Attività di ricerca del gruppo GECOS sui sistemi trigenerativi avanzati, i multi-energy systems e l'efficienza energetica dei processi industriali

Dr. Ing. Emanuele Martelli

Politecnico di Milano, Dipartimento di Energia

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THE DEPARTMENT OF ENERGY @ POLITECNICO, DIVISIONS & OUR GROUP

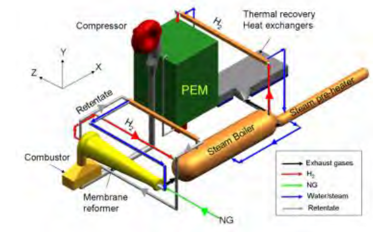
The Department of Energy at Politecnico joins researchers originally belonging to 5 divisions.
It has ~130 permanent researchers and professors

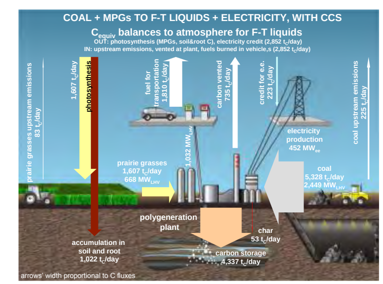
1. Chemical Technologies and Processes and NanoTechnologies Division
2. Electrical Division
3. Nuclear Engineering Division
4. Thermal Engineering & Environmental Technologies Division
5. Fluid Dynamic Machines, Propulsion & Energy Systems Division
   - Fluid-dynamics of turbomachines
   - Internal combustion engines
   - Propulsion and combustion
   - *Group of Energy COnversion Systems (GECOS):*

     1 Emeritus professor (prof. Macchi)
     3 Full professors (Lozza, Consonni, Chiesa)
     9 Associate/Assistant professors
     6 RTDA
     4 Post docs
     5 Temporary researchers
     10 PhD students

MAIN RESEARCH AREAS

1. CARBON CAPTURE TECHNOLOGIES
2. RENEWABLE ENERGY SOURCES AND WASTE-TO-ENERGY
3. ENERGY STORAGE, HYDROGEN AND SYNTHETIC FUELS
4. MICRO-GRIDS AND MULTI-ENERGY SYSTEMS
5. ENERGY EFFICIENCY AND SYSTEMS OPTIMISATION
6. ORC, S-CO2 AND ADVANCED POWER CYCLES
7. FUEL CELLS

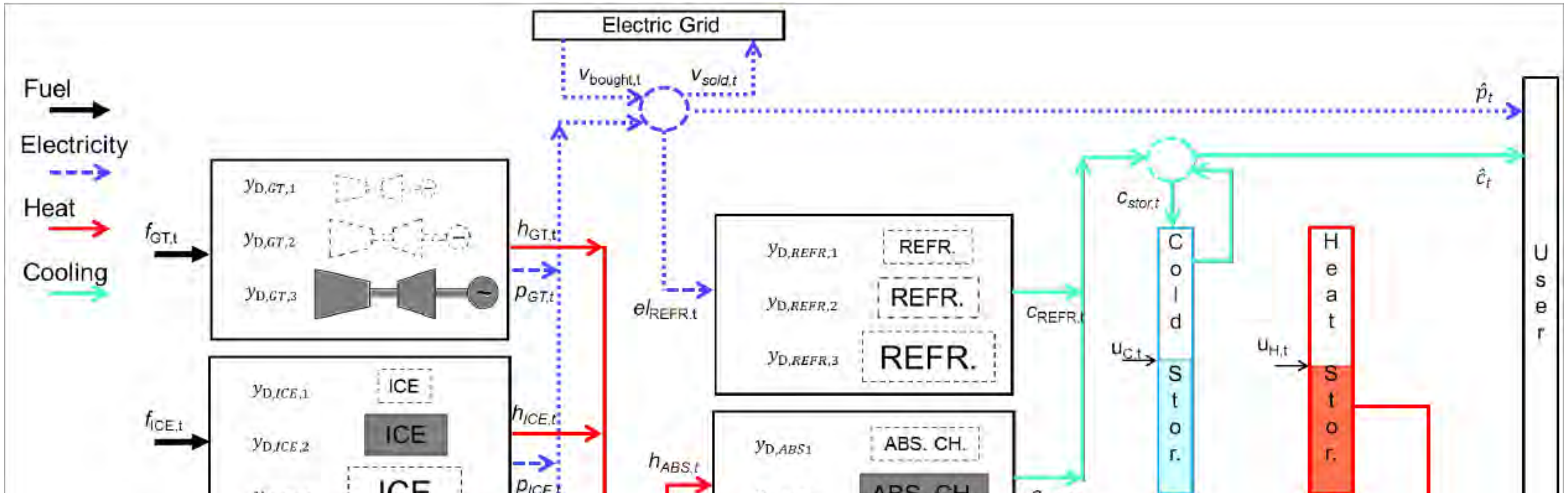




>10 ongoing EU projects (FP7-H2020)

Tens of ongoing research contracts with industries

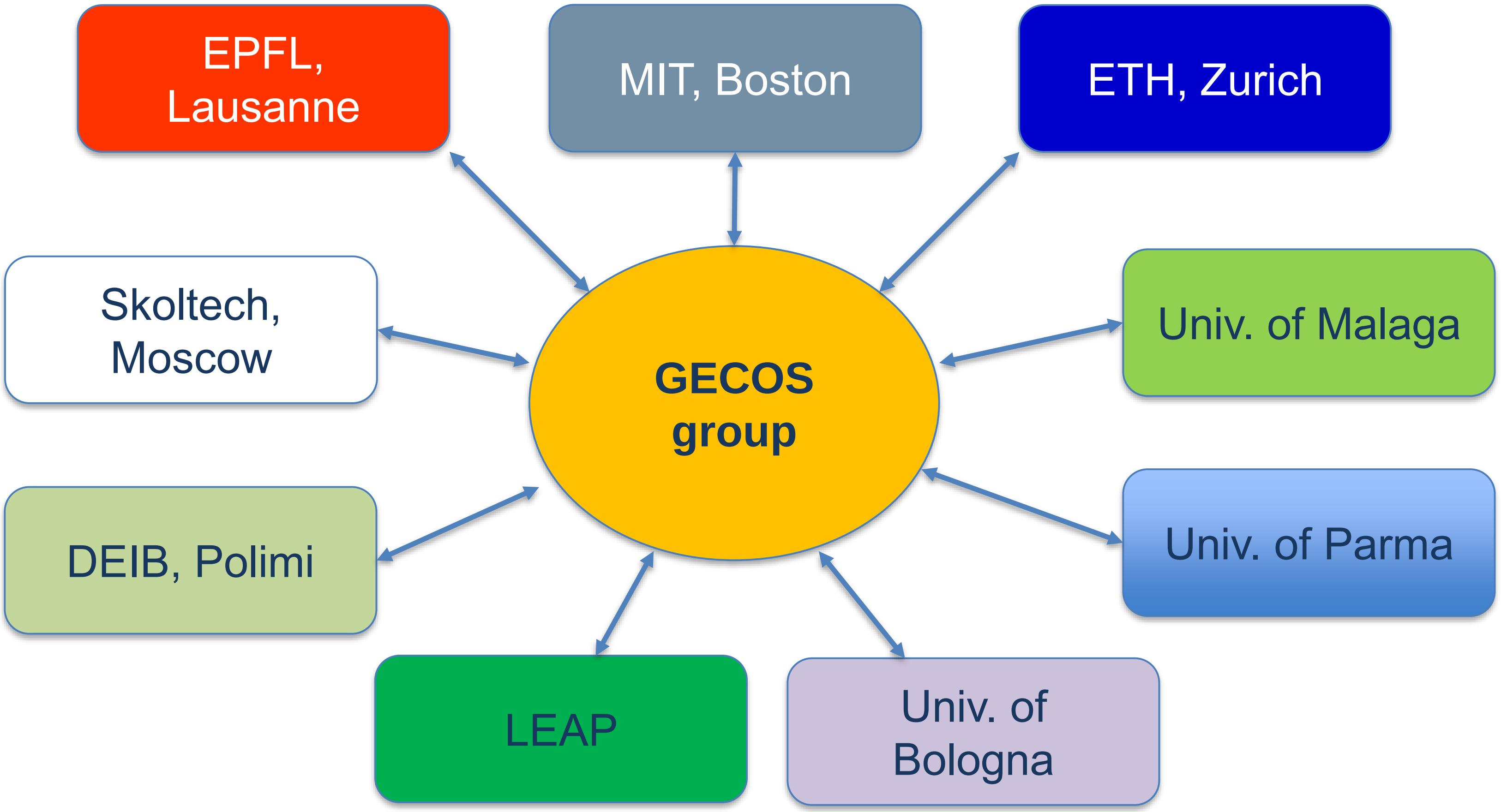
OPTIMIZATION OF MULTI ENERGY SYSTEMS (MES) AND CHP



Types of optimization problems associated to MES (for microgrids and DHC networks):

1. **Design/retrofit of the system («investment planning»)**
2. **Long-term operation planning accounting for yearly constraints (incentives/seasonal storage)**
3. **Short-term scheduling (unit commitment)**
4. **Optimal control (dynamic models of units and networks)**

OPTIMIZATION OF MES AND CHP: ONGOING COLLABORATIONS



Given:

- Forecast of Electricity demand profile
- Forecast of heating and cooling demand profile
- Forecast of production from renewables
- Forecast of time-dependent price of electricity (sold and purchased)
- Performance maps of the installed units
- Operational limitations (start-up rate, ramp-up, etc) of units
- Efficiency and Maximum capacity of storage systems

Objective: minimize the Daily/Weekly Operating Cost

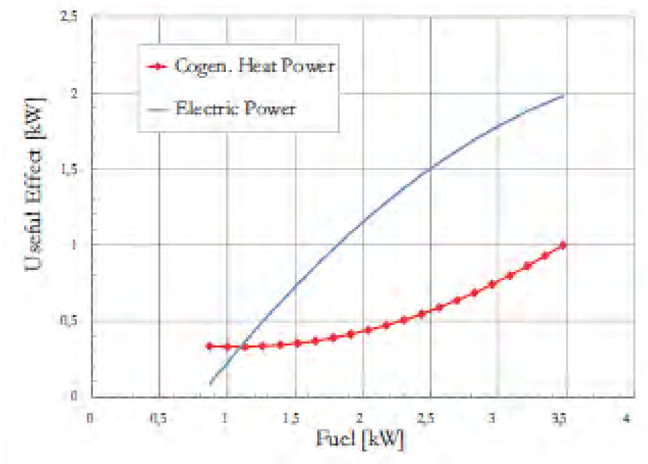
$$\sum_{t=1}^{24\cdot 7} \mathrm{C}_{\mathrm{Fuel,tot,t}} + \sum_{t=1}^{24\cdot 7} C_{O\&M,tot,t} + \sum_{t=1}^{24\cdot 7} \mathrm{C}_{start-up,tot,t} \mp \sum_{t=1}^{24\cdot 7} El_{tot,t}$$

Indep. variables: on/off of units, load of units, storage level in each time period *t*

SHORT-TERM SCHEDULING PROBLEM

Constraints:

→ Electric energy balance constraint ∀ t (linear)
→ Heating energy balance constraint ∀ t (linear)
→ Cooling energy balance constraint ∀ t (linear)
→ Start-up constraints ∀ t, ∀ unit (linear)
→ Ramp-up constraints ∀ t, ∀ unit (linear)
→ Performance maps of units ∀ t, ∀ unit i (nonconvex)



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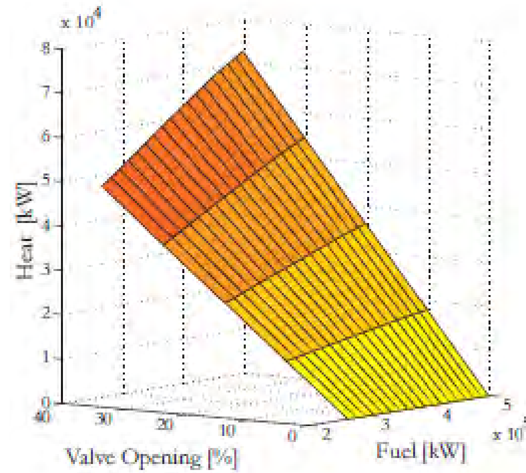
Nonconvex MINLP

Available MINLP optimizers cannot find the optimal solution



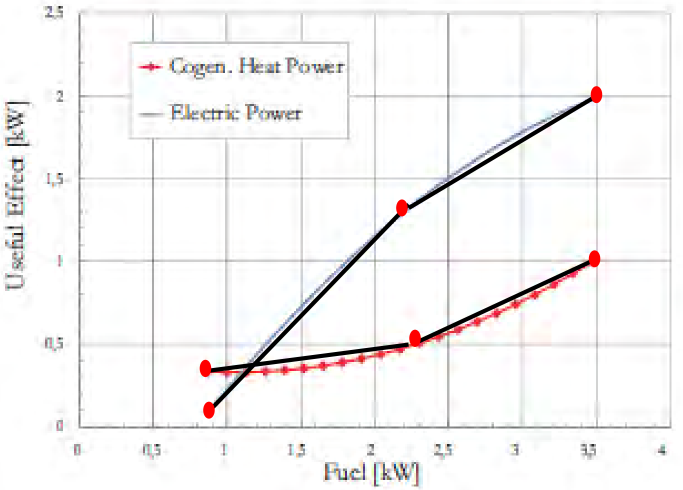
Amaldi et al., 2017. *Short-term planning of cogeneration energy systems via MINLP,* in SIAM book: “Advances and Trends in Optimization with Engineering Applications”.

MILP WITH PWL APPROXIMATION OF MAPS

Basic idea: conversion into MILP via linearization of the performance maps

Advantages of MILP formulations:
- Guarantee on the global optimality of the solution
- Super-efficient commercial MILP solvers (e.g., CPLEX, Gurobi)

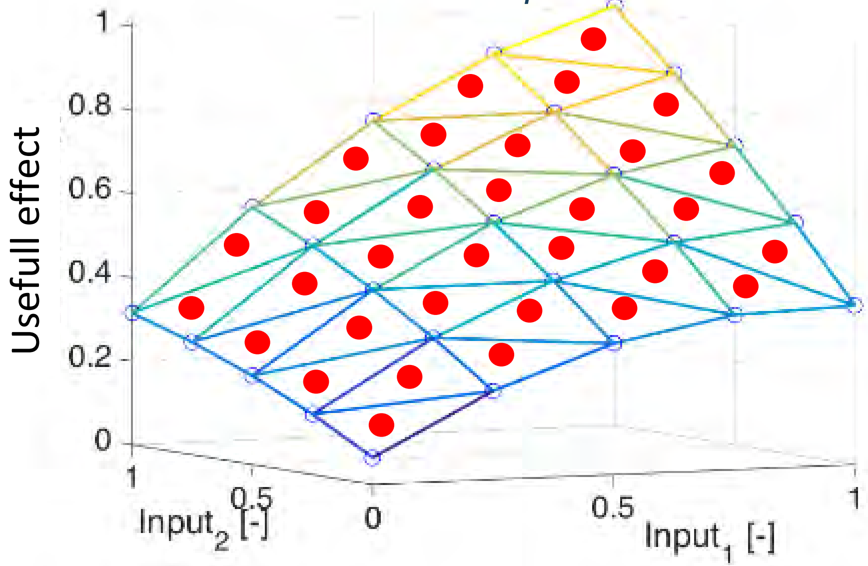
1-D PWL approximation



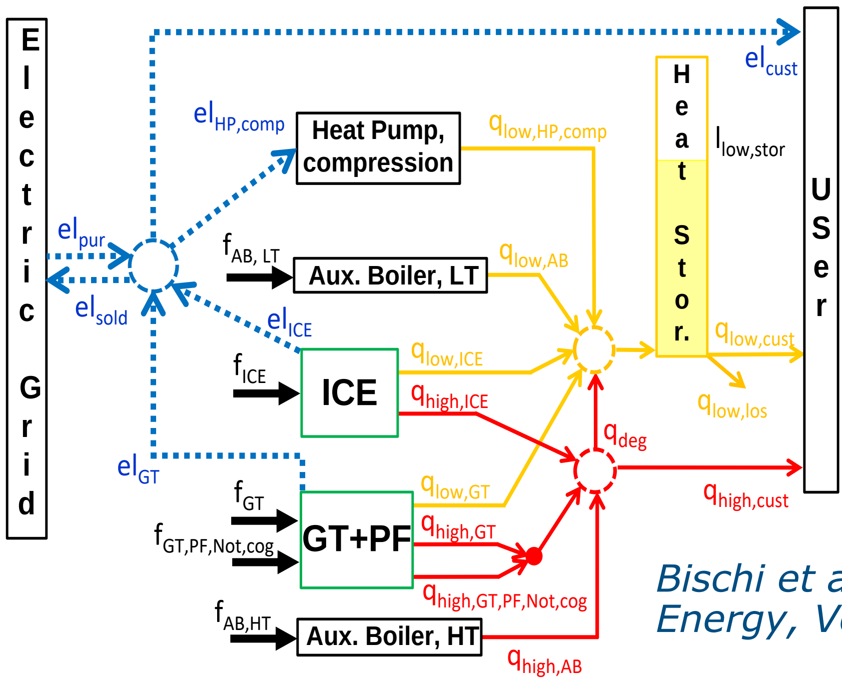
Bischi et al. 2014. Energy, Vol. 74

2-D PWL approximation with the «triangular method»

D'Ambrosio et al. 2010. Op. Res. Letters

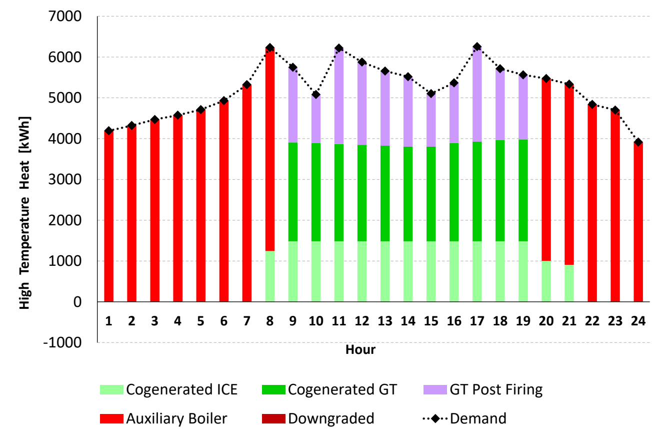


MILP PWL FOR DAILY AND WEEKLY PROBLEMS

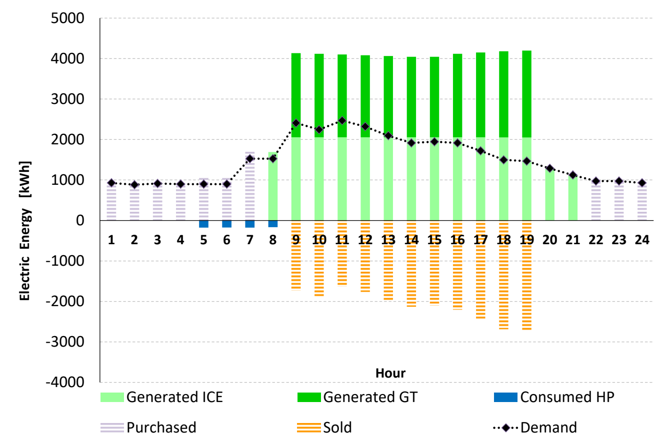


Bischi et al. 2014. Energy, Vol. 74

High temperature heat



Electricity



Computational time:

1 day operation: < 1 sec

1 week operation: < 2 min

Up to 18% primary energy saving compared to usual operation strategies!

OPTIMAL OPERATION WITH COGENERATION INCENTIVES

1. COGENERATION INCENTIVES: if CHP units allow to save fuel compared to "business as usual systems", subsides are granted (additional revenue)

Conditions to be met for ICE CHP:

- **First Principle Efficiency**

$$\frac{Q_{th}+P_{el}}{Fuel} \geq 75\%$$

- **Primary Energy Saving (PES)**

$$\frac{Fuel\_ref - Fuel\_CHP}{Fuel\_ref} \geq 10\%$$

Easily rearranged as linear constraints but yearly-basis!

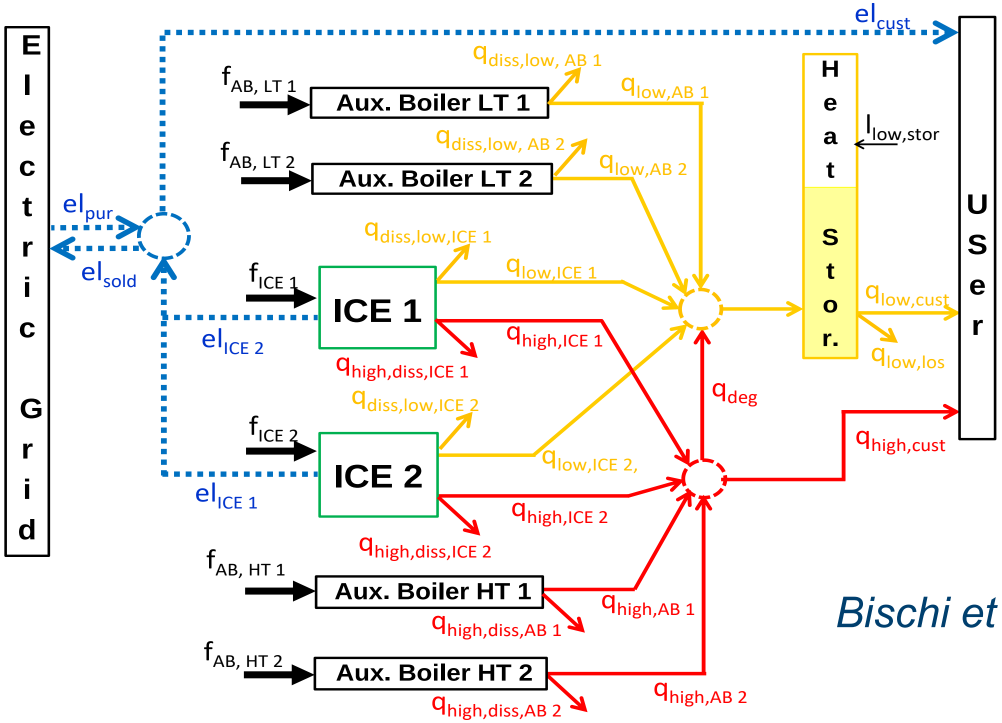
2. SEASONAL STORAGE SYSTEMS: Underground systems (water tanks, aquifers, etc), sorption systems (e.g., sodium sulfide), thermochemical storage systems and H_2 storage.

Challenge: operation must be optimized considering the whole year!

IDEA: Rolling-horizon algorithm (*Bischi et al. 2018. Energy, in press)*

Test case: CHP system of a large hospital

Computational time: 21 hours (worst case) → applicable for day-ahead scheduling



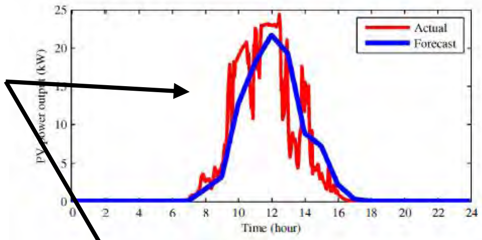
Bischi et al. 2018. Energy (in press)

About <u>7% higher revenue</u> (yearly basis) compared to the weekly optimal operation.

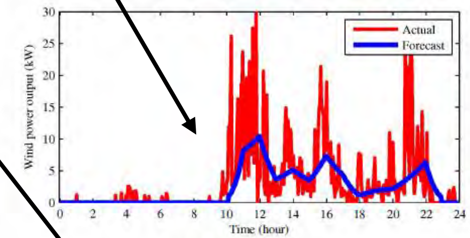
OPTIMAL OPERATION OF MES AND CHP SYSTEMS UNDER FORECAST UNCERTAINTY

Given:

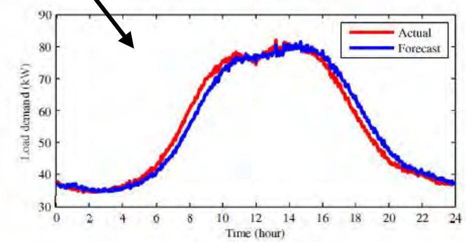
- → Forecast of power production from renewables and its uncertainty
- → Forecast of energy demand profiles and its uncertainty
- → Forecast of electricity prices and its uncertainty
- → Performance maps of the installed units
- → Operational limitations (start-up rate, ramp-up, etc) of units
- → Efficiency and Maximum capacity of storage systems



(a) PV power output.



(b) Wind power output.



(c) Local user demand.

Determine:

Nominal set-points: on/off of units, nominal load of units, storage man.

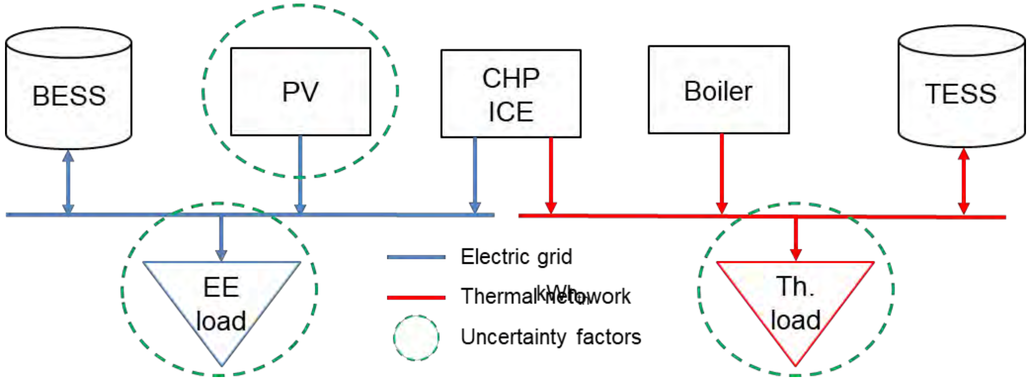
Correction rules: how to adjust units loads during operation

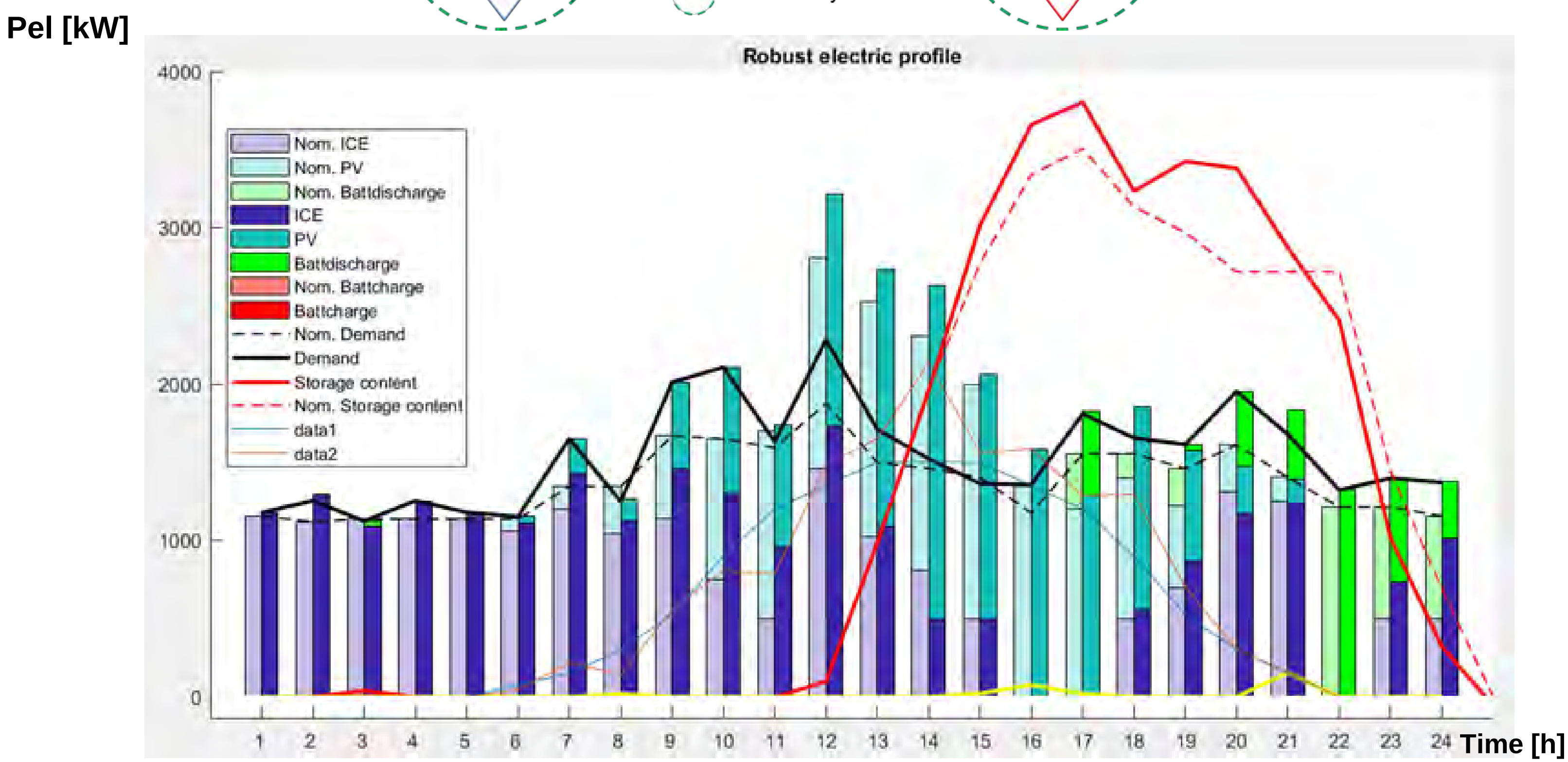
Minimizing the daily operating cost in the most probable scenarios

Constraints: meet energy demands, technical limitations of units, performance maps, etc

EFFICITY PROJECT (LEAP-Polimi, CIDEA, CIRI-EA, CERR) co-funded by Emilia Romagna Region (POR-FESR 2014-2020)

OPTIMAL OPERATION OF MES UNDER FORECAST UNCERTAINTY: ROBUST MILP





OPTIMAL DESIGN OF MES AND CHP SYSTEMS

Given:

- A catalogue of possible units (e.g., CHP ICEs, HP GTs, boilers, heat pumps, etc) and the list of available sizes (discrete or continous)
- A catalogue of heat storage systems
- Forecast of future energy demand profiles (whole year) of each building/site
- Forecast of future energy prices and their time profiles of each building/site

Determine:

- Which units and heat storage system to install in each district/building
- The sizes of the units and storage systems
- The required energy connections between sites/buildings

Considering:

- Nonlinear size effects on investment costs and efficiency
- On/off and part-load operation of the units

Objectives: Maximize the NPV/Minimize the energy consumption/CO2 emissions

Design Optimization Approaches

Linearization without decomposition

(*Gabrielli et al. 2018, Applied Energy, in press*)

(*Zatti et al, 2017, Comp. Aided Chem. Eng., 40*)

Units' selection, sizes and operation optimized in a single large scale MILP

Advantages:

- Linear problem (computationally efficient)
- Global optimality guarantee
- *Uncertainty can be rigorously handled*

Disadvantages:

- Scale effects on investment costs must be linearized
- Size effects on efficiency must be approximated

Design-scheduling decompositiom

(*Elsido et al., 2017. Energy Vol. 121*)

Upper level (evolutionary alg.): optimizes design variables (selection/sizes)

Lower level: MILP scheduling problem

Avantages:

- Size effects accounted for on both performance and costs
- Possibility of considering many operating periods solved in sequence

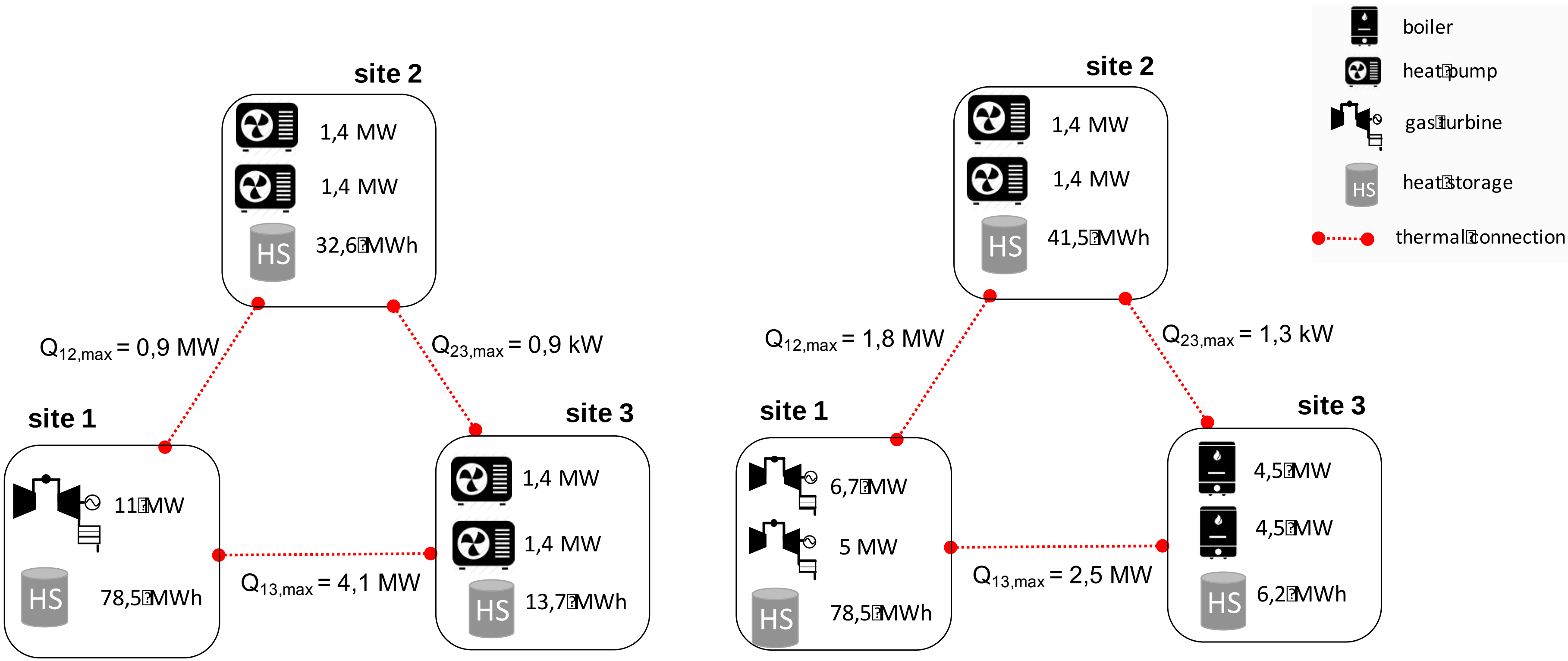
Disadvantages:

- Slow convergence rate of evolutionary algorithms
- No optimality guarantee

Optimal design of MES: Design of DH networks for a City

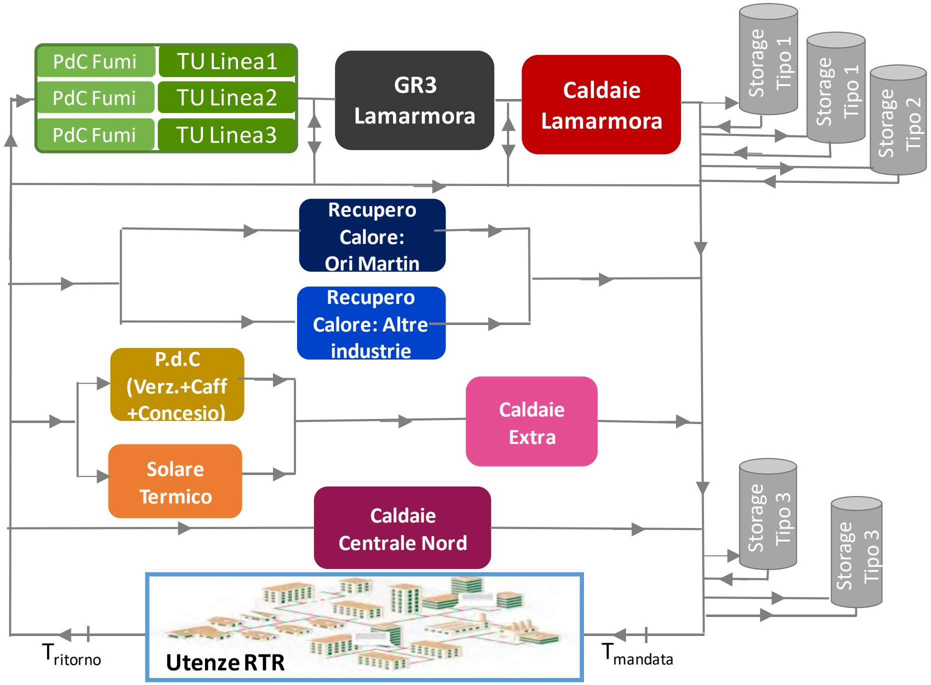
Deterministic MILP solution
CAPEX+OPEX= 21,92 M€

Stochastic MILP solution
CAPEX + OPEX= 18,22 M€



Accounting for uncertainty of forecasts leads to a cost saving of about 20%!

DH network of Brescia



Collab. with Univ. Of Brescia

University of Parma Campus

EFFICITY project:
Collab. with LEAP, CIDEA & SIRAM

LABORATORIES

LAB for MICRO-COGENERATION (LMC)
Test bench for performance and emissions of small scale co- and tri-generation systems (ICE, Stirling engines, PEM, SOFC, etc with < 100 kWel, 300 kWth), electrolizers and H2 production systems (at steady-state and transient conditions).

SOLAR TECH
Facility for developing and testing photovoltaic, photovoltaic-thermal and concentration systems.

MICRO-GRIDS LAB
Facility for testing control strategies of hybrid micro-grids (solar panels, CHP engines, batteries, thermal storages, etc).

LABORATORIO ENERGIA AMBIENTE PIACENZA (LEAP)
Research and consultancy activities in the areas of energy efficiency, waste-to-energy plants, biomass-fired plants, and pollutant emissions.

LAB FOR MICRO-COGENERATION (LMC)

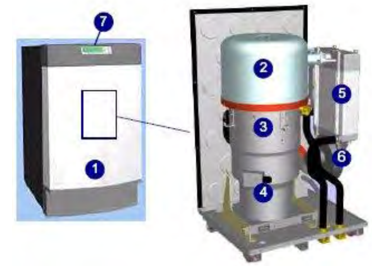
- 1 kWel CHP unit based on Stirling cycle
- 10-20 kWel CHP units based on internal combustion engines
- 20-30 kWel CHP units based on PEM fuel cell with steam reformer
- 1 kWth membrane reactor test stand (metallic membranes for hydrogen separation and application to fuel processing)

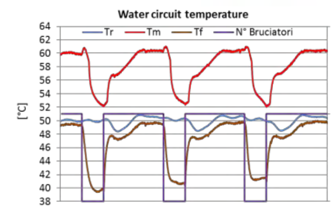
New Energy World JU
fuel cells & hydrogen for sustainability

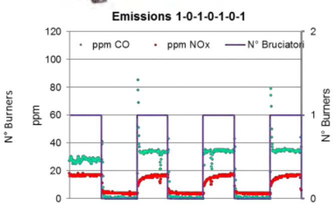
- 0.5 kWth Thermo-photo-voltaic (TPV) generator
- 4 x 2.5 kWel SOFC CHP unit
- 30 kW_{el} - 18 kW_{LHV} H_2 electrolyzer unit

➢ At steady-state and transient / cyclic conditions

➢ Controlled and measured fuel / electricity exchange, temperature, pressure and mass flow of all I/O hot/cold circuits.





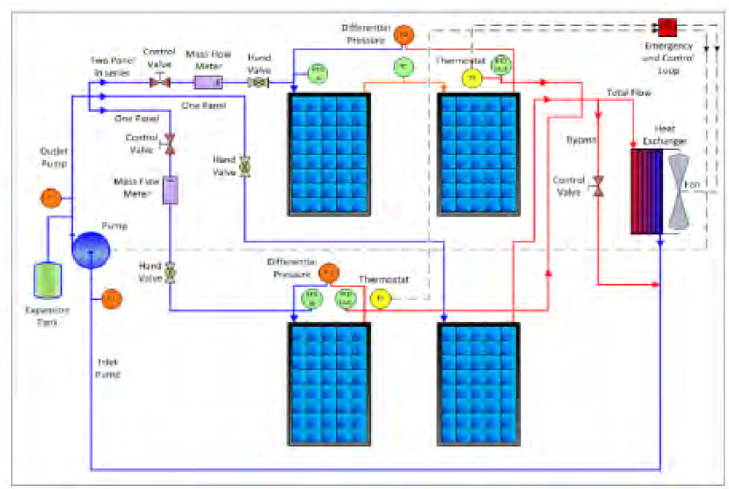


PV system optimization:

- improvements of commercial devices/technologies (e.g., PV, PVT, inverters, etc)
- development of innovative concepts/prototypes (e.g., solar-driven heat pump)
- development of accurate forecasting tools

Facilities:

- PV and PVT panels with adjustable tilt angle and distance
- Thermal oil loop to test PVT panels
- Meteorological station



Attività LEAP nel settore cogenerazione ed efficienza industriale

- Ricerca nel settore MES e sistemi CHP in collaborazione con il gruppo GECOS
- Consulenza scientifica per il recupero di calore/energia da processi industriali (BP, GE, etc)
- Consulenza tecnica e procedurale per l'accesso a sistemi incentivanti sulla produzione efficiente di energia termica:
  CAR (*Cogenerazione ad Alto Rendimento*) e TEE (*Titoli di Efficienza Energetica*)
  - *Audit energetico degli impianti;*
  - *Valutazioni tecnico-economiche sui meccanismi di remunerazione dell'energia;*
  - *Verifica della rispondenza alle normative di riferimento;*
  - *Validazione e supporto tecnico dei modelli per il calcolo del PES (Primary Energy Saving);*
  - *Assistenza per la presentazione dei documenti verso il GSE.*
- Consulenza tecnica e procedurale per il riconoscimento degli incentivi per la produzione di energia elettrica da impianti a fonte rinnovabile:
  - *In particolare: per impianti a biomassa e impianti ibridi alimentati da rifiuti parzialmente biodegradabili.*

MAIN PUBLICATIONS ON MES/CHP/MICRO-GRIDS OPTIMIZATION

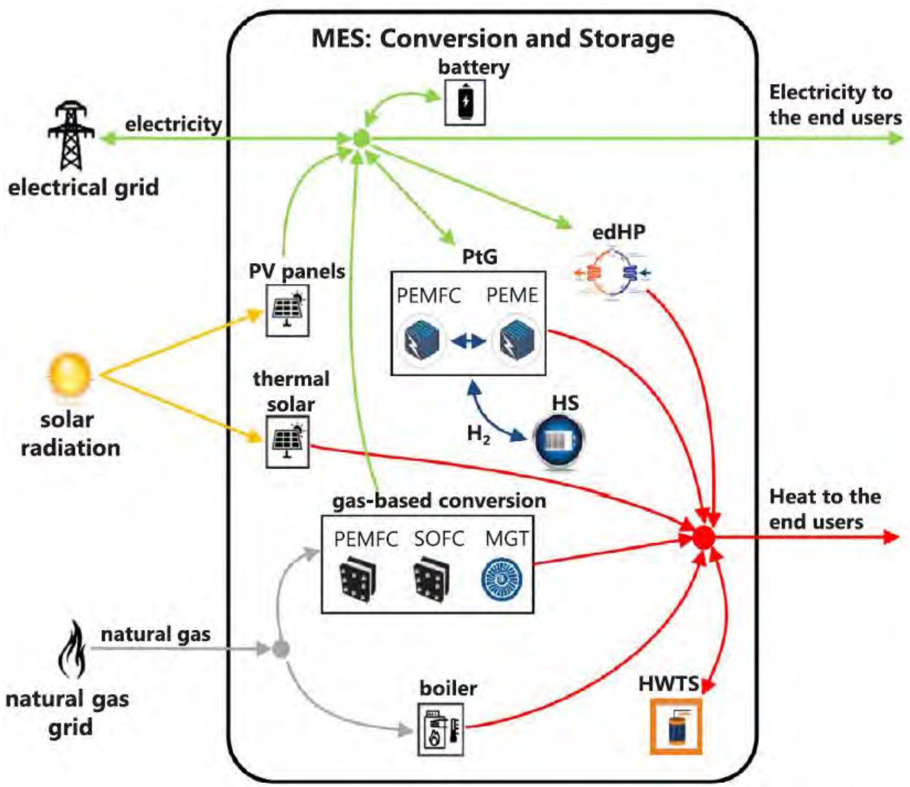
1. *Gabrielli et al., 2018. Optimal design of multi-energy systems with seasonal storage. "Applied Energy" (in press).*
2. *Zatti et al., 2017. A three-stage stochastic optimization model for the design of smart energy districts under uncertainty. "Computer Aided Chemical Engineering" Vol. 40, pp. 2389-2394.*
3. *Elsido et al., 2017. Two-stage MINLP algorithm for the optimal synthesis and design of networks of CHP units. Energy, Vol. 121, pp. 403-426..*
4. *Taccari et al. 2015. Short-term planning of cogeneration power plants: a comparison between MINLP and piecewise-linear MILP formulations. Computer Aided Chem. Eng., 37, pp. 2429-2434.*
5. *Bischi et al., 2014. Tri-Generation Systems Optimization: Comparison of Heuristic and Mixed Integer Linear Programming Approaches. Proceedings of ASME Turbo-Expo 2014.*
6. *Bischi et al., 2014. A detailed optimization model for combined cooling, heat and power system operation planning. Energy, Vol. 74, pp. 12-26.*
7. *Bischi et al. 2016. Distributed cogeneration systems optimization: multi-step and mixed integer linear programming approaches. International Journal of Green Energy, Volume 13.*
8. *Mazzola et al., 2015. A detailed model for the optimal management of a multigood microgrid. Applied Energy, Vol. 154.*
9. *Mazzola et al., 2017. Assessing the value of forecast-based dispatch in the operation of off-grid rural microgrids. Renewable Energy, Vol. 108.*
10. *Mazzola et al., 2016. The potential role of solid biomass for rural electrification: A techno economic analysis for a hybrid microgrids in India. Applied Energy, Vol. 169.*

Thank you for your attention!

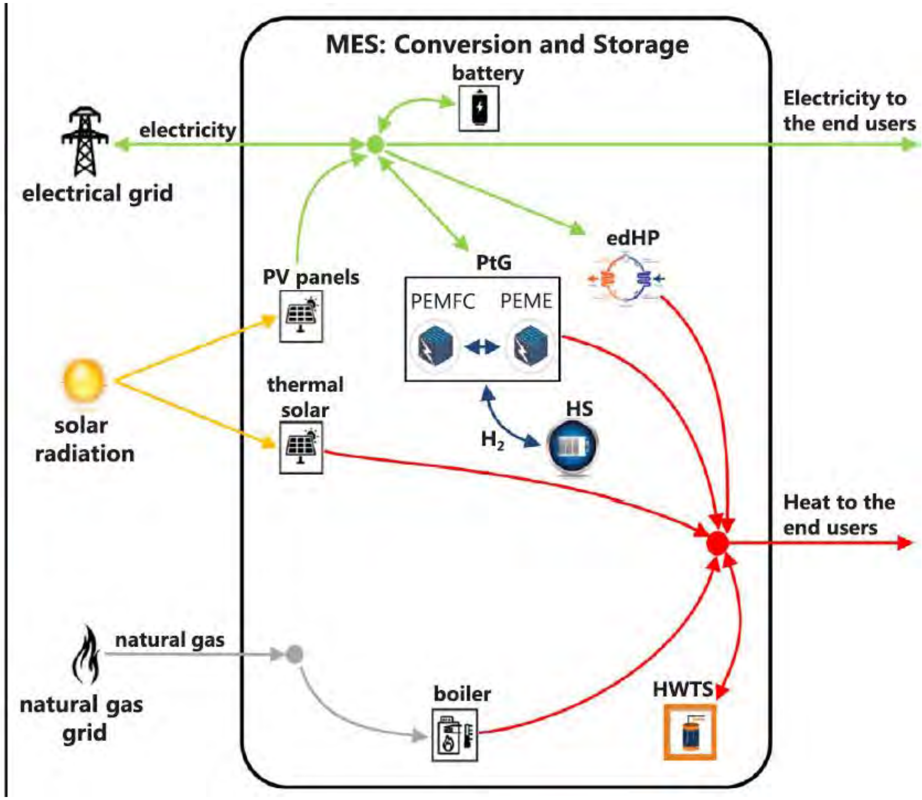
emanuele.martelli@polimi.it
www.gecos.polimi.it

OPTIMAL DESIGN OF A SWISS ENERGY DISTRICT (WITH ETH)

Possible units



Selected units



Gabrielli et al. 2018, Applied Energy, in press