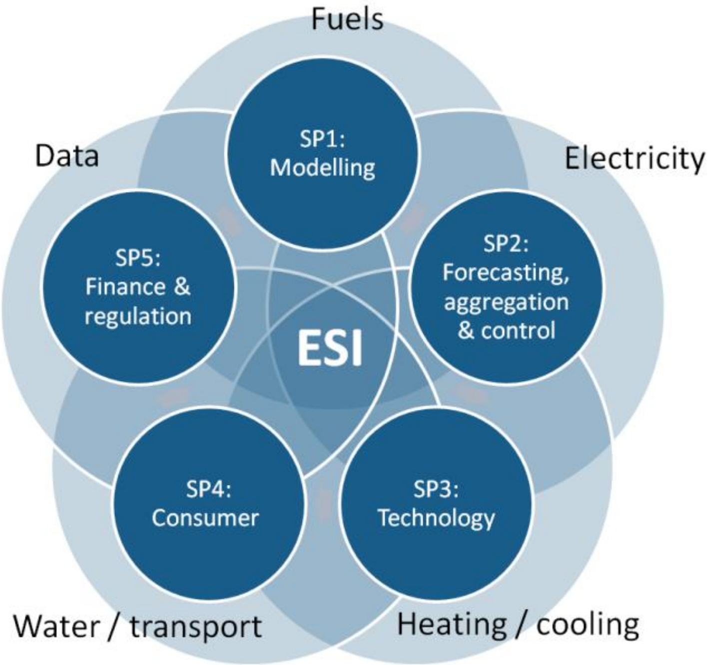

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MODELLING AND OPTIMAL INTEGRATION OF ENERGY SYSTEMS IN BUILDINGS

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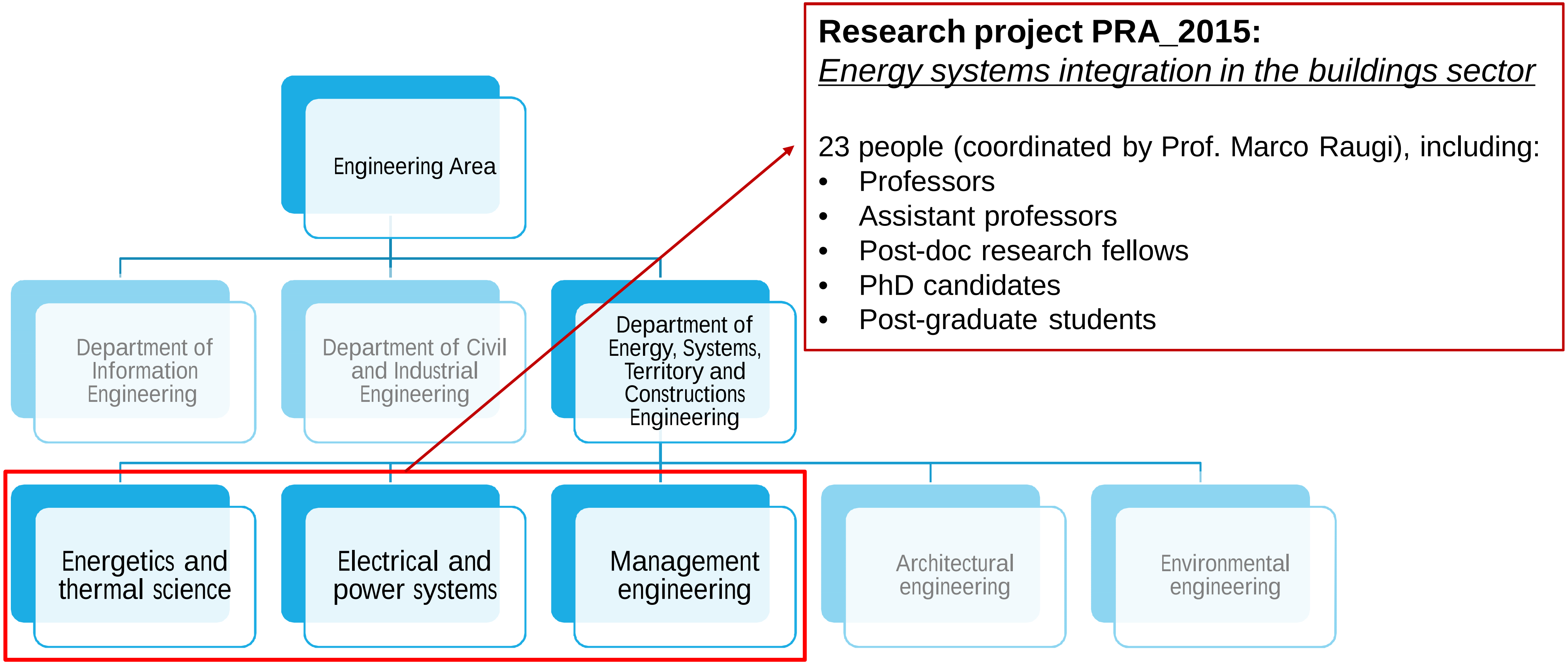

Research project PRA_2015:
Energy systems integration in the buildings sector

23 people (coordinated by Prof. Marco Raugi), including:

- Professors
- Assistant professors
- Post-doc research fellows
- PhD candidates
- Post-graduate students

OPTIMIZATION/MODELLING PHILOSOPHY

The modern engineering approach: from the «precautionary principle» to the cost-benefit optimization

- Modern engineering approach is not aimed only at sizing system components to meet project specifications and constraints, but it seeks the optimal design and management strategies in terms of proper performance indexes

Simulation-based optimization approach

- The optimal configuration can be found through a holistic simulation of all subsystems involved in the energy conversion process and their mutual interactions
- A proper modelling of the system is a pillar for the overall analysis

A 4 in 1 activity

- Design process (system architecture, components sizing and control strategy)
- Performance analysis
- Optimization
- Feasibility study

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OPTIMIZATION/MODELLING: METHODS AND CHALLENGES

Context analysis	• Energy load • Availability of energy sources • Economical, social, environmental, and regulatory contexts
Definition of system architecture	• Energy sources and technologies • Subsystems connections and control strategy
Lifetime scenario(s)	• Operational and investment scenario(s)
Modelling	• Choice of the main physical mechanisms • Length and time scales
Optimization	• Objective function(s) • Strategy and algorithm
Results analysis	• Sensitivity/Robustness • Uncertainty

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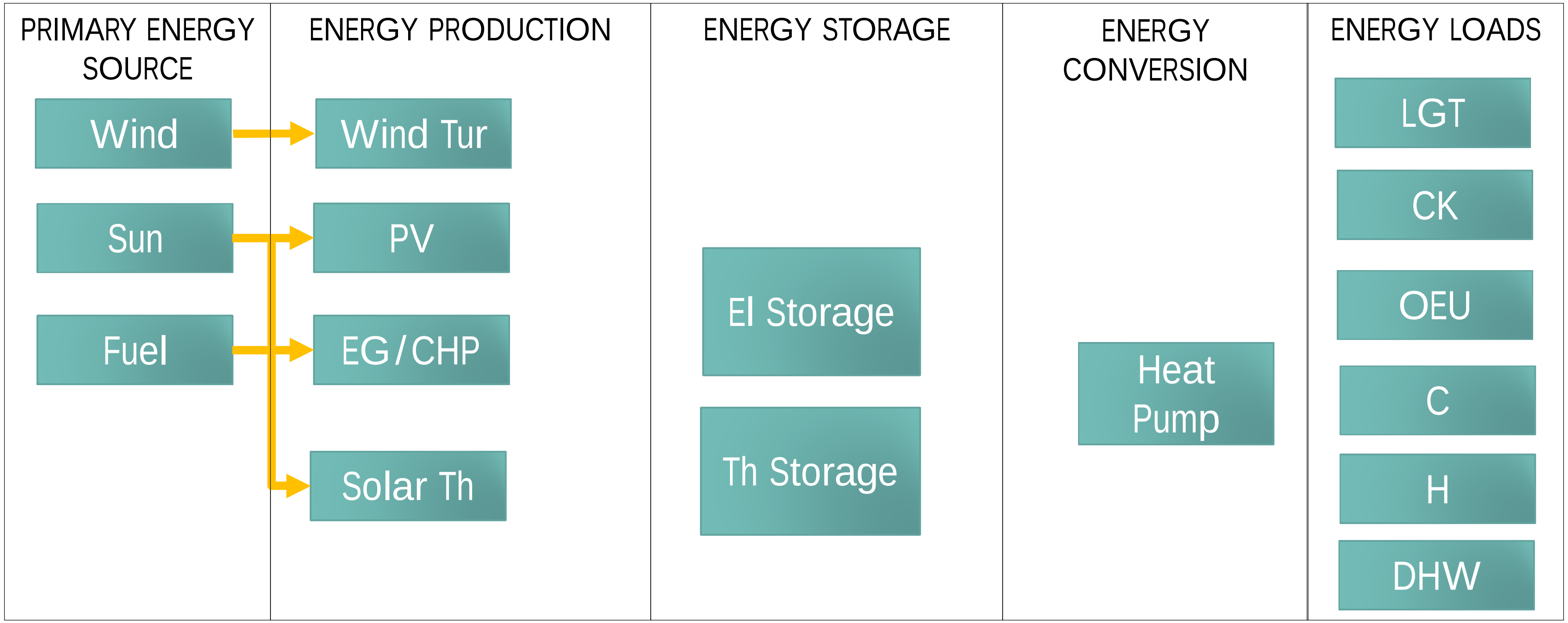
SYSTEM ARCHITECTURE: ENERGY SOURCES AND TECHNOLOGIES

Example from: Aloini *et al.*, *Investment Evaluation under Multiple Uncertainty: Optimal Sizing and Configuration of an Integrated Energy Production System by Renewable Sources*, *19th International Working Seminar on Production Economics*, Innsbruck (A), 2016.



PRIMARY ENERGY SOURCE
- Wind
- Sun
- Fuel

ENERGY PRODUCTION
- Wind Tur
- PV
- EG/CHP
- Solar Th

ENERGY STORAGE
- El Storage
- Th Storage

ENERGY CONVERSION
- Heat Pump

ENERGY LOADS
- LGT
- CK
- OEU
- C
- H
- DHW

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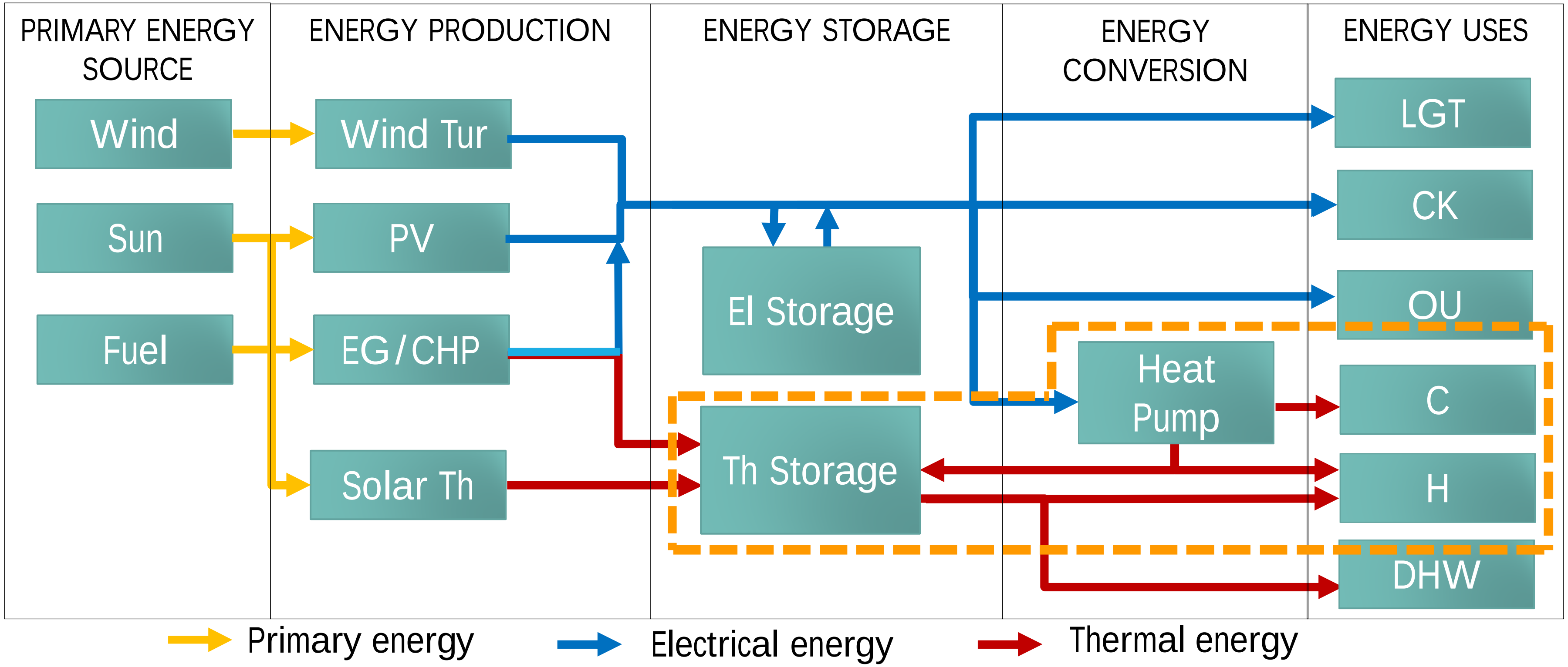
SYSTEM ARCHITECTURE: CONNECTIONS

Example from: Aloini *et al.*, *Investment Evaluation under Multiple Uncertainty: Optimal Sizing and Configuration of an Integrated Energy Production System by Renewable Sources*, *19th International Working Seminar on Production Economics*, Innsbruck (A), 2016.



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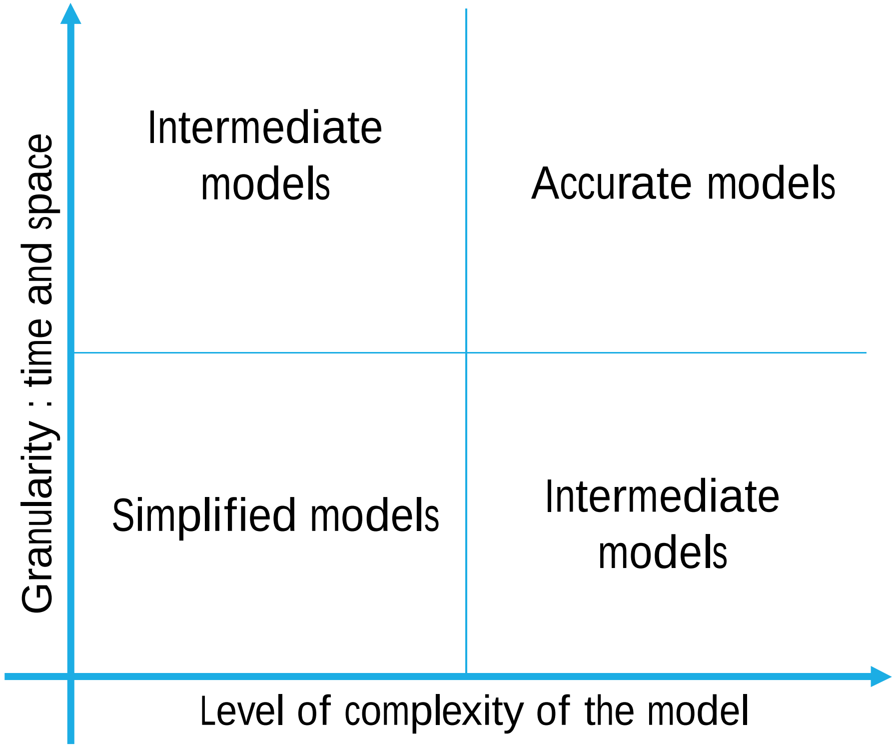
MODELLING CHALLENGES



Granularity : time and space

Intermediate models

Accurate models

Simplified models

Intermediate models

Level of complexity of the model

Classes/Criteria

A. Flexibility and manageability in large, non-linear, multi-source energy systems
B. Suitability in optimization procedures (e.g. computational time)
C. Accuracy: complex enough to capture all the significant governing physical and technical features
D. Availability of sufficiently accurate input variables and parameters.

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EXAMPLE: LEVELS OF BUILDING MODELLING

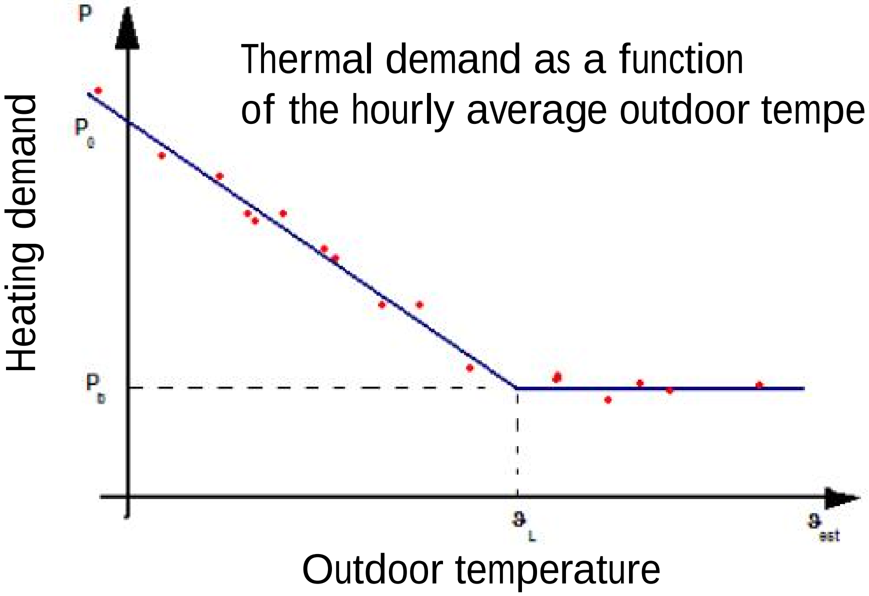
Aims/Goals: evaluate the energy fluxes of the building in order to reproduce the indoor climate conditions and/or the energy demand profile

- ✓ Accurate models
  - Dynamic simulation (Minutes to hour time stepping)
  - Resolution of partial differential equation in time and space
- ✓ Intermediate models
  - Lumped parameter model
- ✓ Simplified models: quasi-steady state
  - Simplified methods (ISO 13790) - Possible time discretization: Hourly/monthly/ Bin

EXAMPLE: LEVELS OF BUILDING MODELLING

Simplified models: quasi-steady state

"Energy Signature"



Thermal demand as a function of the hourly average outdoor temperature

Simplified monthly methods (EN 13790)

Monthly heating demand

$$Q_{H,nd} = (Q_{H,tr} + Q_{H,ve}) - \boldsymbol{\eta_{H,gn}} (Q_{int} + Q_{sol,fin})$$

Monthly cooling demand

$$Q_{C,nd} = (Q_{int} + Q_{sol,fin}) - \boldsymbol{\eta_{C,ls}} (Q_{C,tr} + Q_{C,ve})$$

$\boldsymbol{\eta_{H,gn}}$: dimensionless gain utilization factor
$\boldsymbol{\eta_{C,ls}}$: dimensionless utilization factor for heat losses

Correction factors in order to reproduce the dynamic effects due to the building heat capacity

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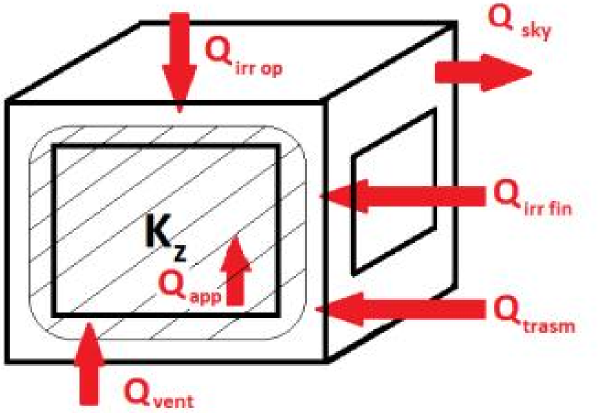
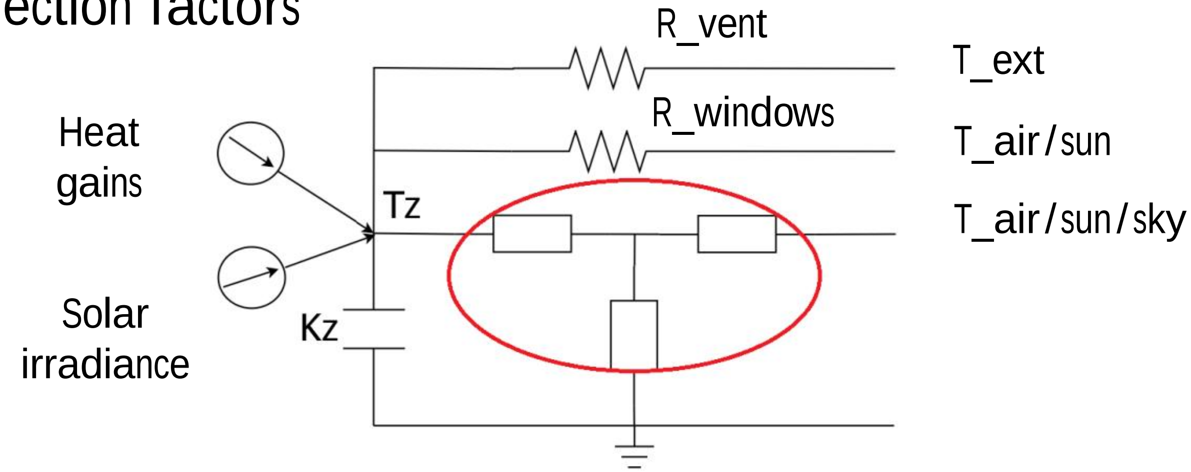
EXAMPLE: LEVELS OF BUILDING MODELLING

Intermediate modelling: lumped parameter simulation with empirical/semi empirical correction factors

(Example from: Testi *et al. 2014)*





$\boldsymbol{K_z = C_m\beta_H}$: equivalent air/walls heat capacity
$\boldsymbol{C_m}$: periodic heat capacity (ISO 13786)
$\boldsymbol{\beta_H}$: correction factor

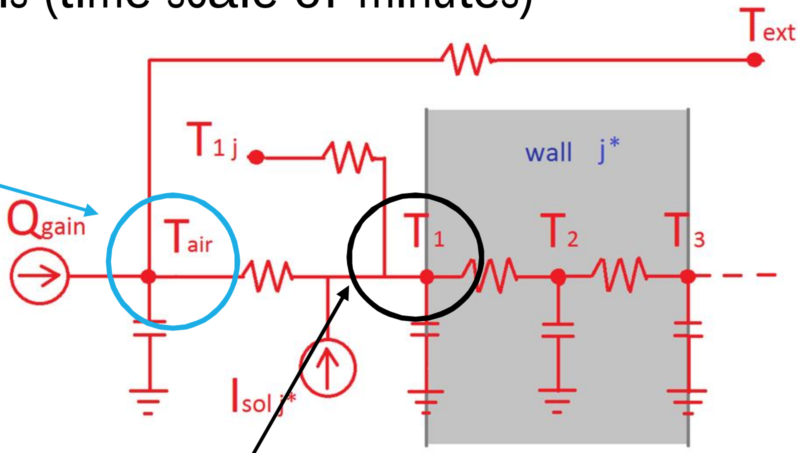
$\boldsymbol{\dot{Q}_H = \epsilon_H \sum \dot{Q}_{ls} - \dot{Q}_g}$: Heating demand of zone Z
$\boldsymbol{\dot{Q}_{ls}}$: Thermal losses $\boldsymbol{\dot{Q}_g}$: Heat gains
$\boldsymbol{\epsilon_H}$: correction factor due to the spatial distribution of walls temp

EXAMPLE: LEVELS OF BUILDING MODELLING

Accurate modelling: dynamic RC simulation models (time scale of minutes)

- Air node balance

$$(\rho\, c_p\, V)_a \frac{T_{a\,k} - T_{a\,k-1}}{t_k - t_{k-1}} = \sum_j h_{conv}\, A_j \left(T_{j1\,k} - T_{a\,k}\right) + (\rho\, c_p\,)_a \dot{V}\,(T_{e\,k} - T_{a\,k}) + \sum_w f_{sa}\, I_{w\,k}\, \tau_w\, A_w + Q_{gain\,k}$$



- Internal wall node balance

$$(\rho\, c\, V)_{j^*\,1} \frac{T_{j^*1\,k} - T_{j^*1\,k-1}}{t_k - t_{k-1}} = \sum_w (1 - f_{sa})(1 - f_{sl})\, f_{sdp}\, I_{w\,k}\, \tau_w\, A_w + \cdots$$

$$+ h_{conv}\, A_{j^*}\left(T_{a\,k} - T_{j^*1\,k}\right) + h_{rad} \sum_j A_{j^*}\left(T_{j\,1\,k} - T_{j^*\,1\,k}\right) F_{j^*j} + \frac{\lambda_{j^*\,1}}{\Delta s_{12}}\, A_{j^*}\left(T_{j^*\,2\,k} - T_{j^*\,1\,k}\right)$$

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EXAMPLES: SIMPLIFIED MODELS FOR ENERGY SYSTEM INTEGRATION IN BUILDINGS

Latent load

$$x_z^{'} - x_z = \frac{x_{prod} - x_{dehum}}{\rho_z V_z} + n_{air}\left(x_{ext} - x_z\right); \qquad x_{dehum} = f\left(UA_{dehum}, C_{dehum}\right)$$

UA_{dehum} and C_{dehum} are heat transmittance-surface product and coil characteristic for dehumidifying coils

Heat terminal unit: radiant floor

$$\Delta T_{RF} = T_{w,RF} - T_z = \Delta T_{RF,nom}\left(\frac{En_{th}}{S_{RF} K_{RF,\mathrm{nom}}}\right)^{\frac{1}{n_{RF}}} \qquad T_{f,RF,C} = T_{w,RF,C} + \frac{En_{th,C}}{S_{RF} U_{wf}}$$

EXAMPLE: SIMPLIFIED MODELS FOR ENERGY SYSTEM INTEGRATION IN BUILDINGS

Heat pump u

- Black-box moc
- Cycle-based m

Defrost cycle mode
minutes, when T_{ext}<

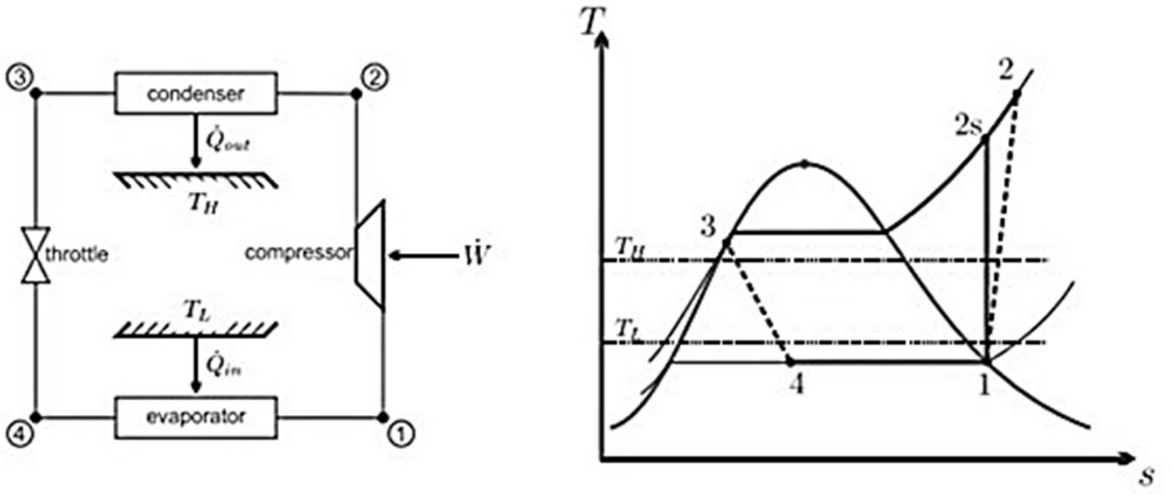

Fig. 10.5 Schematic and T-s-diagram for a standard vapor refrigeration cycle exchaning heat with environments at T_L, T_H

$$_{P,H} \frac{T_{cond}}{T_{cond}-T_{eva}};$$

$$_{P,C} \frac{T_{eva}}{T_{cond}-T_{eva}}$$

Solar thermal

$$E_{th,ST} = n_{ST}\left(\eta_{S}\right.$$

$$\left(\cos\vartheta\right)\Big)$$

$$\frac{_{ST,in}-T_{ext}\Big)}{I_{sol.ST}}$$

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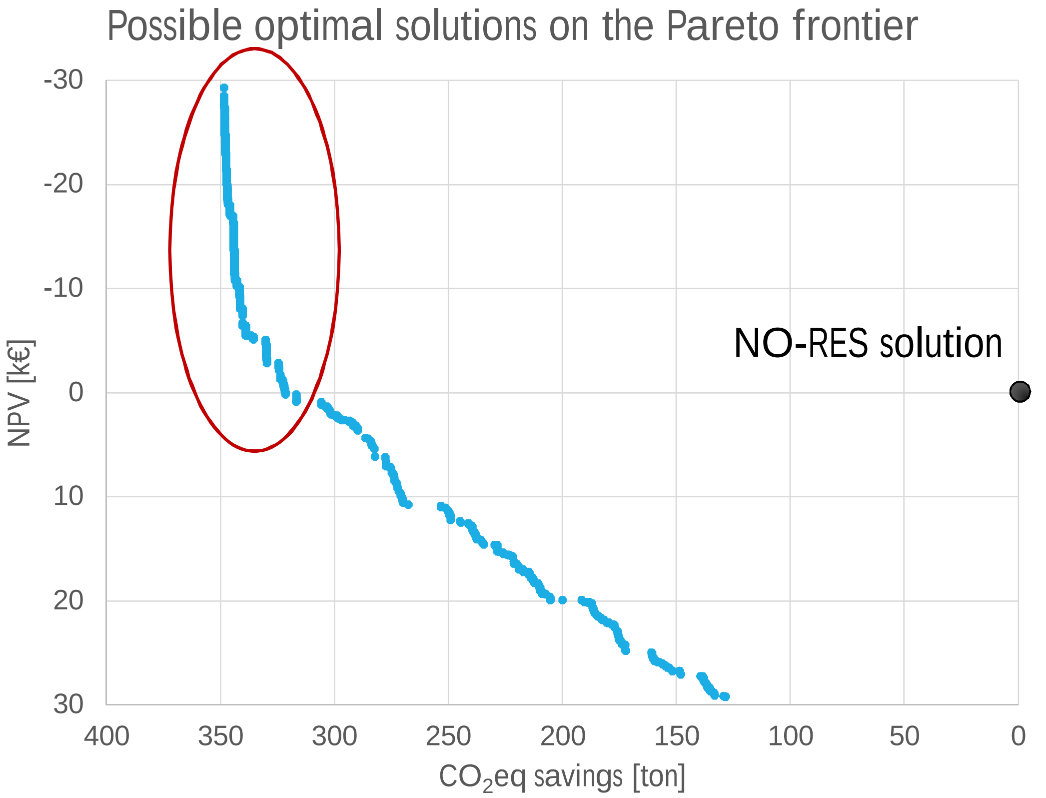
OPTIMIZATION: WHICH PERFORMANCE INDEX?

Possible performance indexes are related to different (and sometimes impairing) objectives, leading to very different results.

- Energy savings
- Economy viability: es. total cost, NPV, profitability index
- Environmental indexes: e.g. CO_2eq savings
- Multi-objective optimization
- Role of uncertainty?



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RESULTS ANALYSIS: SENSITIVITY ANALYSIS

Aims/Goals: evaluation of the output response depending on input variability

- Help for modelling

  Is it possible to analyze the relevance of input parameters of physical mechanisms on the final results, leading to on what components or inputs have to be analyzed in more details

  Examples: users behavior modelling (is it worth spending time with it?)

- Help for uncertainty analysis

  According to the relevance of input parameters on final results, it is possible to select and focus the uncertainty analysis only on some selected parameters

RESULTS ANALYSIS: UNCERTANTY

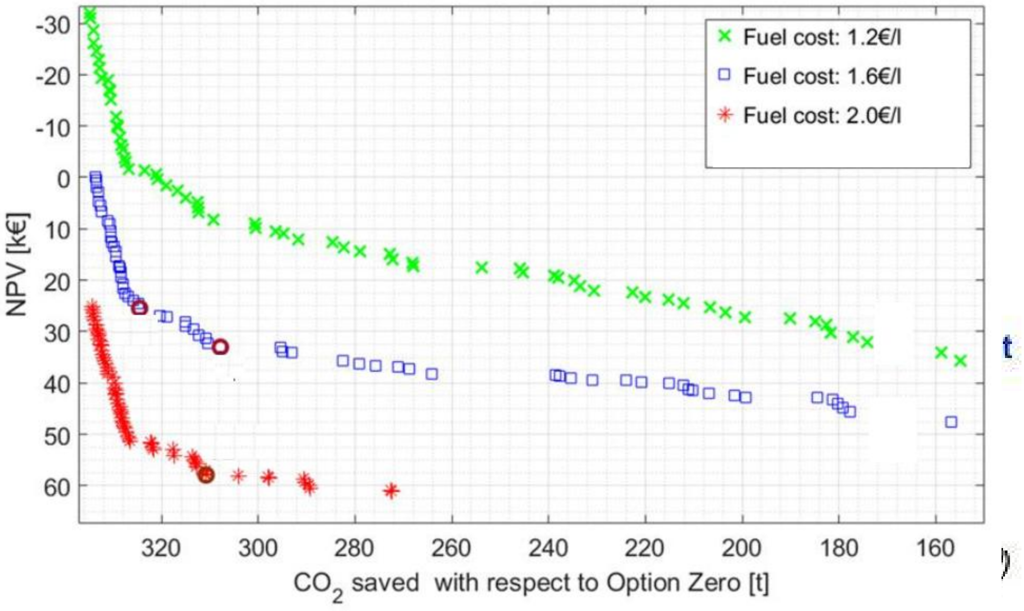
Scenario-based analysis

All the environmental, technical, and economic-financial variables are deeply uncertain.

- Fuel cost, end-user behavior, energy price evolution, discount rate for the project, energy prices…
- Robustness evaluation: <u>*what happens if something differ from the expected scenario?*</u>

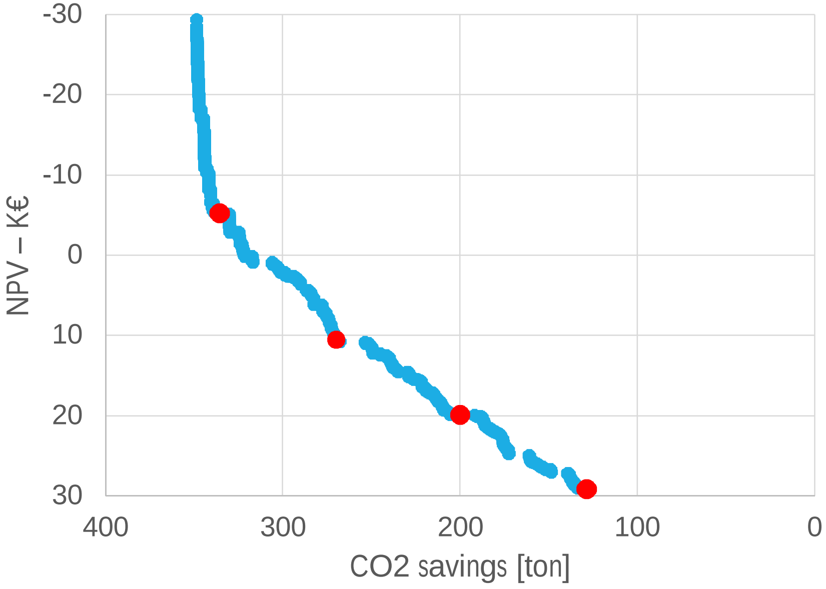
e.g. different weather conditions, different users behavior, unexpected changes of financial parameters…

Uncertainty analysis



UNCERTAINTY ANALYSIS

Possible optimal solutions on the Pareto frontier

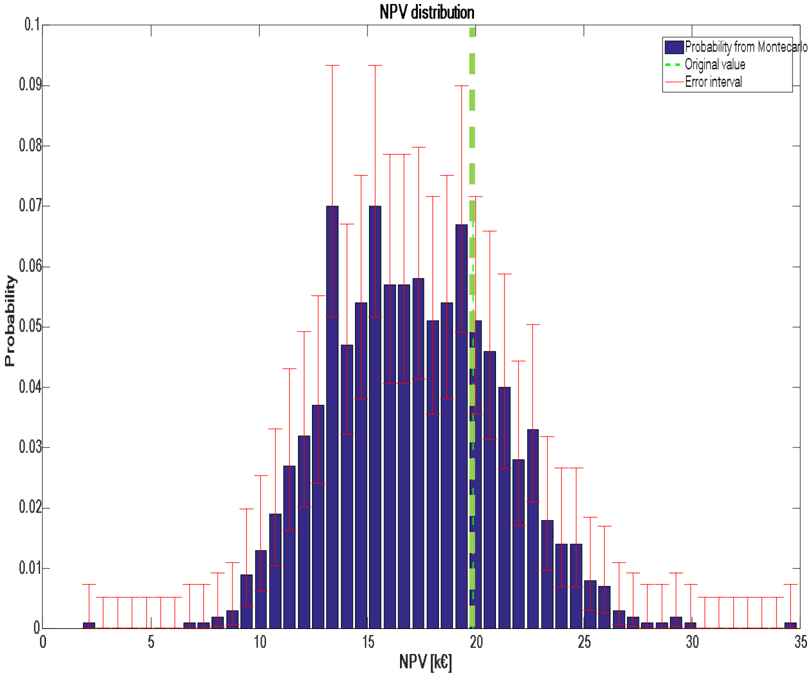


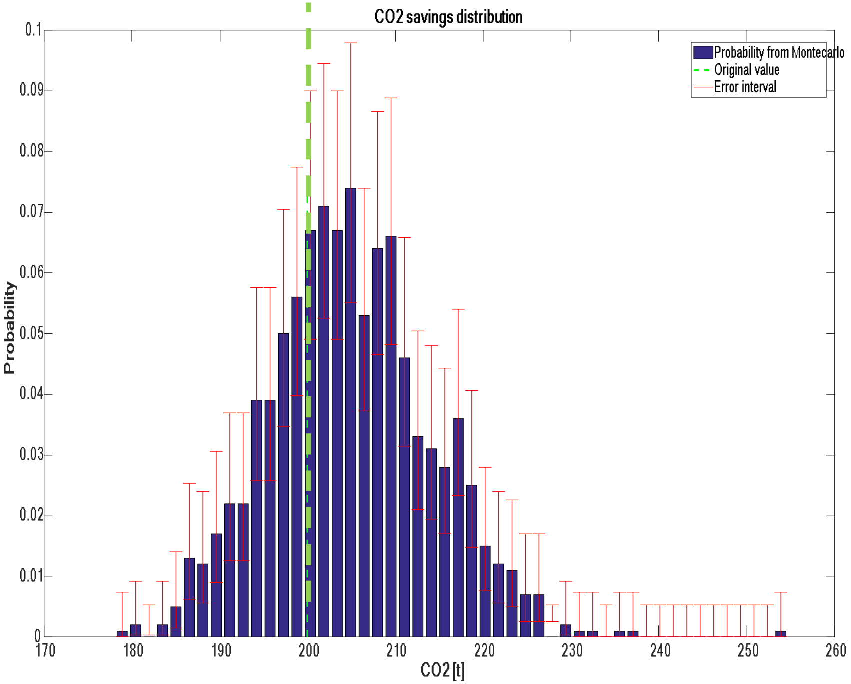
Methodology

1. Select relevant points on the Pareto frontier
2. Associate a PDF function to relevant input parameters (e.g. weather, number of users, thermal efficiencies of generators and storages)
3. Determine through a randomized algorithm (i.e. Monte Carlo analysis) the corresponding PDF function of the selected performance indexes

UNCERTAINTY ANALYSIS

1000 samples – Confidence of 0.9999





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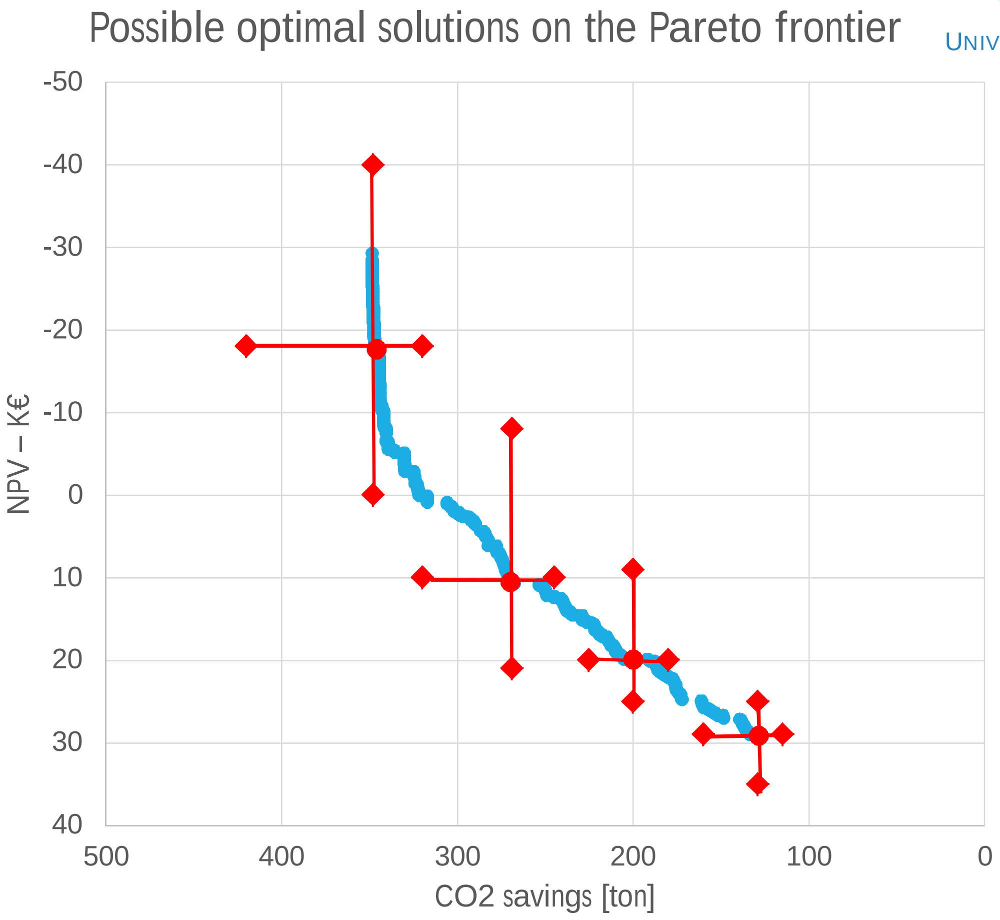
UNCERTAINTY ANALYSIS

- It is possible to define a uncertainty area around selected «design points» (e.g. 1 to 99 percentile)

- Moving towards sustainability-oriented design configurations (thus increasing the number of system components and the initial investment) decreases the reliability of the relevant figures of merit.

- The uncertainty might represent a further performance index to be considered in the multi-objective optimizations



SUMMARY OF ONGOING RESEARCHES ON ENERGY SYSTEM INTEGRATION AT THE DESTEC DEPARTMENT

- ✓Multidisciplinary approach to energy system integration
  - Thermal and electrical engineering
  - Management strategies and investments evaluation
- ✓Modelling for optimization purposes
  - Buildings and indoor climate
  - Equipment for energy conversion and storage
  - Development of dynamics models to be couple with optimization algorithms
  - Tradeoff between accuracy and computational effort
- ✓Simulation-based multi-objective optimization approach
  - Concurrent analysis of design and control variables
- ✓Development of rigorous methods of decision making
  - Probabilistic characterization of input parameters/variables and output performance indexes
  - The role of uncertainty within the optimization procedure

Further readings

- Aloini, D., Dulmin, R., Mininno, V., Raugi, M., Testi, D., & Tucci, M. Investment Evaluation under Multiple Uncertainty: Optimal Sizing and Configuration of an Integrated Energy Production System by Renewable Sources. Proceedings of the 19th International Working Seminar on Production Economics. Innsbruck (Austria), February 22-26, 2016.
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- Testi, D., Schito, E., & Conti, Paolo (2016). Cost-optimal Sizing of Solar Thermal and Photovoltaic Systems for the Heating and Cooling Needs of a Nearly Zero-Energy Building: The Case Study of a Farm Hostel in Italy. Energy Procedia, 91, 528–536. http://doi.org/10.1016/j.egypro.2016.06.286
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- Testi, D., Schito, E., Tiberi, E., Conti, Paolo, & Grassi, W. (2015). Building Energy Simulation by an In-house Full Transient Model for Radiant Systems Coupled to a Modulating Heat PumPaolo Energy Procedia, 78, 1135–1140. http://doi.org/10.1016/j.egypro.2015.11.072

THANKS FOR YOUR KIND ATTENTION!

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