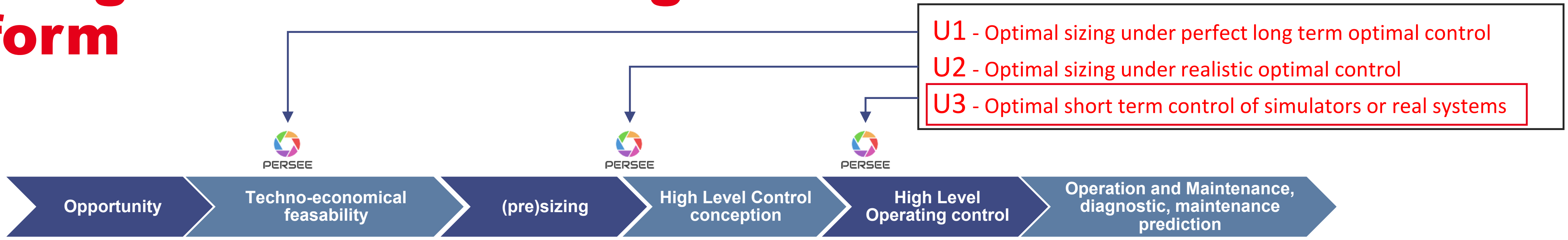


Starting point: Relaxed optimum

Progressively split the main branch into two branches fixing one integer variable to 0 or 1 and study the « relaxed » optimum

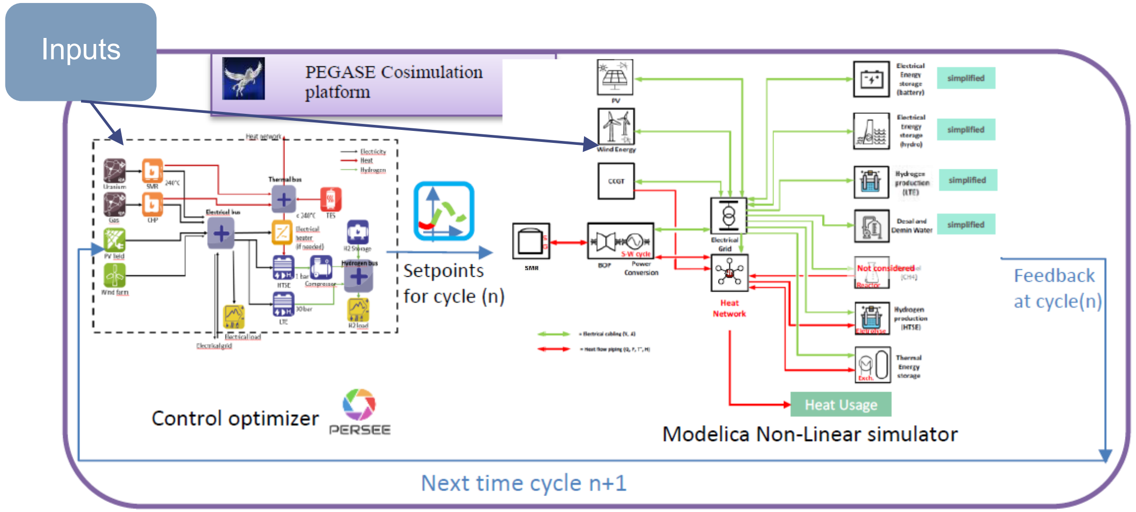
4. PEGASE/PERSEE

Couplings PERSEE and Pegase cosimulation platform



- History:
  - 2016: First Pegase application (PyFMI: 2016*)
  - 2021: Base layer of Pegase is open source (FBSF)

  https://github.com/L-3S/SiFFra



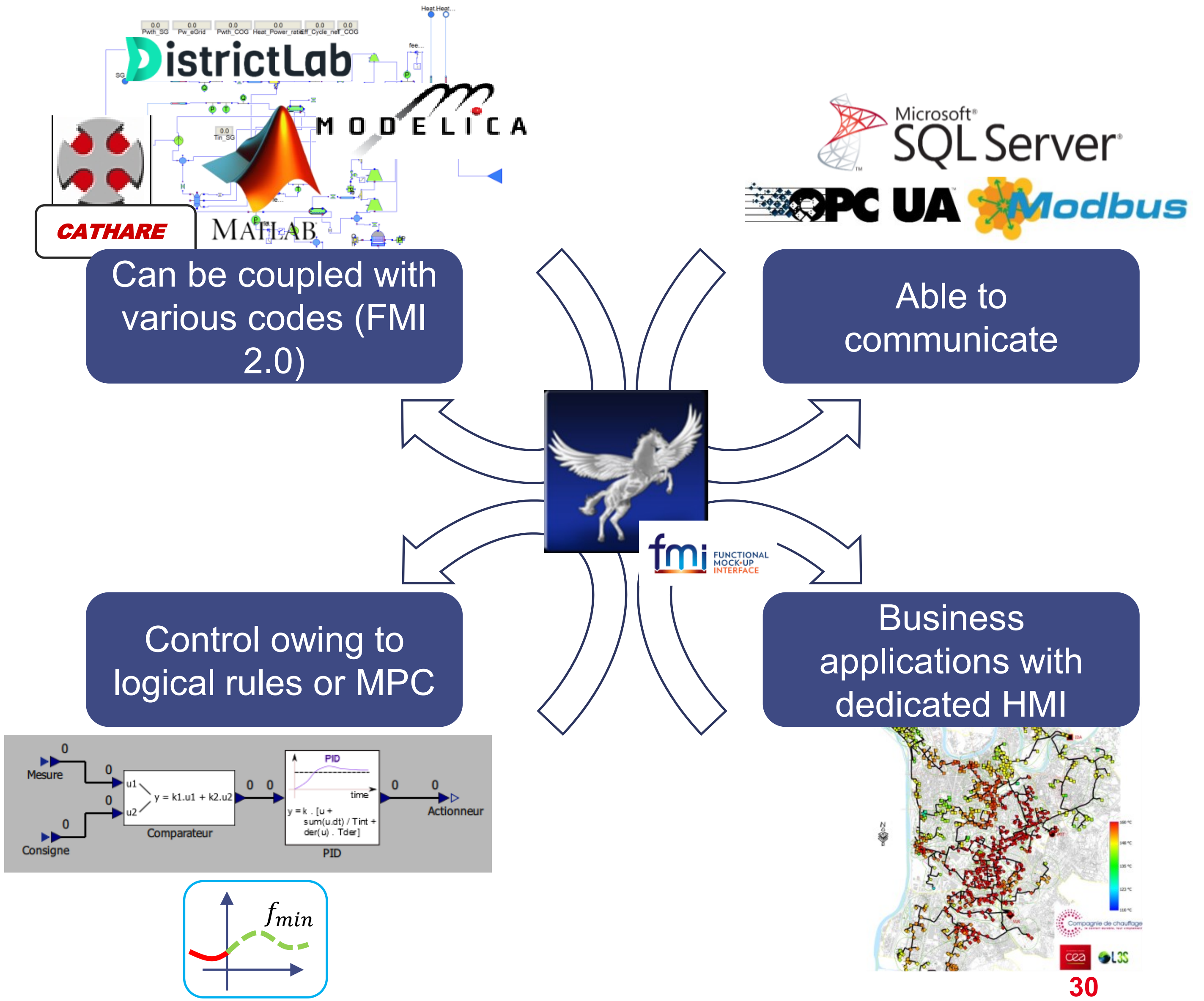
The Functional Mock-up Interface is a free standard that defines a container and an interface to exchange dynamic simulation models using a combination of XML files, binaries and C code, distributed as a ZIP file. It is supported by 200+ tools and maintained as a Modelica Association Project.

*Andersson et al., PyFMI: A Python Package for Simulation of Coupled Dynamic Models with the Functional Mock-up Interface, volume LUTFNA-5008-2016 of Technical Report in Mathematical Sciences. Centre for Mathematical Sciences, Lund University, 2016.

Pegase cosimulation platform

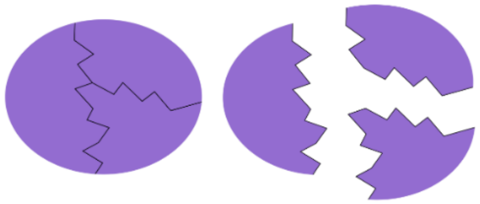
Pegase is a multi-carriers simulation platform used to analyse and operation optimize complex energy systems

- Integration platform supporting FMI2.0-cs standard
- Cosimulation platform with the possibility to have several modules running in parallel
- Modeling environment to operate systems (logical rules or optimal)
- Can be interfaced to industrial systems (databases, automations)

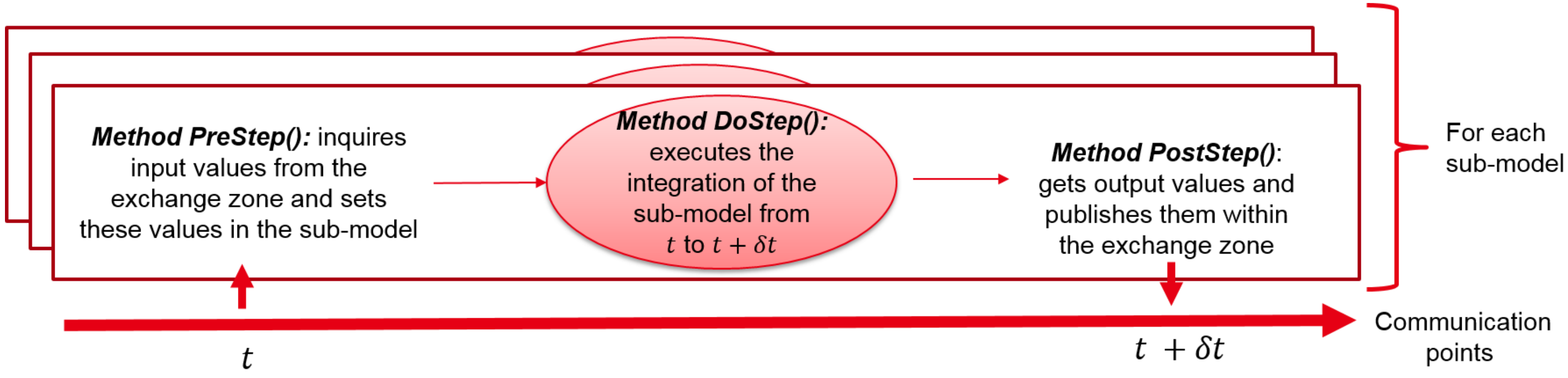


Pegase principles (1/2)

Cosimulation



- Decomposition of a complex system into a collection of non-overlapping sub-systems
- Modelling of each sub-system using an adapted simulation tool
- Individual simulation of each sub-system
- Exchange of the input/output interface variables at discrete instants (called communication points) via an Exchange Zone
- When they are not available, input variables at $t + \delta t$ are provided by output variables evaluated at t.

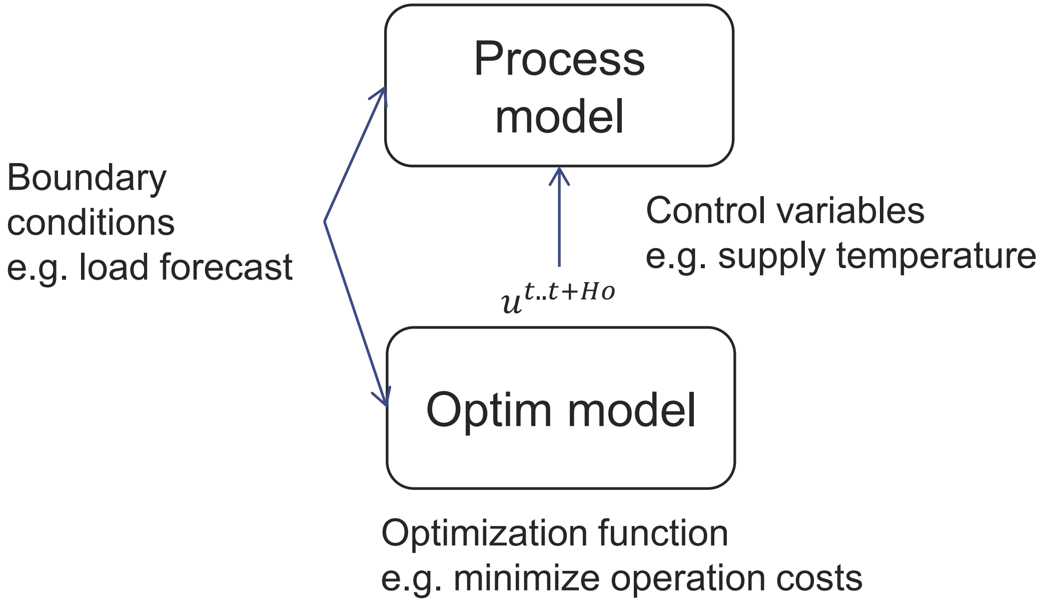


Pegase principles (2/2)

Model Predictive Control (MPC): Optimization of the operation + rolling horizon

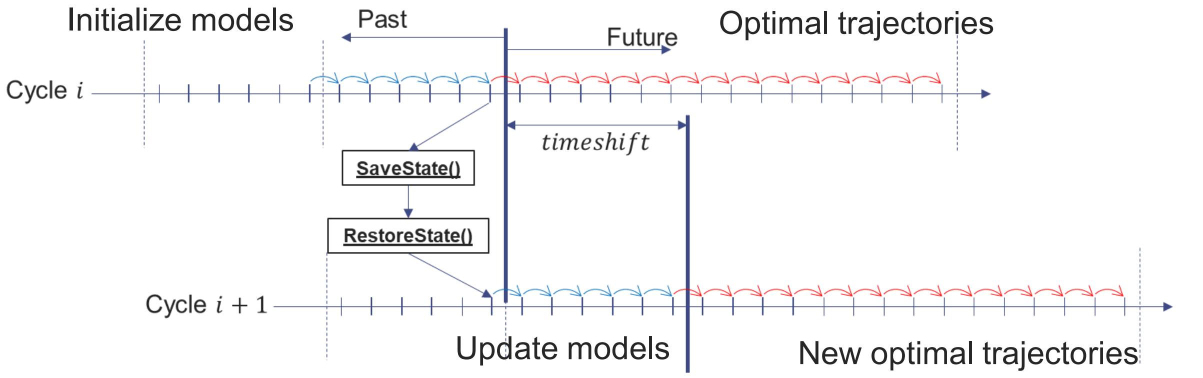
Focus on optimization

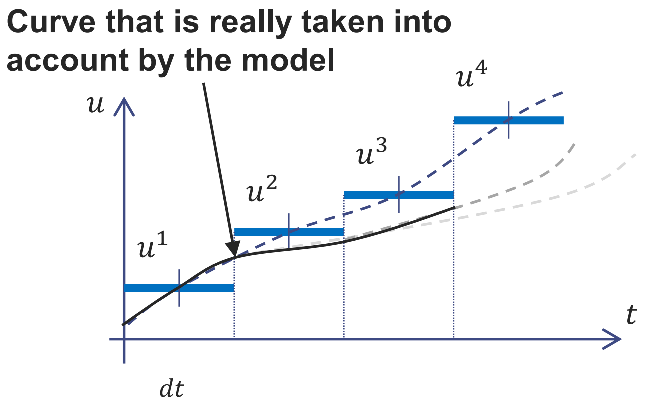
Calculation of optimal trajectories for control variables u over a time horizon $t \dots t + H_0$



Focus on temporality

Regular update of boundary conditions (+ the process model) and re-calculation of optimal trajectories





At each cycle, optimal trajectories of variables $u^{t..t+Ho}$ are built and sent to the detailed model, Setpoints are applied and new state is taken into account at the next cycle to generate new optimal trajectories

DistriSim example (1/2)

U1 - Optimal sizing under perfect long term optimal control

Compare the robustness of two optimal architectures for a newly built district at Grenoble*

- The electricity-driven architecture
- The district heating architecture

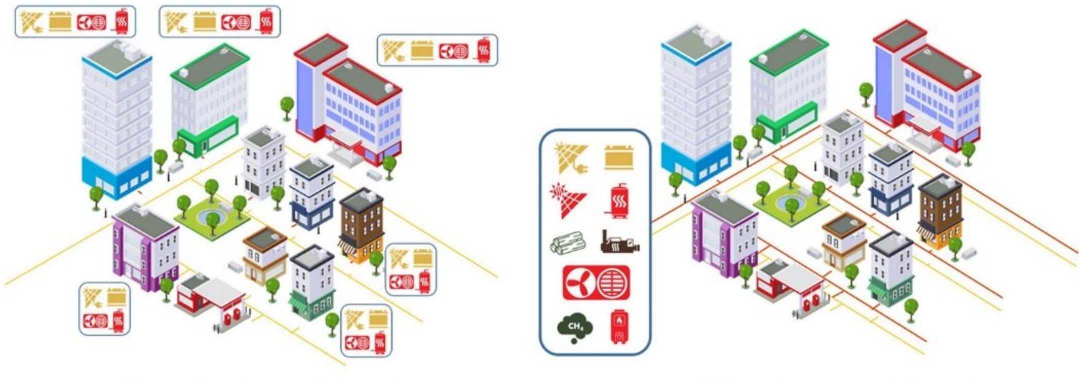
PERSEE used in stand-alone mode to optimize:

- The size of the components
- The operation of the system

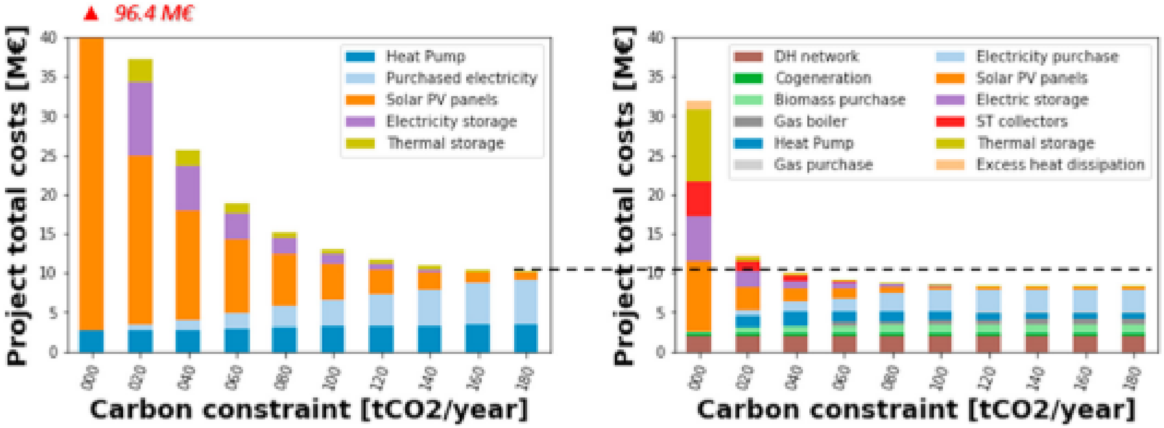
Multi-objective approach:

- Total project cost versus CO2 emissions

→ Electricity driven architecture is less robust especially to SH demands and to heat pump performance



(Electricity-driven architecture) *(District heating architecture)*



(Electricity-driven architecture) *(District heating architecture)*

*Fito et al., “Robustness of District Heating versus Electricity-Driven Energy System at District Level: a Multi-Objective Optimization Study”, Smart Energy, 6, 100073, https://doi.org/10.1016/j.segy.2022.100073

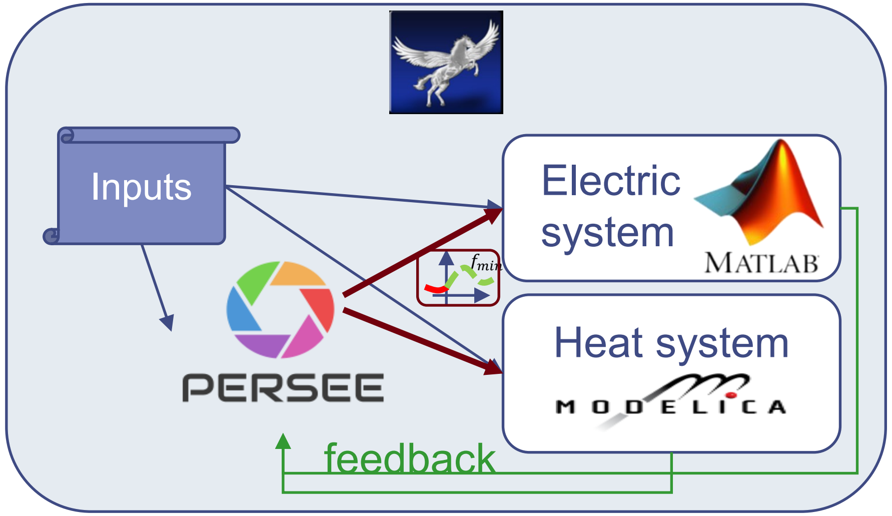
DistriSim example (2/2)

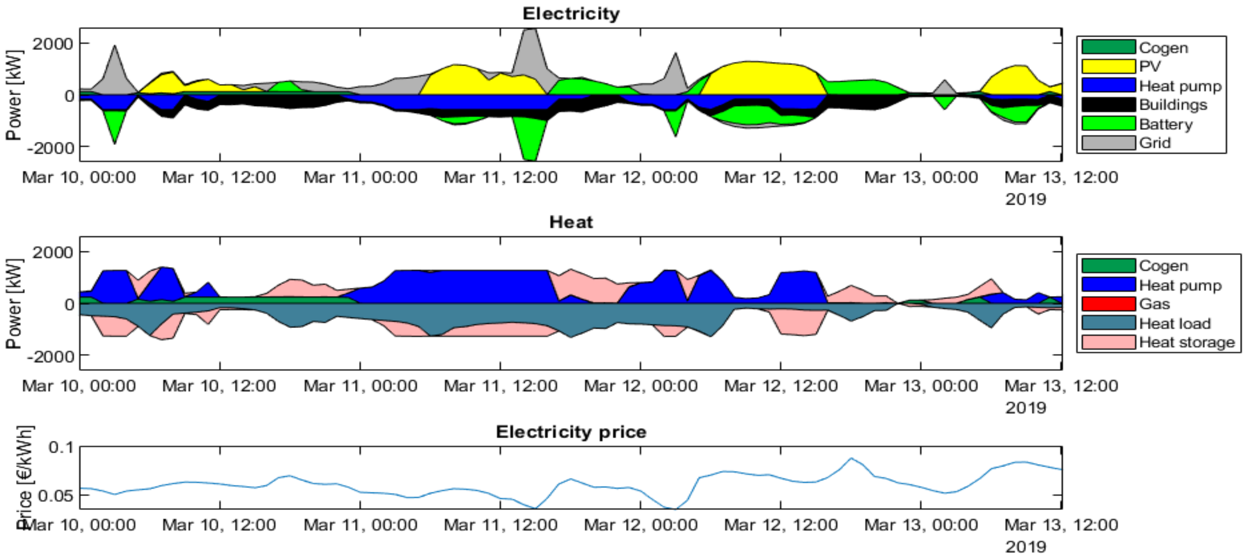
U3 - Optimal short term control of simulators or real systems

Study the operation of the district heating architecture with finer models*

- Coupling Pegase/Persee/Modelica and Simulink finer models
- Objective function: minimize operation cost and CO_2 emissions
- Study the coupling strength between the electric and heat system

→ **No use of Gas-boiler backup even when accounting for more realistic modelling**





*Rava et al., "Assessment of Varying Coupling Levels between Electric & Thermal networks at District Level using Co-Simulation and Model-predictive Control", Proc. Int. Conf. ECOS 2022, Copenhagen, Denmark

Thank you