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Combined cooling, heat and power systems operation planning & design: Mixed Integer Non Linear Programming

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- Combined Cooling, Heat and Power (CCHP) Generation
- CCHP Scheduling Optimization
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- Design optimization
- Future Plans
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Gecos
Group of Energy COnversion Systems
http://www.gecos.polimi.it/

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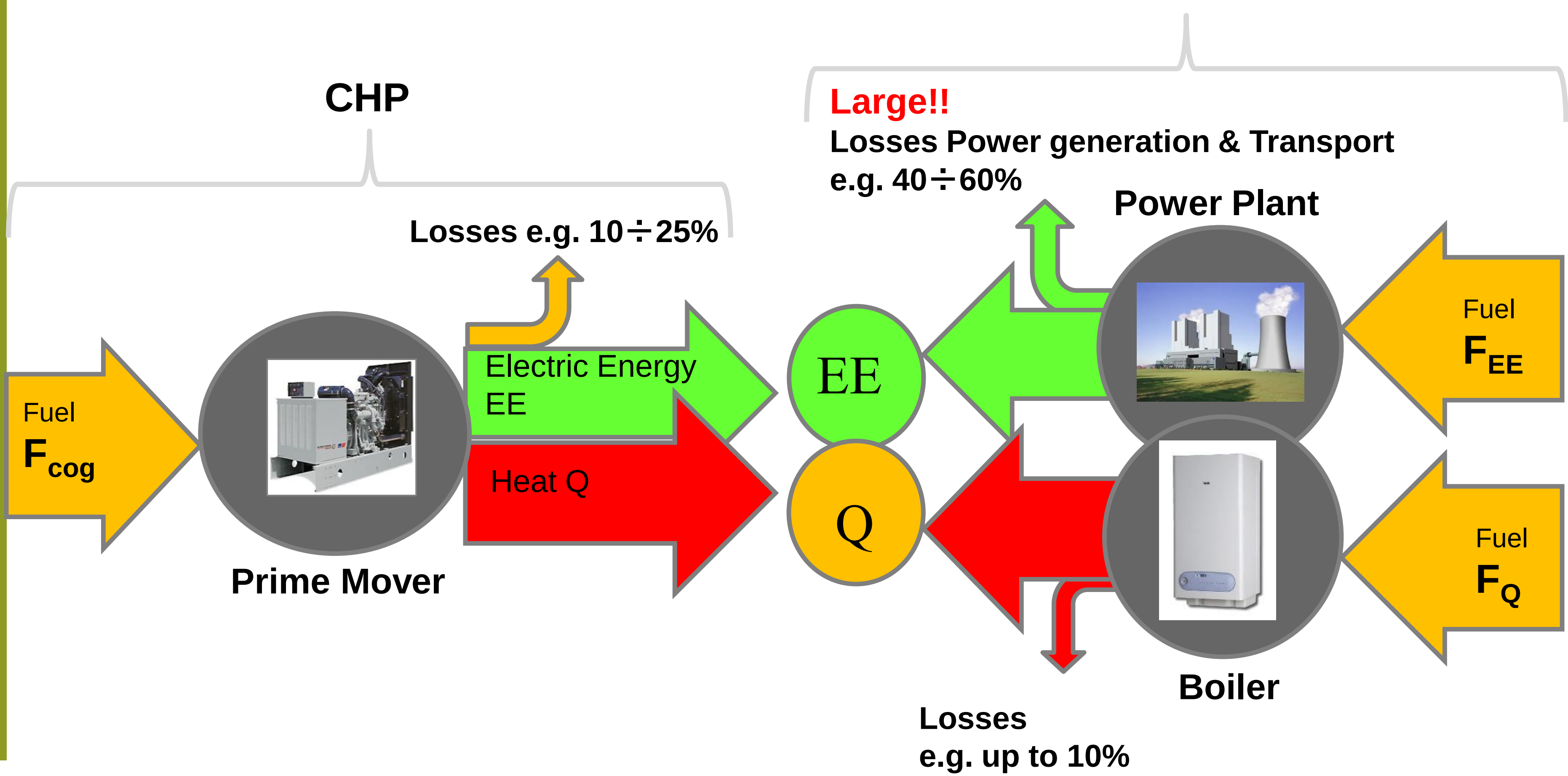
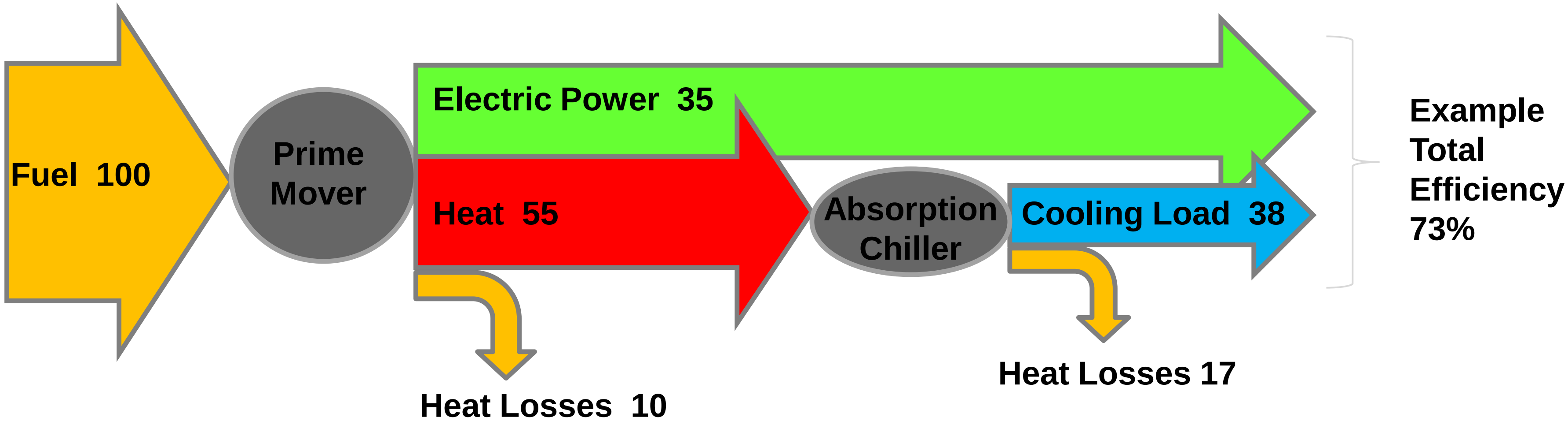
Combined Heat and Power (CHP)

Rational use of primary energy generating simultaneously heat, electric/mechanical power



Combined Cooling, Heat and Power (CCHP)

.....and refrigeration effect



- Effective way to reduce Primary Energy consumption & CO_2 emissions
- Advantageous for Electric Power Distribution system,
- No Construction of New Large Power Plants & High Voltage Network
- Reliability, Peakshaving, Power quality, liberalization of electricity market

Technologies: Size & Application Families

Load/Customer

- **Micro, 50kW$_{el}$**

  ”Non-Standard” loads
  Family (e.g. 1kWel), Small industries/Artisans
  …eventually with large variations ‣ Unforeseeable

  “Standard” loads:
  Several Families, Tertiary sector, Small industries/Artisans, ‣ Foreseeable

- **Small Scale, < 1MW$_{el}$**

  District Heating/Cooling
  Extra challenges due to both pressure & thermal load losses

  Industrial Processes, Case-Specific!
  - Temperature the heat is required
  - N° of Temperature levels the heat is required
  - Thermal loads small dependency on the season

  Eventually unforeseeable!
  ‣ e.g. Oil & Gas,
  Project SNAM Recompression Power Stations

- **Large Scale**

  (Large size & small number e.g. <200 units represent > 20% of Italian Th.Power, about 75GW)

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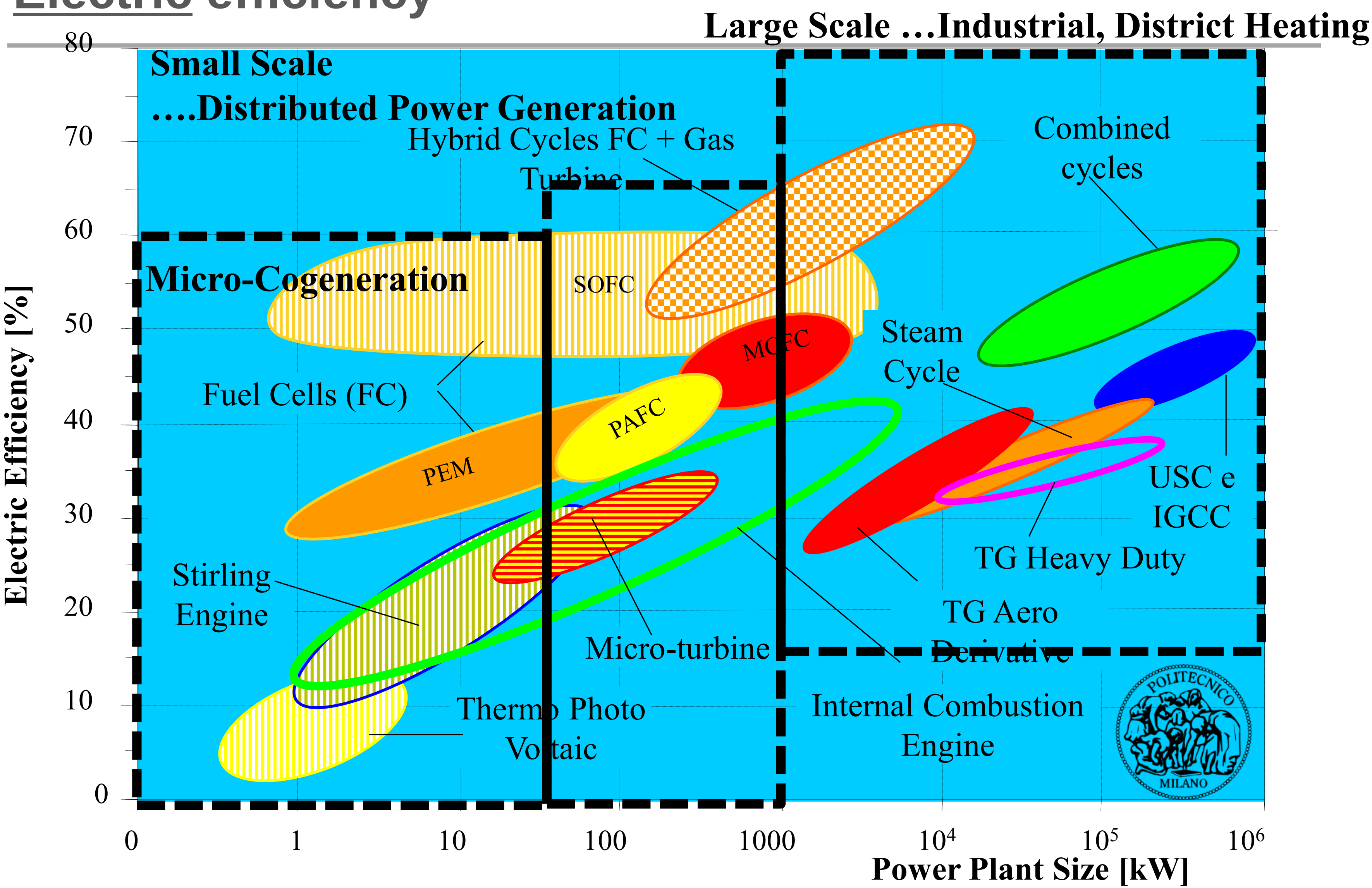
Technologies: Size & Application Families

Electric efficiency



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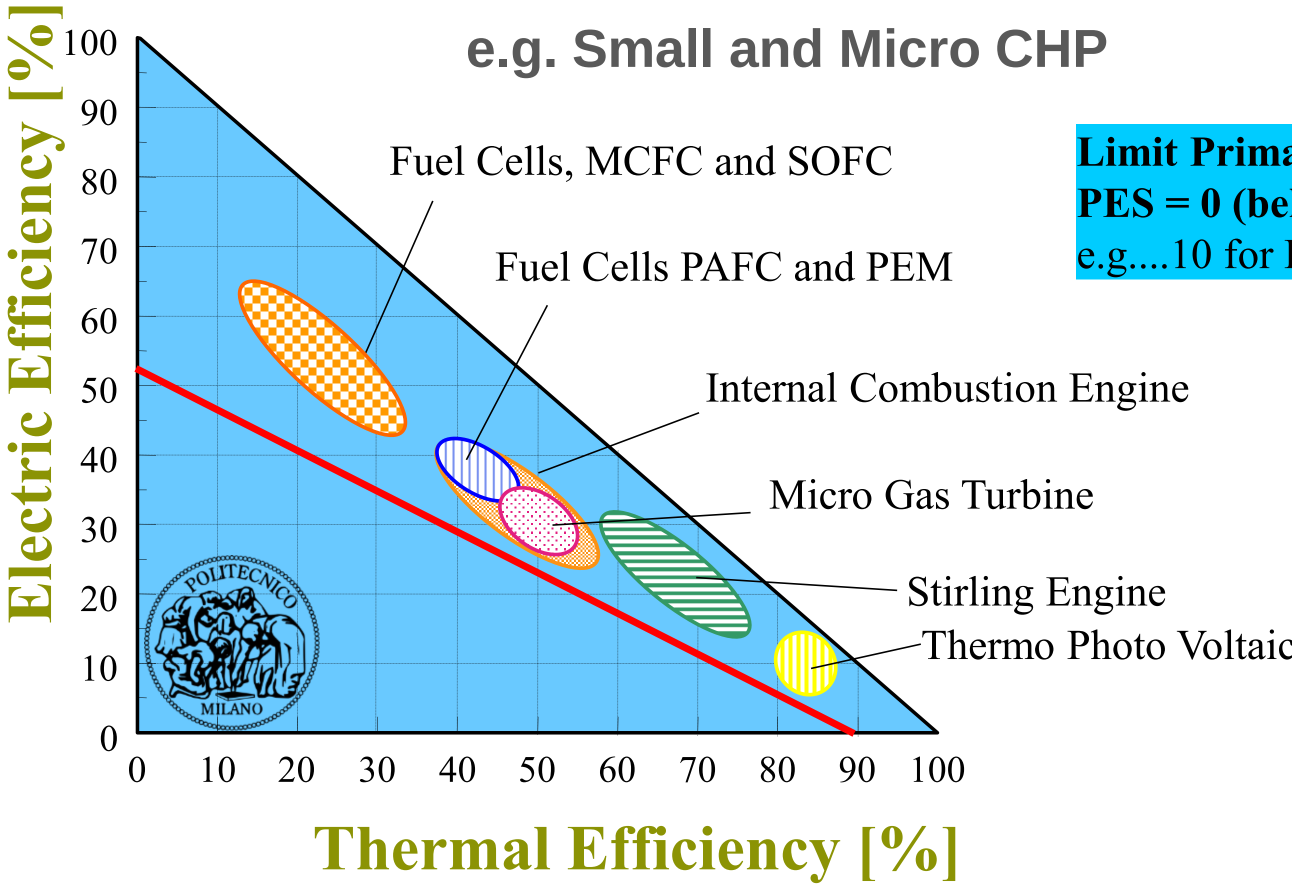
Technologies: Size & Application Families

(Electric & Thermal efficiency)



Limit Primary Energy Savings
PES = 0 (below 1MW)
e.g....10 for Power plants above 1MW

$$\mathbf{PES} = \left(1 - \frac{E_{fuel}}{\frac{E_{el}}{\eta_{el,ref} \bullet p} + \frac{Q_{rec}}{\eta_{th,ref}}}\right) \bullet 100$$

CCHP Challenges

- Larger Investment Costs
- Not Simultaneous Request of Electric Power & Heat

  Storage…Thermal/Cooling Load Power!
- Bureaucracy & deep knowlege of the Legislation, Gas & Power Tarifs

  Vary on hourly basis & depend on monthly/yearly consumption!
- Temperature Level ......

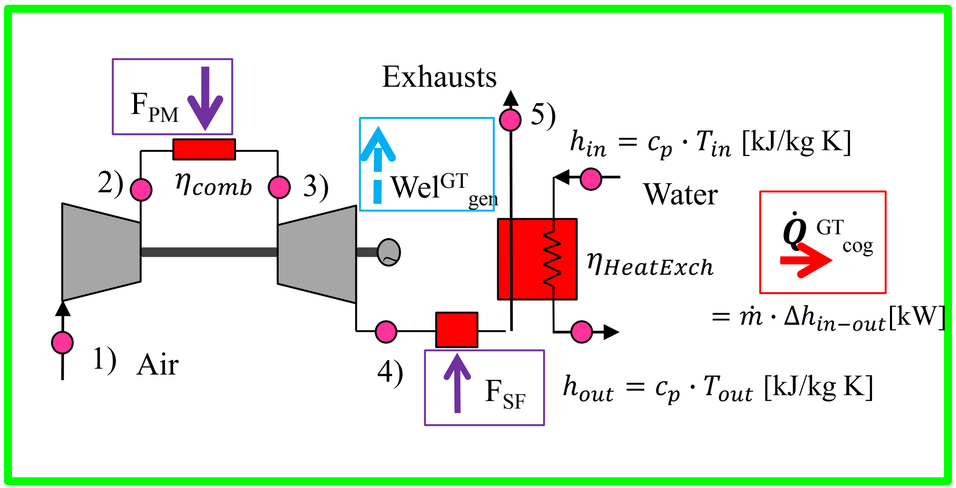
  Different Level ▸ Different Unit & Thermal Efficiency

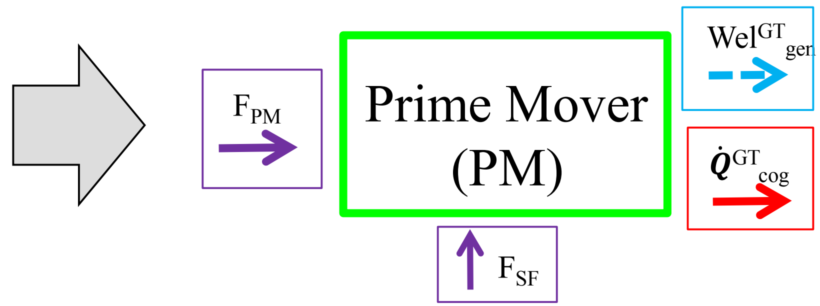
  More than one Level/Downgrade

Optimal Design & Scheduling

Co-generative Units Characterization,

- Experimental Measurements
- Thermodynamic cycle calculation (each point),





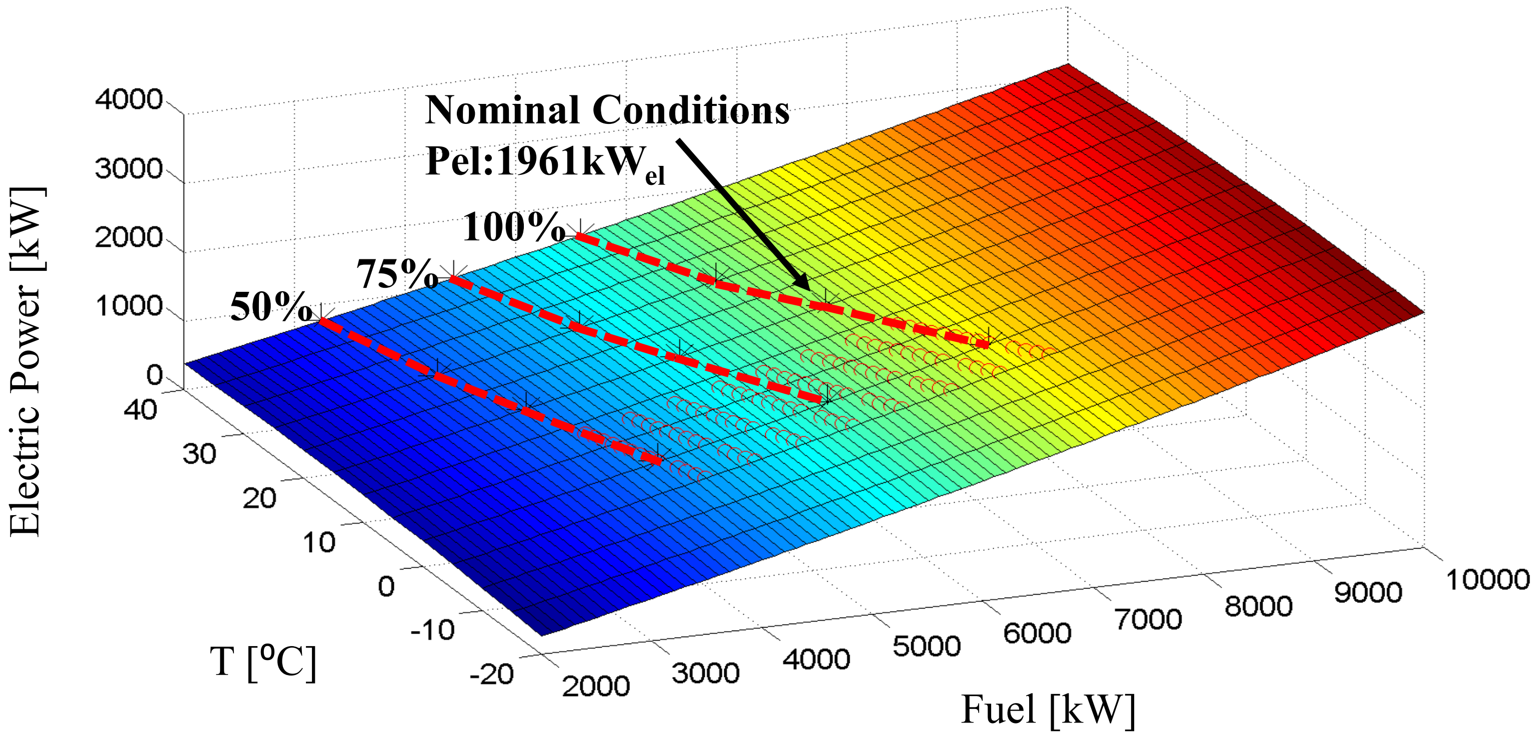
Associate characteristic curves to each unit, taking into consideration just the fluxes in & out.

For several **Ambient Temperatures**

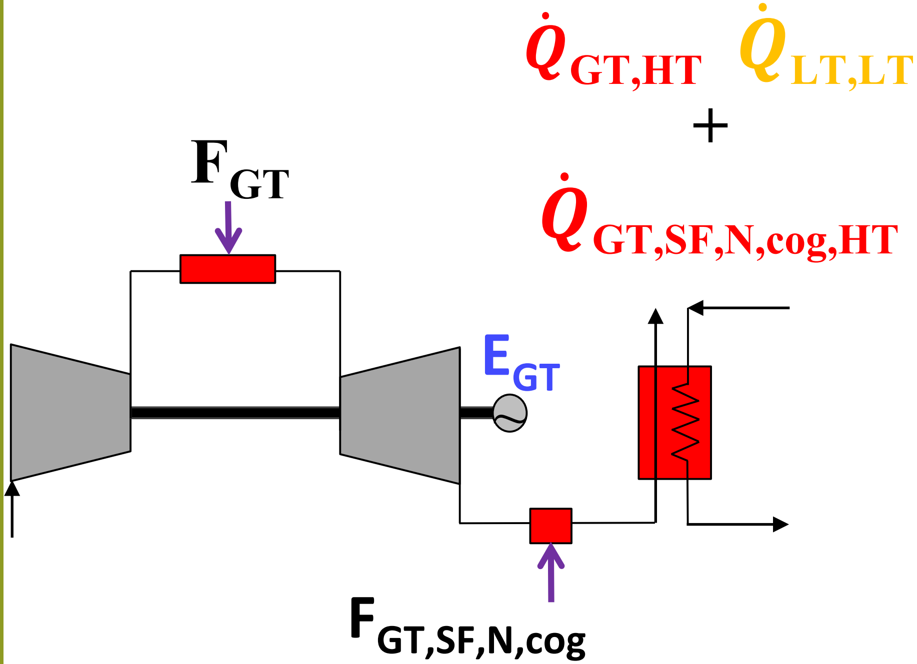
For several **Fuel input**, from Minimum to Nominal load

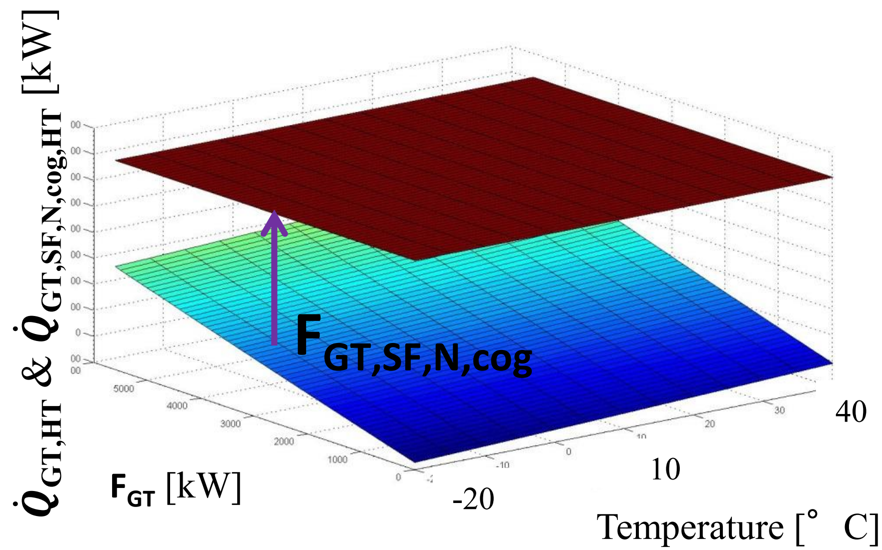
High Level of Detail for Units Characterization

Gas Turbine Pratt & Whitney ST18A



“Two-degrees-of-freedom” units





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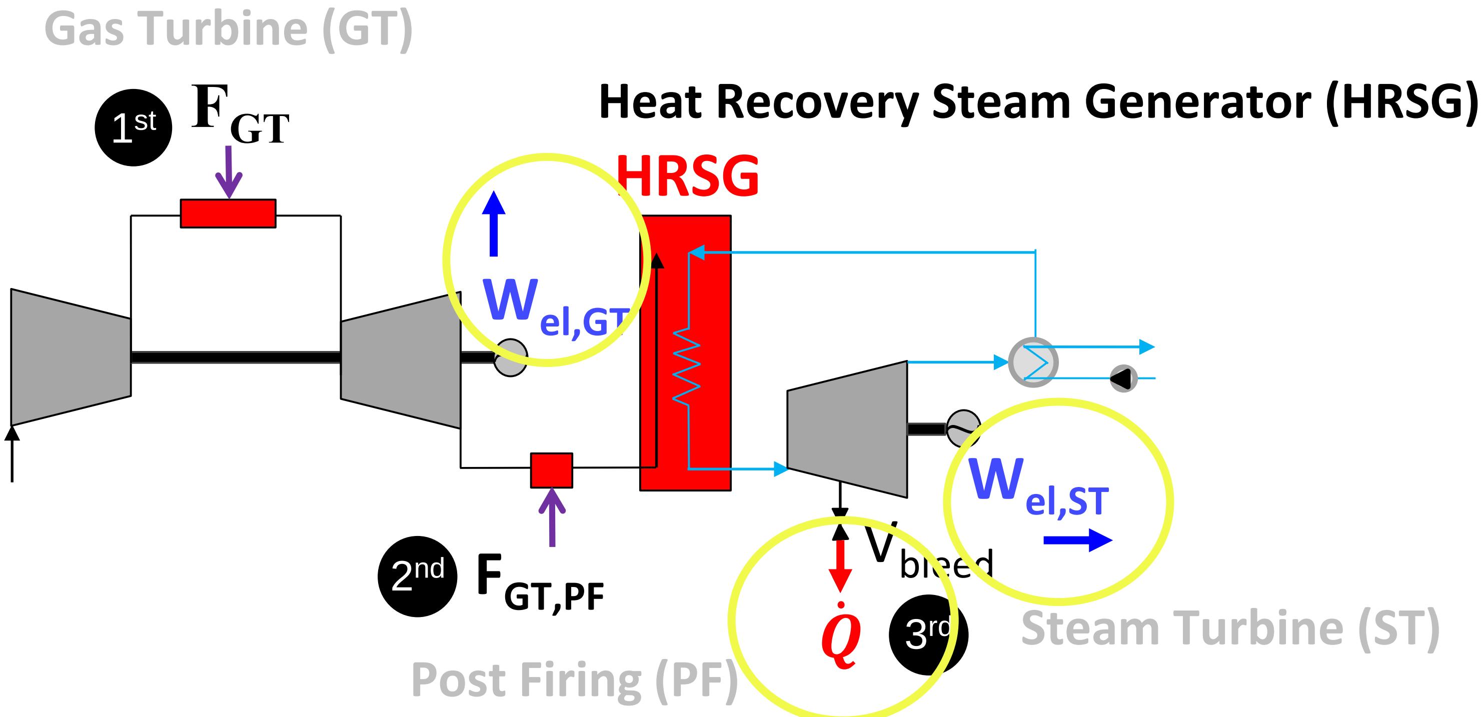
“Three-degrees-of-freedom” units

e.g. Natural Gas Combine Cycle with Post Firing



$$W_{el,GT} = f(F_{GT})$$

$$\dot{Q} = f(F_{GT}, F_{GT,PF}, V_{bleed})$$

$$W_{el,ST} = f(F_{GT}, F_{GT,PF}, V_{bleed})$$

vs. “White Box” approach!

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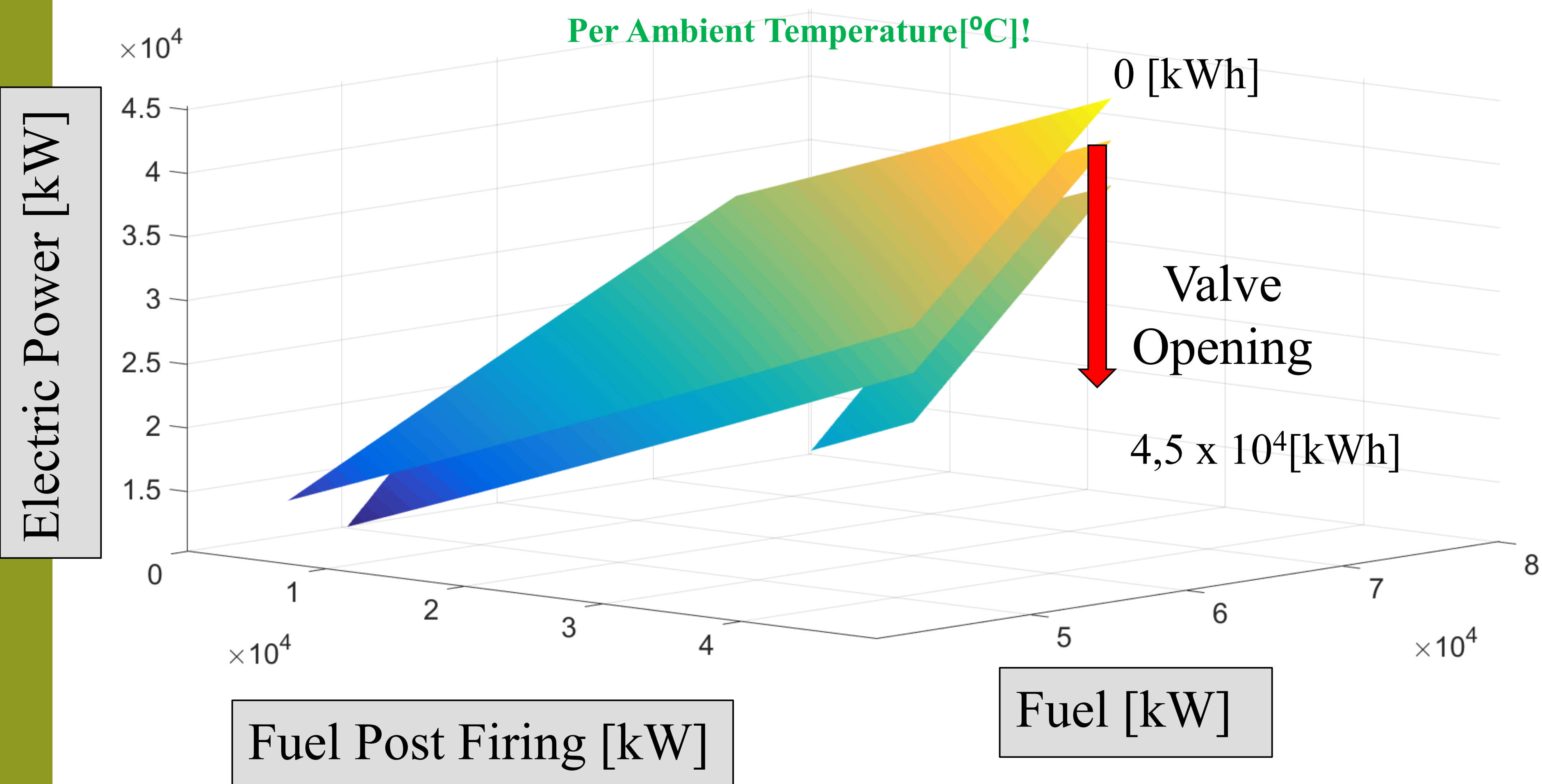
“Three-degrees-of-freedom” units

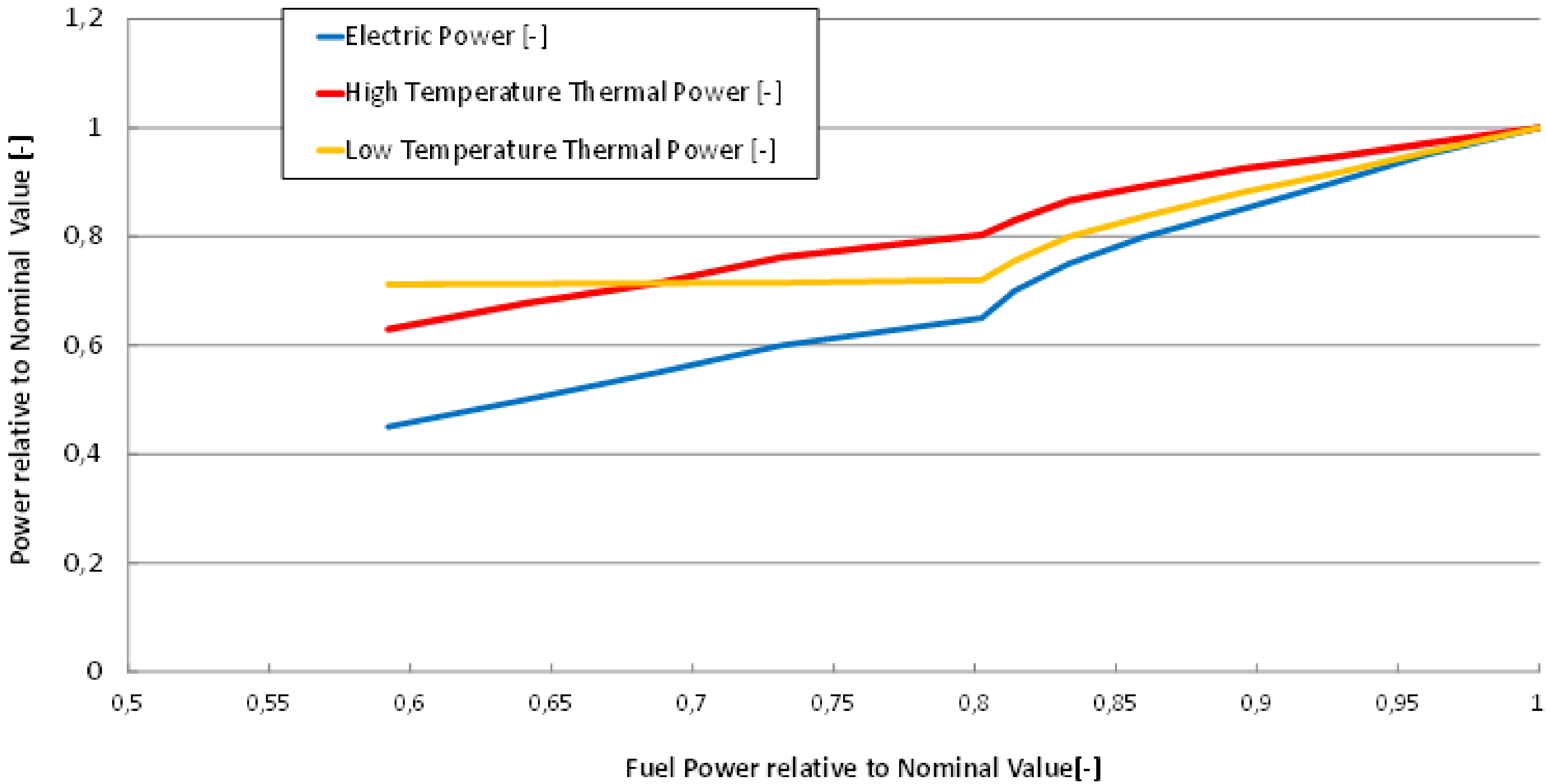
e.g. Natural Gas Combine Cycle with Post Firing



Simulation performed with https://www.thermoflow.com/

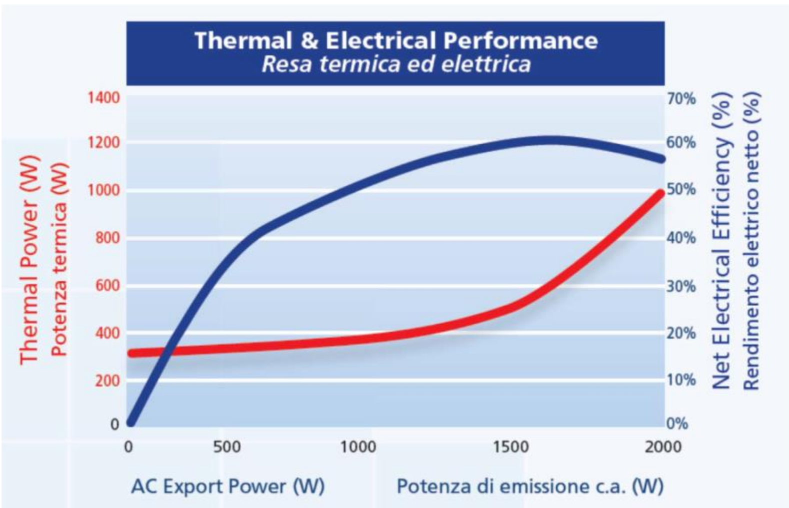
Performance curves NON Smooth

…..e.g. gas turbine (depends on the control strategy)

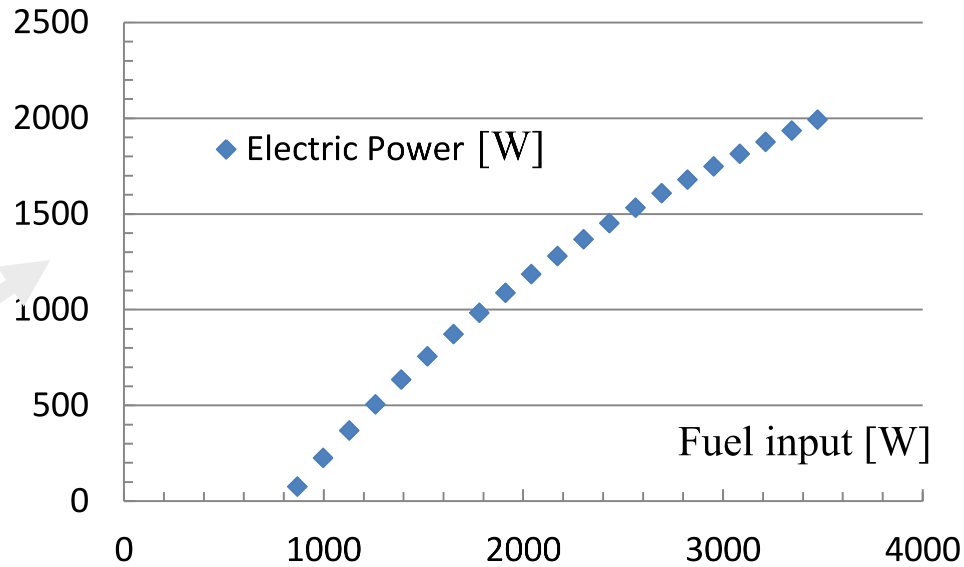


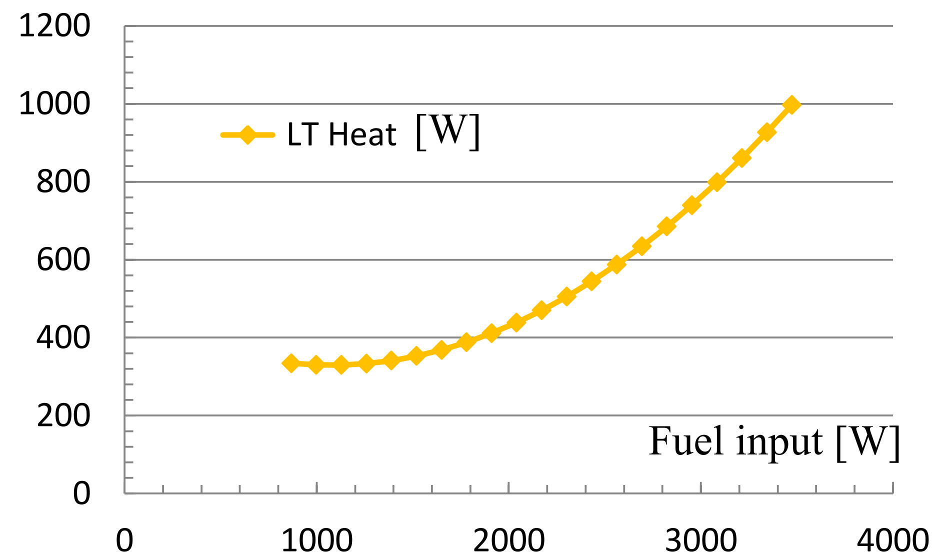
"Natura non facit saltus"….sometimes yes, but it is unusual

Non-Concave Functions
e.g. Solid Oxyde Fuel Cell (SOFC)



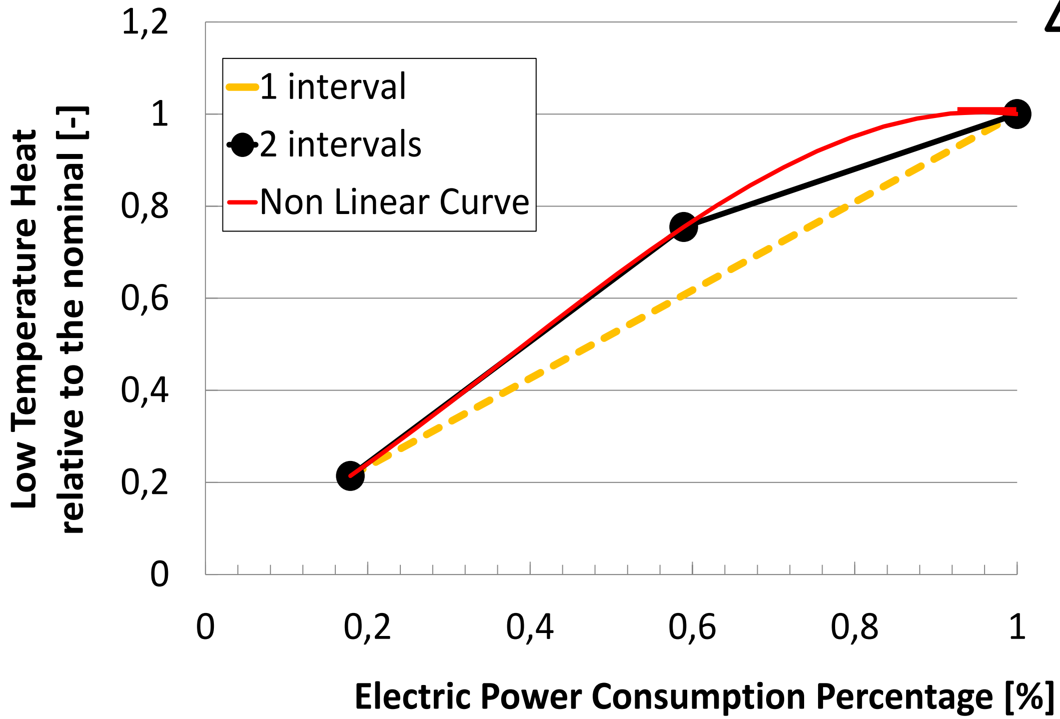
Original Source, https://www.bluegen.net/

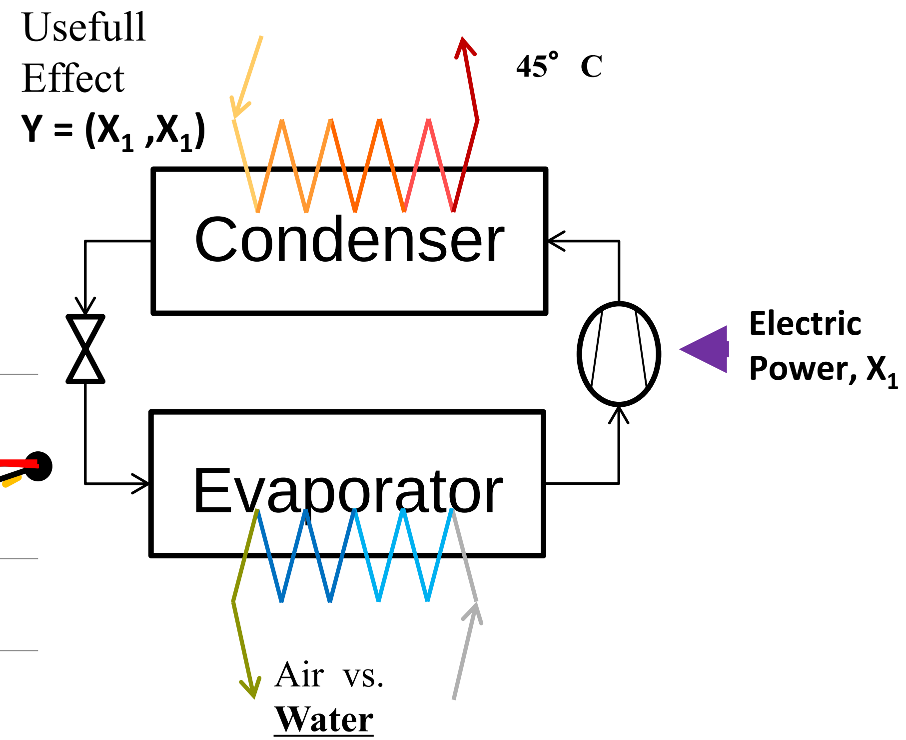




Performance curves highly NON Linear

……..e.g. Heat Pump/Part Load





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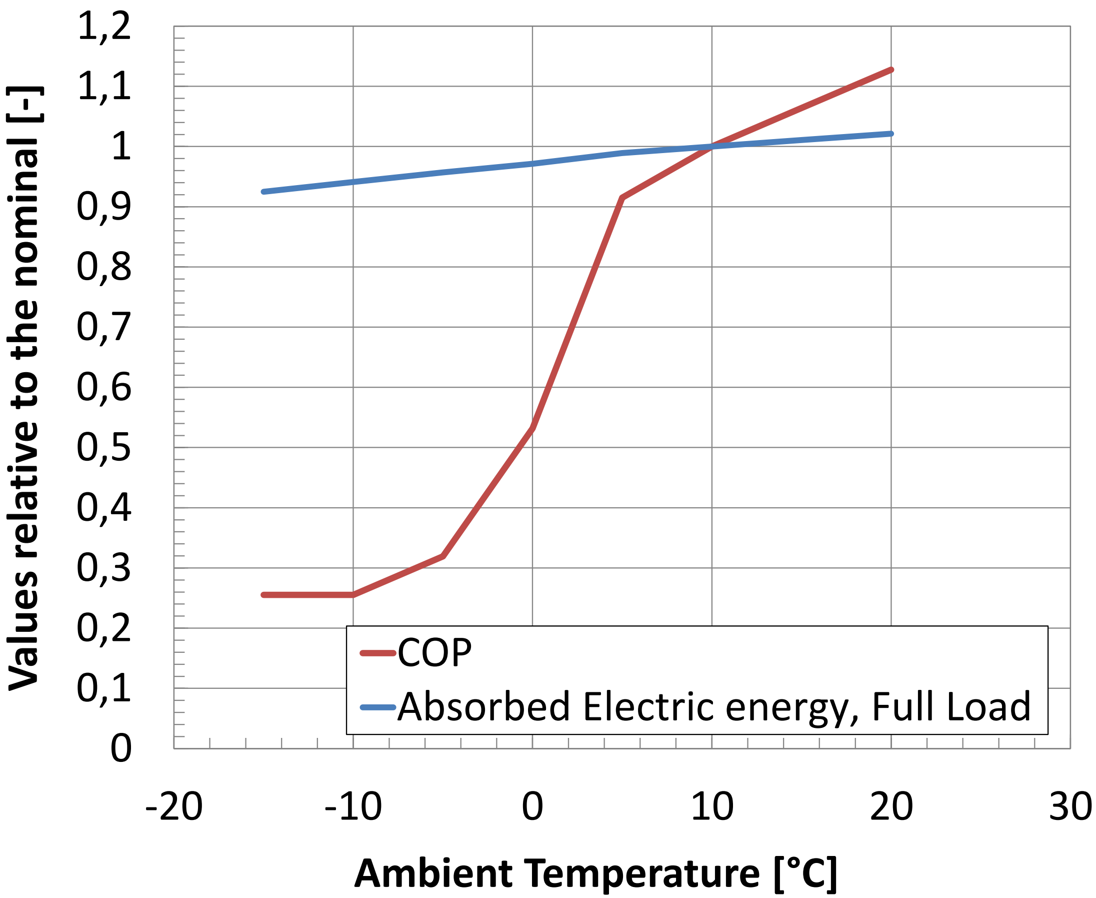
Performance Strong Temperature Dependency

→ ……..e.g. Heat Pump/Evaporator Temperature



Scheduling Application

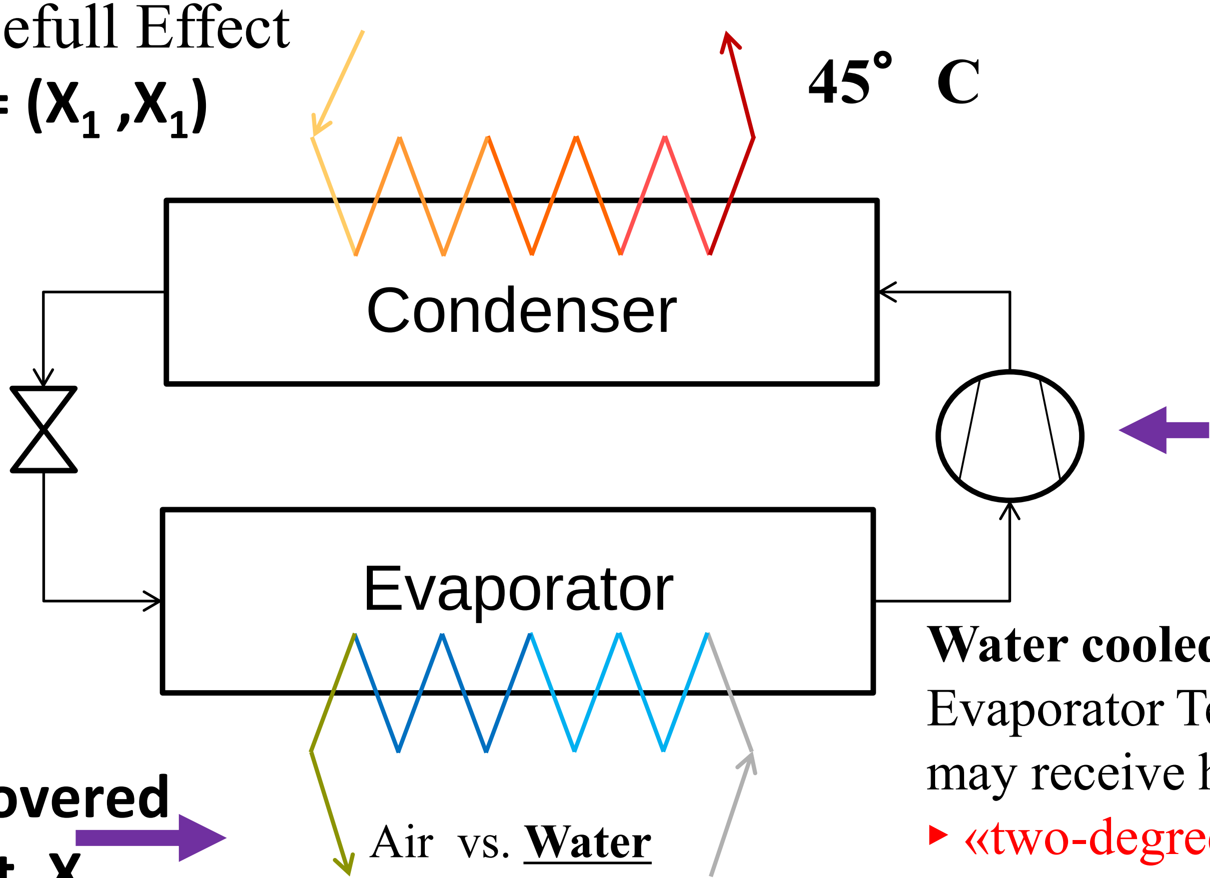
Air Cooled Heat Pump
Evaporator Temperature = T_{amb},
NOT a variable

T_{amb} reduction▸

- < cycle efficiency
- < mass flow compressor

Performance Strong Temperature Dependency

→ Temperature as a “second-degree-of-freedom”



Water cooled Heat Pump
Evaporator Temp,
may receive heat from CHP system

- «two-degrees-of-freedom»!!

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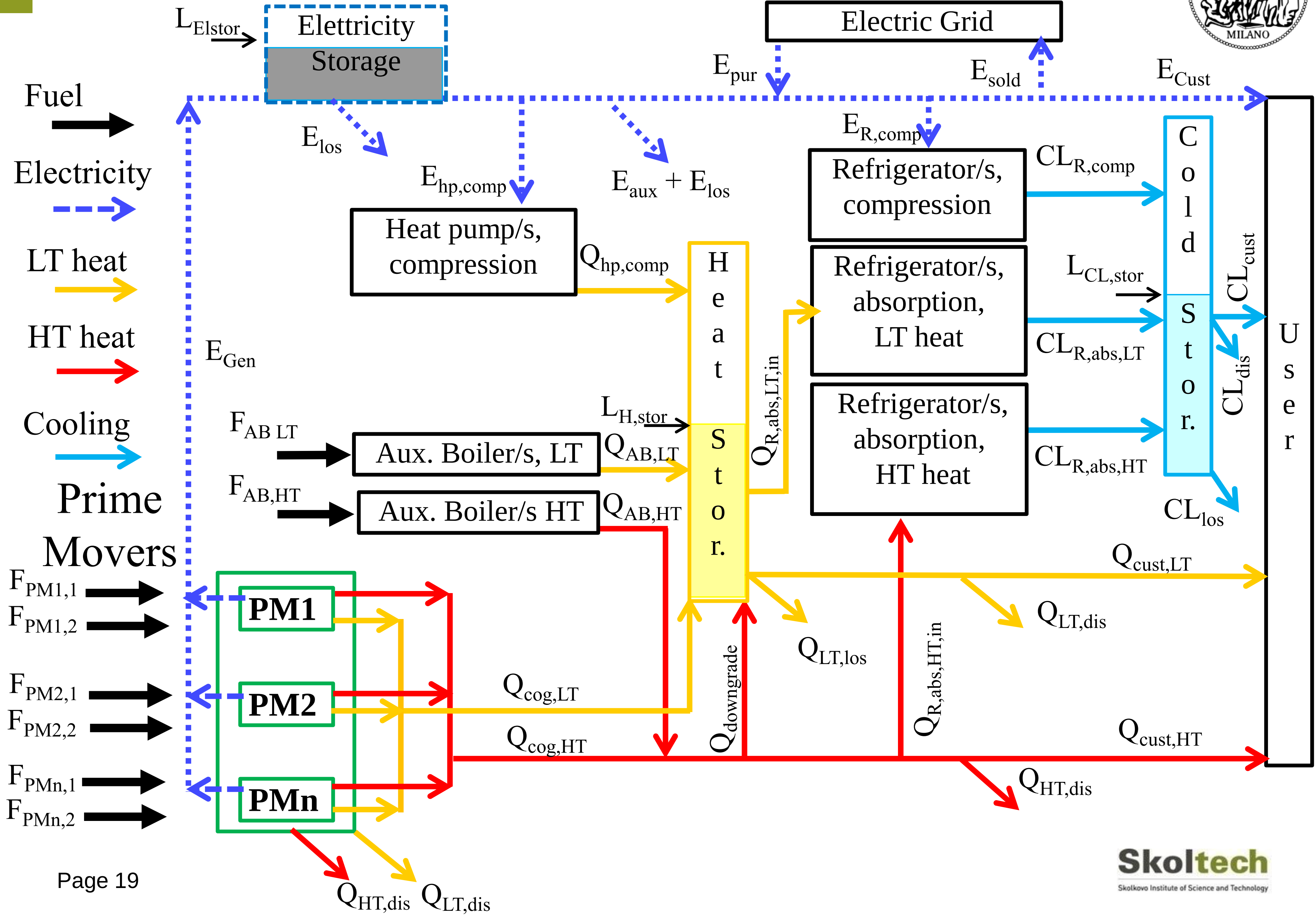
Integrated Energy Infrastructures Conceptual Layout



Problem Statement:

Optimized Management of a CCHP System

Given the Customer demands:

- Time-dependent Electrical Load
- Time-dependent Cooling, High and Low Temperature Heating Load
- …

Other known parameters:

- Time-dependent ambient Temperature
- Time-dependent Price of Electricity (Sold and Purchased)
- Units (engines, boilers, chillers, heat pumps…) performance curves
- …

Given the set of Equipment units:

- n_1 Prime Movers (Gas Turbines, Internal Combustion Engines, etc)
- n_2 Auxiliary Boilers, n_3 Heat Pumps, n_4 Compression Chillers, n_5 Absorption Chillers
- Low temperature storage tank with fixed capacity
- …

Objective: minimization of Daily/Weekly Costs of Operation

$$\sum_{t=1}^{24\cdot 7} C_{F_{tot,t}} + \sum_{t=1}^{24\cdot 7} C_{O\&M_{tot,t}} + \sum_{t=1}^{24\cdot 7} C_{On/Off_{,t}} \mp \sum_{t=1}^{24\cdot 7} E_{tot,t}$$

Fuel Consumed

Operation & Maintenance (Hours, Energy input, Start-up)

Extra Fuel/Electricity required for start-up

Electricity Sold/Purchased

Problem Statement:

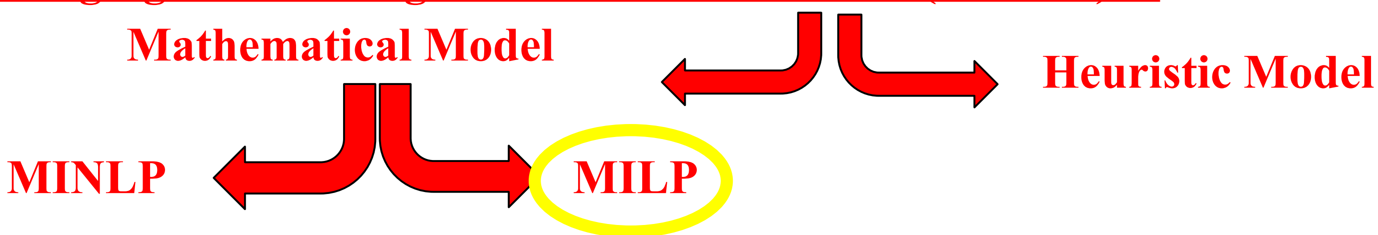
Optimized Management of a CCHP System

Objective: **Minimization of Daily/Weekly Cost of Operation (linear)**

Decision Variables, each time period:
Units Operative Variables, Units On/Off status (Binary Variables), Heat Storage Level, Thermal Power Downgraded, Sold/Purchased Electricity

Main Constraints:
- → **Satisfaction of heat and cooling load demands (linear)**
- → **Max and Min load of each unit (linear)**
- → **Max number of start-ups per day (linear)**
- → **Energy balance of heat storage tank (linear)**
- → **Performance curves of equipment units (Non-Linear, typically Non-Convex)**

Challenging Mixed Integer Non-Linear Problem (MINLP)!!!



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→ Heuristic/Multi-Step

Set of pre-defined Plant Operating Modes, Nested “For-cycles” saving best hourly results
Challenging with respect to several CHP units & NO accurate Storage (too many combinations)

A.Bischi, S.Campanari, A.Castiglioni, G.Manzolini, E.Martelli, P.Silva, E.Macchi, “Tri-Generation systems optimization: comparison of heuristic and mixed integer linear programming approaches”. **ASME Turbo Expo 2014**
A.Bischi, E.Pérez-Iribarren, S.Campanari, G.Manzolini, E.Martelli, P.Silva, E.Macchi, J.M.P.Sala-Lizarraga. “Cogeneration Systems Optimization: Comparison of Multi-Step and Mixed Integer Linear Programming Approaches”, ***International Journal of Green Energy (2016)***

→ MINLP

lack of

- **Guarantees to find the global optimum**
- **Effective large scale solvers,**

L.Taccari, E.Amaldi, A.Bischi, E.Martelli (2015). “Short-term planning of cogeneration energy systems via MINLP”, ***book chapter*** from ”Advances and Trends in Optimization with Engineering Applications”. ***Society for Industrial and Applied Mathematics*** *(SIAM)*
L.Taccari, E.Amaldi, A.Bischi, E.Martelli. ”Short-term planning of cogeneration power plants: a comparison between MINLP and piecewise-linear MILP formulations”. **Computer Aided Chemical Engineering,** Volume 37, 2015, Pages 2429-2434

→ MILP

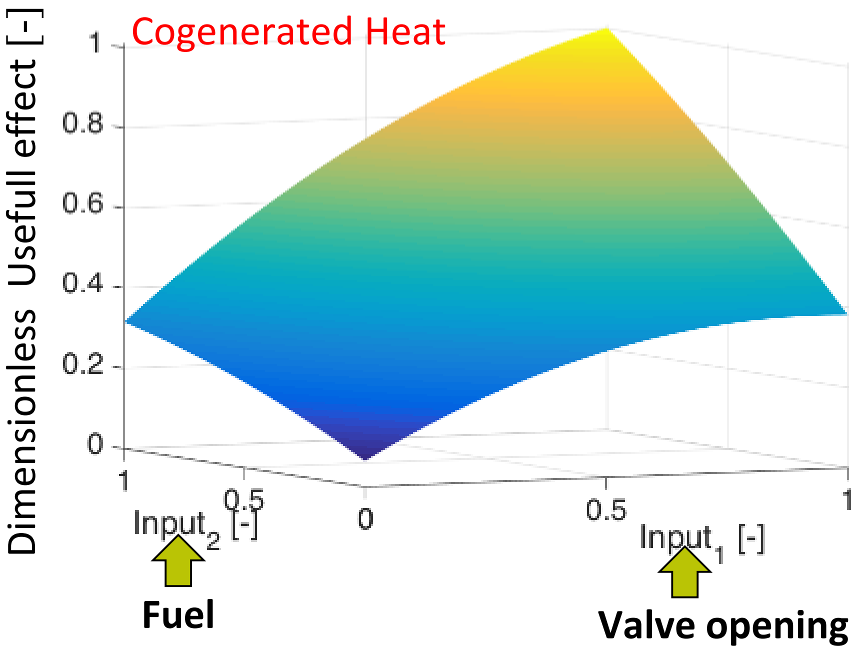
LINEARIZE it into a Mixed Integer Linear Program (MILP)
So as to use more robust and effective MILP solvers (e.g., CPLEX, GUROBI)

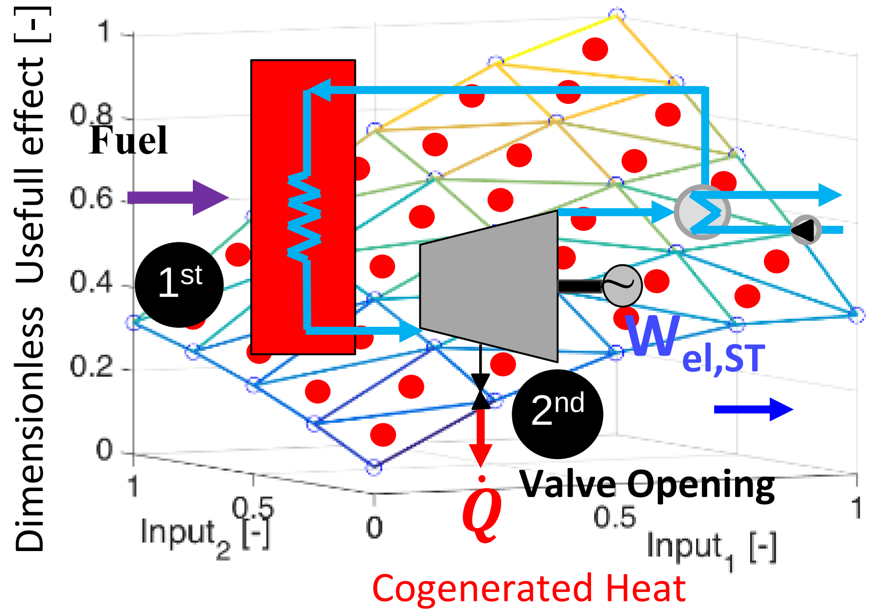
A.Bischi, L.Taccari, E.Martelli, E.Amaldi, G.Manzolini, P.Silva, S.Campanari, E.Macchi (2014). “A detailed MILP optimization model for combined cooling, heat and power system operation planning”. ***Energy,*** Volume 74, Issue C, 2014, Pages 12-26

PieceWise Linear (PWL) Approximation

Mixed Integer Non Linear Problem (MINLP)

"Two-degrees-of-freedom" units: Output & Performance depend on two operative variables (e.g., extraction condensing steam turbine)





For Each Temperature! **Highly NON linear & Highly dependent on both variables interconnected**

* C. D'Ambrosio, A. Lodi, S. Martello, "Piecewise linear approximation of functions of two variables in MILP models", Operational Research Letters, 38 (2010) 39-46

PWL Computational Performance

- Weekly problems with one hour time step i.e. 168

  e.g. six "one-degree-of-freedom" units + thermal storage ranges 1000÷5000 seconds, with 5000 as time limit & 0,01% MILP-gap!

- Heat storage up to 2000% higher computational time!

- Number of variables;

  e.g. 6000 Integer, 14000 real and 20000 constraints:

$$\prod_{k=1}^{n}(i_k + 1)$$

Integer per each time-step

…*n* degrees of freedom and *i* intervals

Weekly below/about 1% MILP-gap in one minute
….good but not enough!

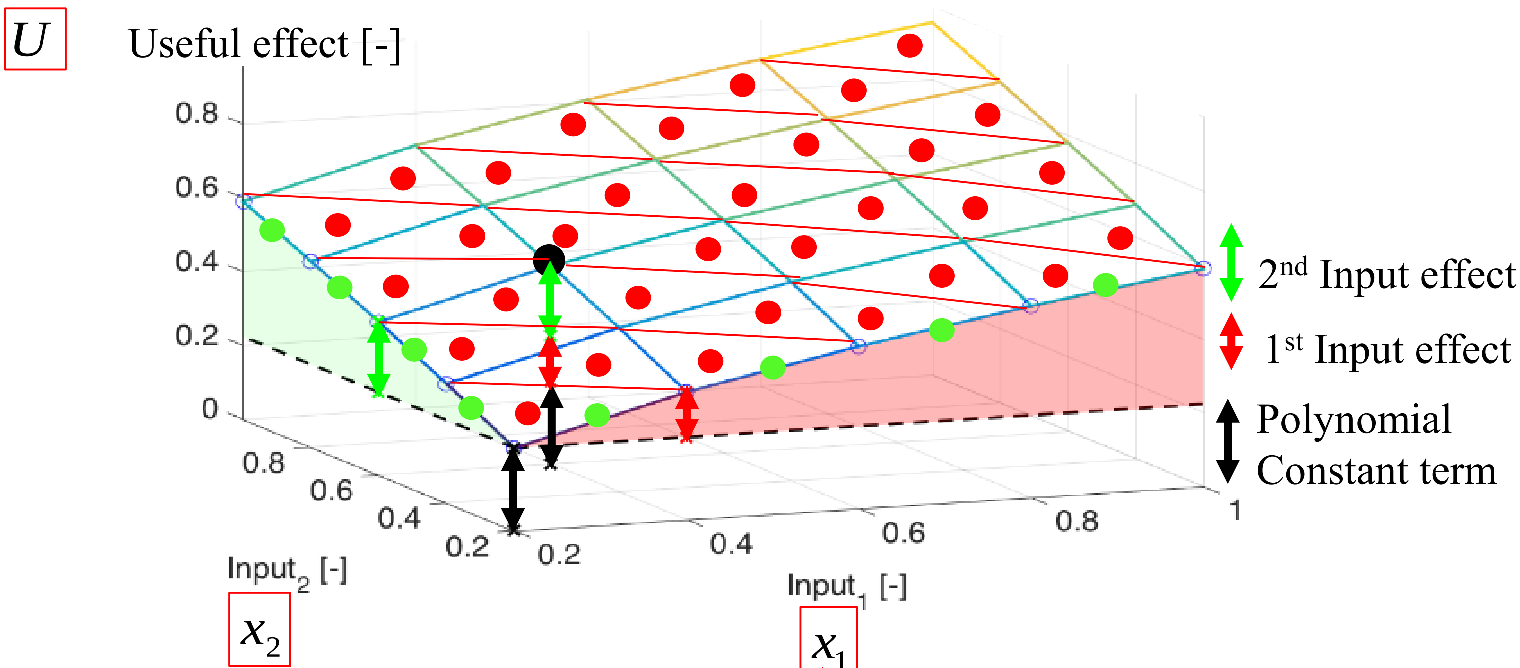
Intel Xeon with E5-2690V2 @3.0GHz CPUs and 8GB of RAM limit imposed for the tests, with eight cores

Superposition Principle:

Integer variables reduction & “N-degrees-of-freedom”

From $\prod_{k=1}^{n}(i_k+1)$ ...to $\sum_{k=1}^{n}(i_k+1)$ Integer variables

...*n* degrees of freedom and *i* intervals



$$U = C_0 + C_1x_1 + C_2x_2 + C_3x_1x_2 + C_4x_1^2 + C_5x_2^2$$

•A.Bischi, S.Lico, T.Cortigiani, G.Manzolini, P.Silva, E.Martelli (2016), “*Scheduling optimization of Combined Heat and Power units with multiple degrees of freedom based on the superposition principle*”, **ECOS 2016** – Proceedings of the 29th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems, June 19-23 2016, Portorož, Slovenia (**Extension to journal under preparation**).

Superposition Principle:

Integer variables reduction

Eliminate the mixed term by linearly transforming the control variables!

$$U = C_0 + C_1 x_1 + C_2 x_2 + C_3 x_1 x_2 + C_4 x_1^2 + C_5 x_2^2 = x^T Q x + b^T x + c$$

Q, Polynomial Quadratic Term Matrix:

- Symmetric
- Diagonalizable to avoid mixed term

By means of the orthogonal Q eigenvectors matrix M

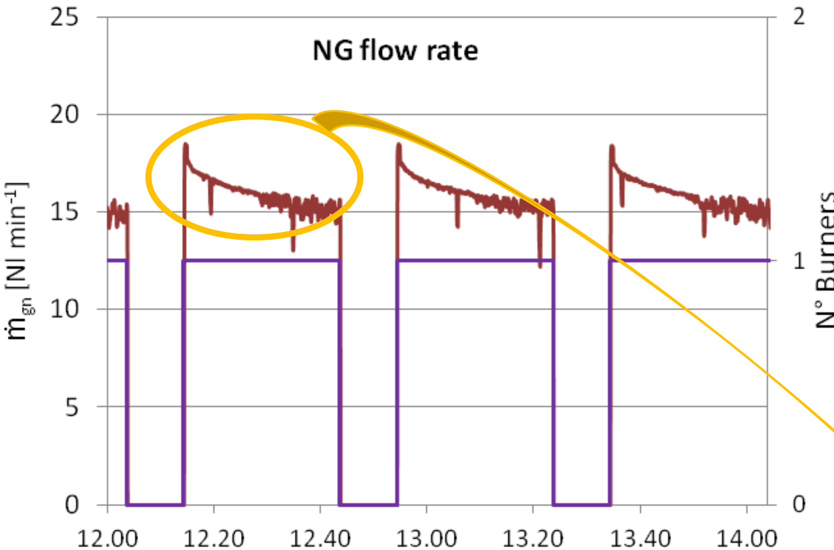
$$M = \begin{bmatrix} k_{11} & k_{12} \\ k_{21} & k_{22} \end{bmatrix} \qquad \begin{cases} x_{1T} = k_{11} x_1 + k_{12} x_2 \\ x_{2T} = k_{21} x_1 + k_{22} x_2 \end{cases}$$

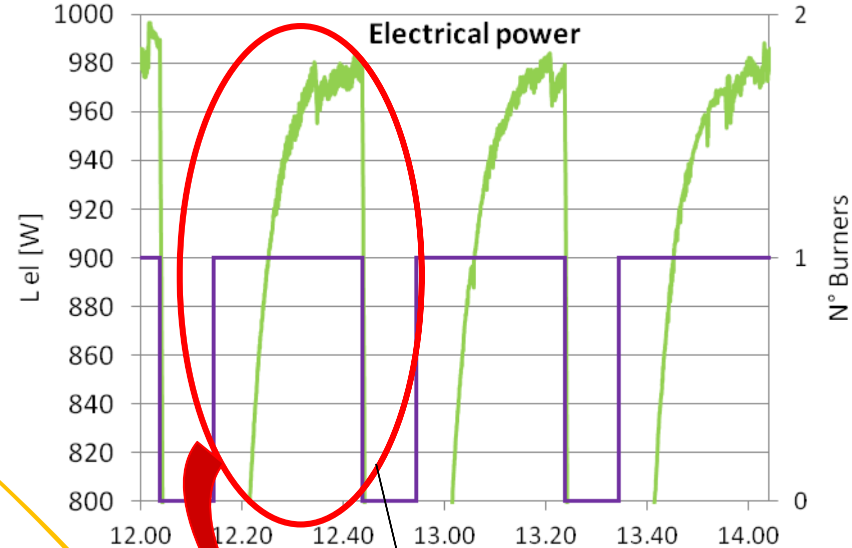
$$U = c_0 + c_1 x_{1T} + c_2 x_{2T} + c_3 x_{1T}^2 + c_4 x_{2T}^2$$

•A.Bischi, S.Lico, T.Cortigiani, G.Manzolini, P.Silva, E.Martelli (2016), "*Scheduling optimization of Combined Heat and Power units with multiple degrees of freedom based on the superposition principle*", **ECOS 2016** – Proceedings of the 29th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems, June 19-23 2016, Portorož, Slovenia (**Extension to journal under preparation**).

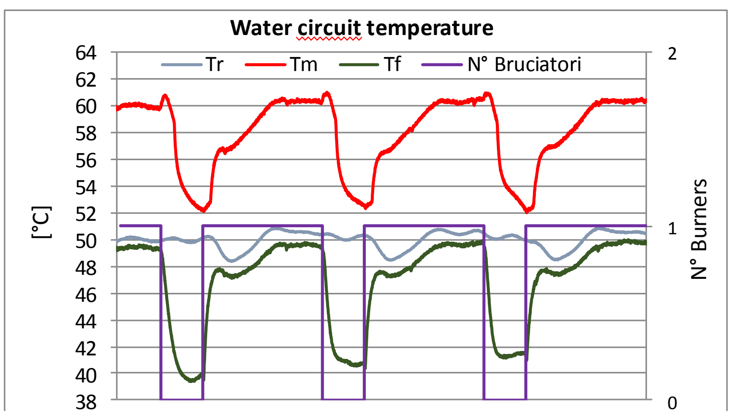
Startup & Shutdown Constraints

/ Commercial Stirling Engine – Laboratory

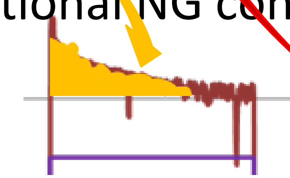


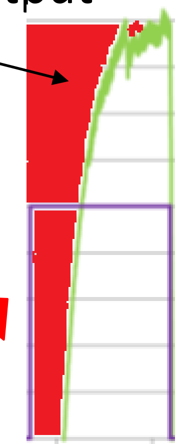


Lower electricity output



Additional NG consumption





Thermal Power

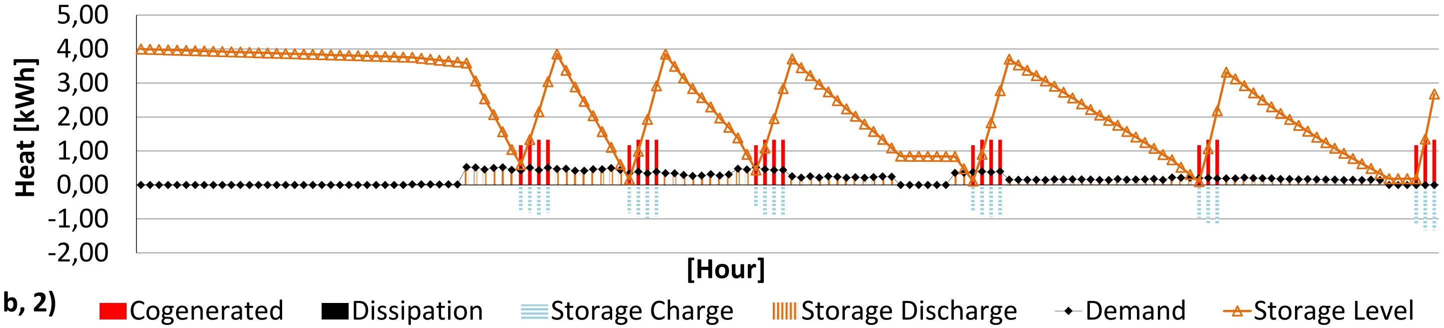
$$\dot{m} \cdot c_p \cdot (T_{hot} - T_{cold})$$

G.Valenti, S. Campanari, P. Silva, A. Ravidà, E. Macchi, A. Bischi. “On-off cyclic testing of a micro-cogeneration Stirling unit”, Energy Procedia (2015), pp. 1197-1201 DOI information: 10.1016/j.egypro.2015.07.152

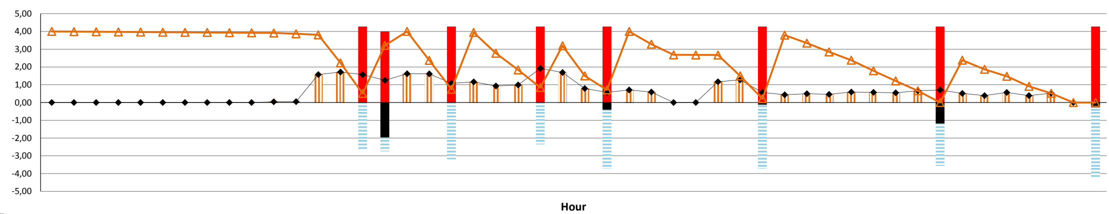
Startup & Shutdown Constraints

/ Optimal Scheduling Impact

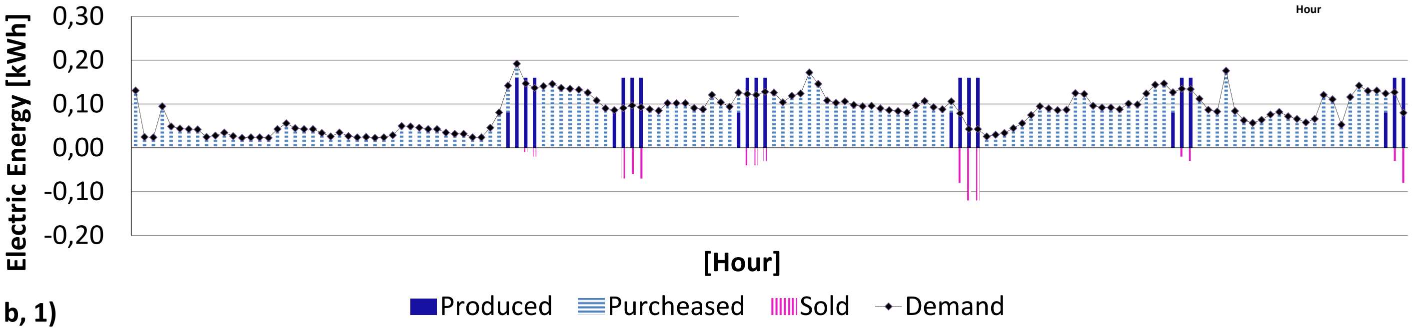
10 minutes time step



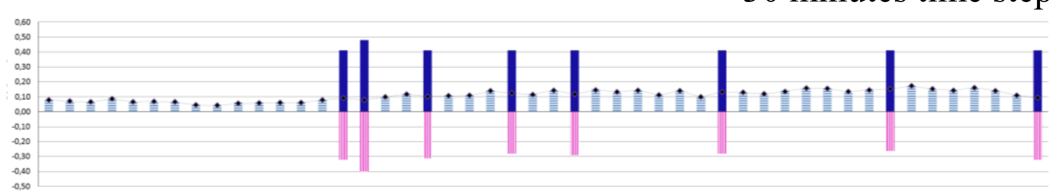
30 minutes time step



10 minutes time step



30 minutes time step



G.Valenti, S.Campanari, A.Bischi, P.Silva, A.Ravidà, E.Macchi (2016), *"Experimental and numerical study of a micro-cogeneration Stirling unit under on-off cycling operation"*, under preparation.

Yearly problem & Performance-dependent parameters

Objective: minimization of Yearly Costs of Operation

$$\sum_{t=1}^{24\cdot365} C_{F,tot,t} + \sum_{t=1}^{24\cdot365} C_{O\&M,tot,t} + \sum_{t=1}^{24\cdot365} C_{on/off,tot,t} + - \sum_{t=1}^{24\cdot365} El_{tot,t} + \sum_{t=1}^{24\cdot365} Ex_{h,t} + Ex_{forf} - Inc$$

Hourly taxation on the electric energy consumption (excise)
Monthly Threshold!

Periodic taxation on the electric energy consumption (excise)
Monthly Threshold!

Periodic Incentives on the primary energy savings (“white certificates”)
Yearly Bases!

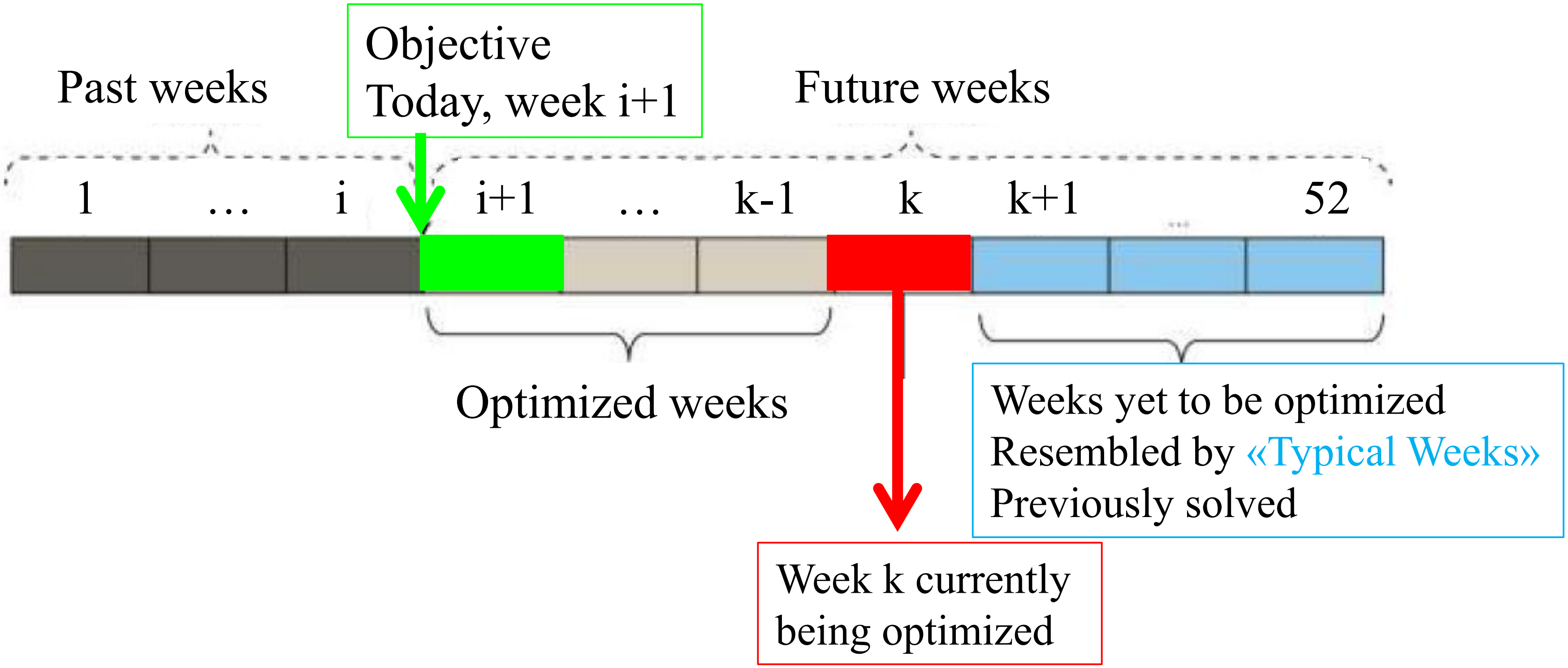
Yearly constraints, e.g. Primary Energy Savings (PES) & first principle efficiency!

Extremely Challenging Mixed Integer Non-Linear Program (MINLP)
Due to Non-Linearity & High number of variables solving at once the whole problem

«ad hoc» Rolling Horizon heuristic for the yearly schedule

Rolling Horizon heuristic optimization method

Overall problem subdivided into a **sequence of smaller (weekly) sub-problems**:

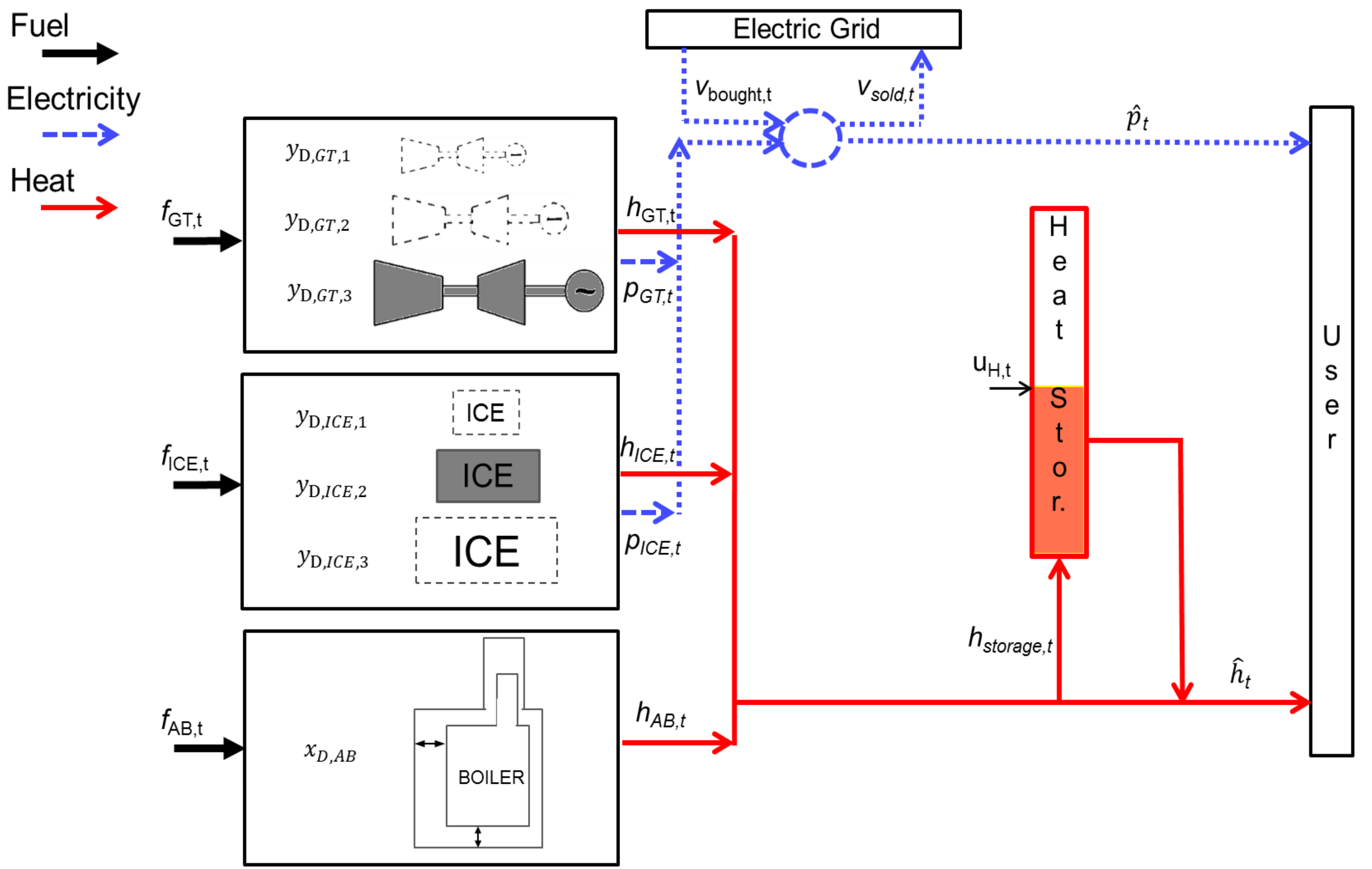


Iteratively Optimize only the variables corresponding to a subproblem while fixing the variables of all the other subproblems based on aggregated information (Past weeks, already optimized weeks, future weeks based on typical weeks)

A.Bischi, L.Taccari, E.Martelli, E.Amaldi, G.Manzolini, P.Silva, S.Campanari, E.Macchi. "A Rolling Horizon MILP Optimization Model for the Scheduling of Tri-generation Systems with Incentives". **ECOS 2015 – Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems** 30 June-3 July 2015, Pau, France

Combined Heat and Power (CHP) plants,

Networks of CHP units feeding district heating



C.Elsido, A.Bischi, P.Silva, E.Martelli (2016), *“Two-stage MINLP algorithm for the optimal synthesis and design of networks of CHP units”*, under revision (**Energy**).

Non linear effects of the size on the performance

The larger the size…

1) Lower fluid friction losses for isentropic efficiencies of machineries
(Pumps, Compressors, Turbines)

2) Positive effects on specific costs
(larger heat transfer areas, better materials and technologies)

- **Steam Turbine**

Isentropic efficiency of turbine stages from 60% till 92%

- **Medium-small Gas Turbines plant** (< 100 MW_{el}):

electric efficiency from 28,5% (5MW) till 41% (100 MW):

- **Large Gas Turbines & Natural Gas Combined Cycles plants**

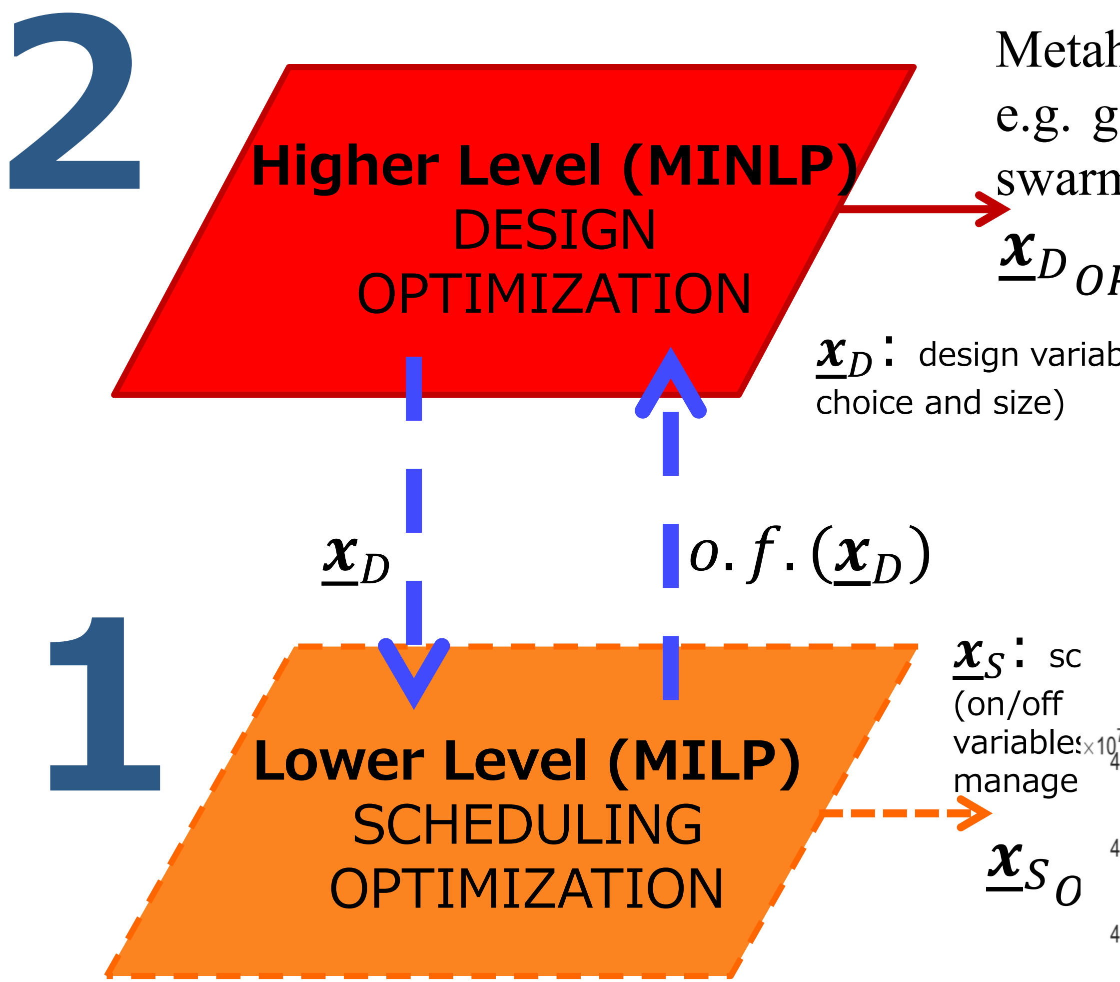
Lower BUT Not-Negligible

- **Gas-Fired Industrial Boilers**

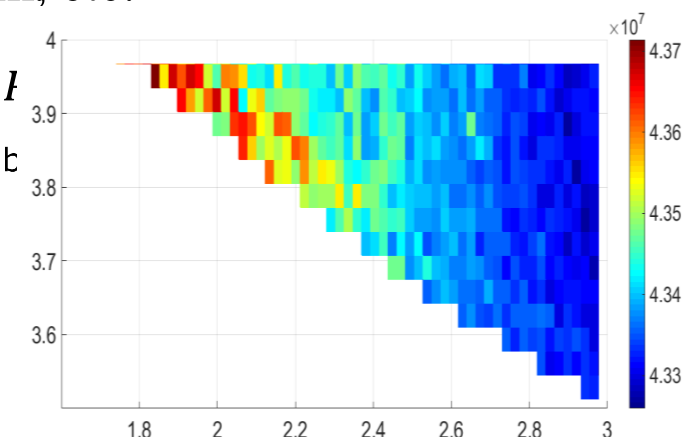
Thermal efficiency from 90% (1MW) till 93% (20MW)

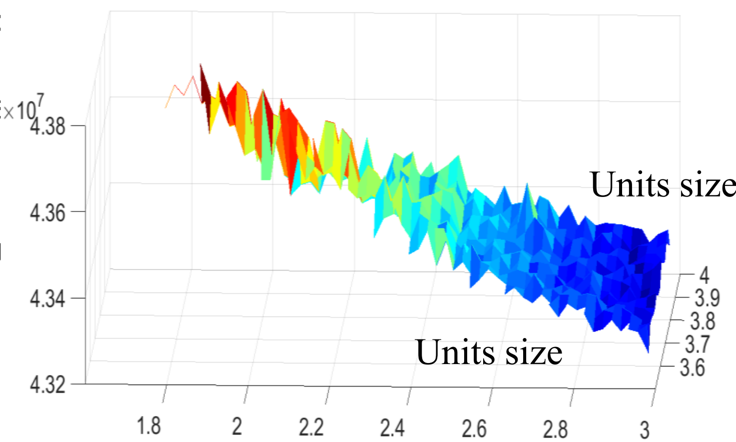
Two stages optimization algorithm

Decomposition Method



Metaheuristic,
e.g. genetic algorithm, particle swarm, etc.





C.Elsido, A.Bischi, P.Silva, E.Martelli (2016), *"Two-stage MINLP algorithm for the optimal synthesis and design of networks of CHP units"*, under revision (**Energy**).

Typical Weeks decomposition

based on the optimization results!

Reduce computational load by an accurate selection of typical periods, e.g. Clustering techniques (K-means).

Weights calculation for input data (x_a) like Thermal load, Electric load, Temperature to reduce the approximation error

1) Base Typical weeks determination via standard methods
2) Optimize the Total Operating Costs for the Base typical weeks (TOC_0)
3) Each input data variation (Δx_a)….keeping constant the others
4) For Each of the input variation optimize Total Operating Costs (TOC_a)
5) Compute the weight (w_a) for the input x_a

$$w_a = \frac{\frac{TOC_0 - TOC_a}{TOC_0}}{\Delta x_a}$$

….for N design configurations

Approximation error from 10 (standard typical Weeks) to 3%!

C.Elsido, A.Bischi, P.Silva, E.Martelli (2016), *"Two-stage MINLP algorithm for the optimal synthesis and design of networks of CHP units"*, under revision (**Energy**).

Achievements

- Development of an accurate MILP model for CCHP scheduling
  - Daily/Weekly basis ……………… **heat storage**
  - **Validation** ……………… **Qualitative, Quantitative with Heuristic**

- Extension up to Yearly Simulations

Iterative Simulations to Adjust Assumptions avoiding Non Linearity

  - Natural Gas / Electricity price according to monthly-yearly consumed volumes
  - Incentive calculation based on annual energy indexes, Primary Energy Savings

- Extension up to:
  - **Higher number of degrees of freedom > 2,**

    by superposition principle & domain change for N variables (degrees of freedom)
  - **Design, by two stage optimization algorithm,**

- Future plans:
  - **Load Forecast & Integration with Building physics model**
  - **Topology & Transport: Integration with Electric, Gas & Thermal grid**
  - **Stochastic & Robust optimization**

Thank you for your attention.

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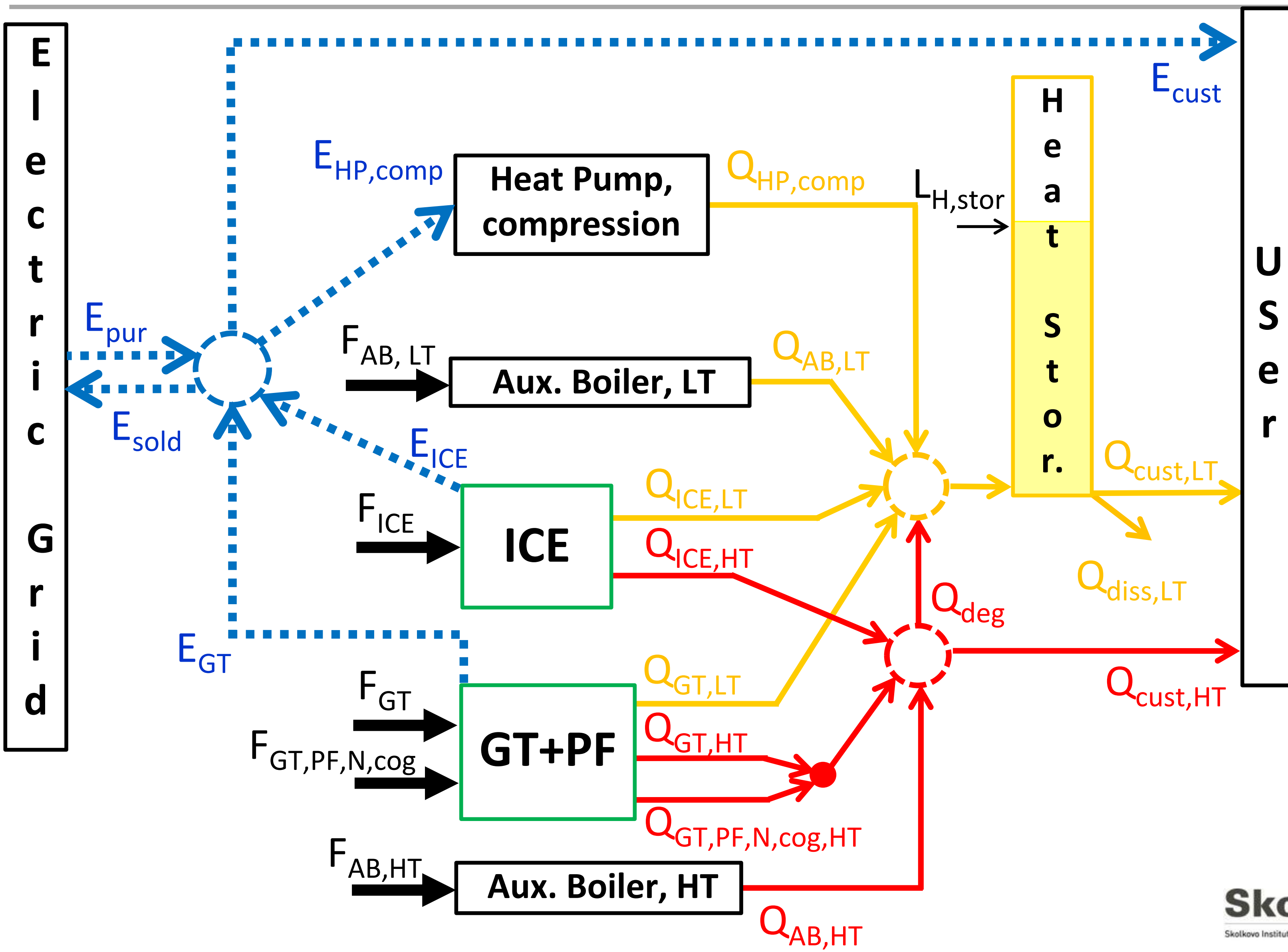
Test Case – Energy Fluxes



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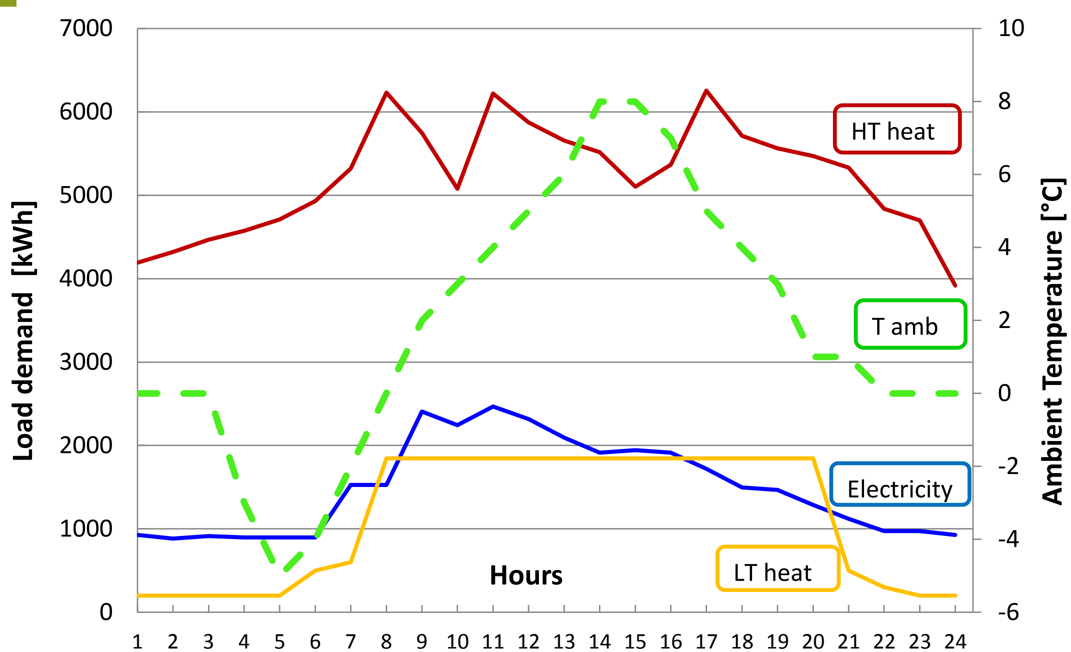
Test Case – Units & Load Characterization

Unit Performance* [kW]	Input	Electric Power	Heat, HT	Heat, LT
Gas Turbine + Post Firing	6765 +2500	2029	2380 +2350	944
Internal Combustion Engine	5198	2048	1483	988
Heat Pump, LT	280			1316
Auxiliary Boiler, HT	6818		6000	
Auxiliary Boiler, LT	2666			2400

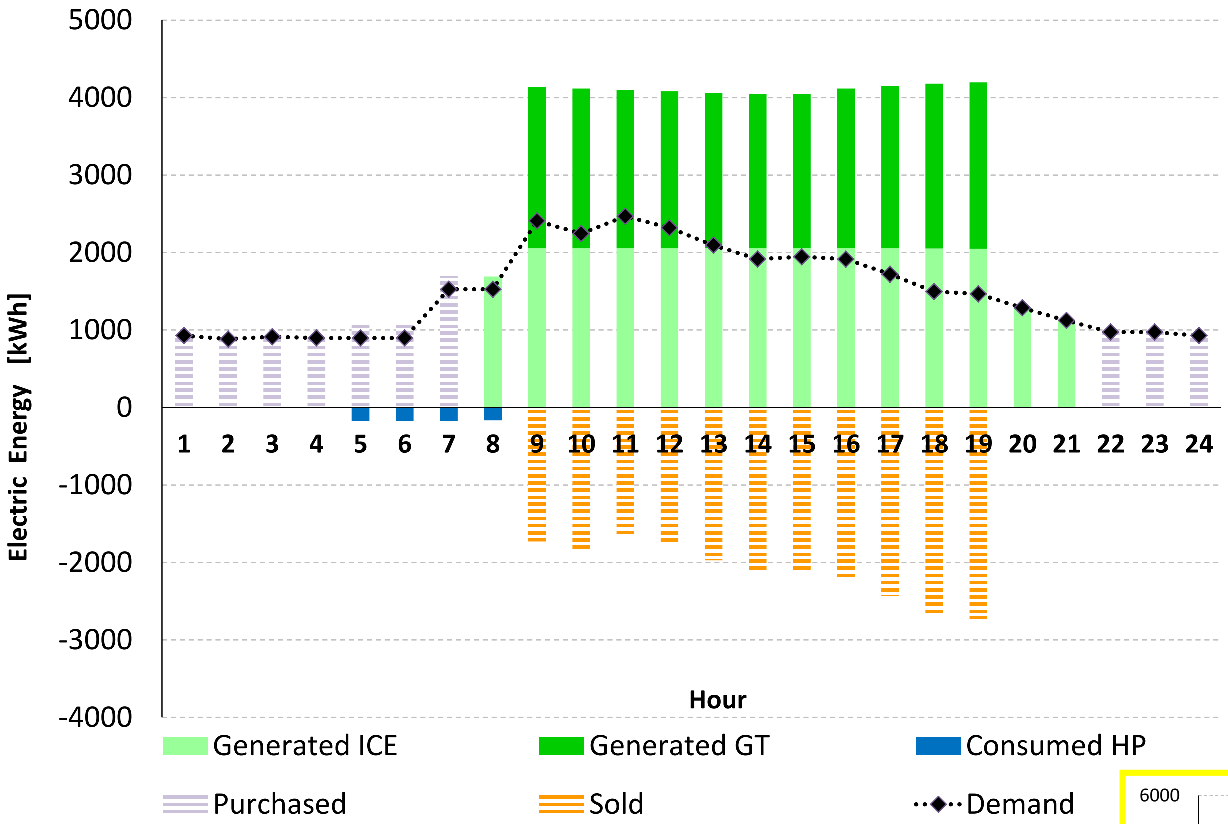
*Nominal Conditions, Temperature will change the units performance



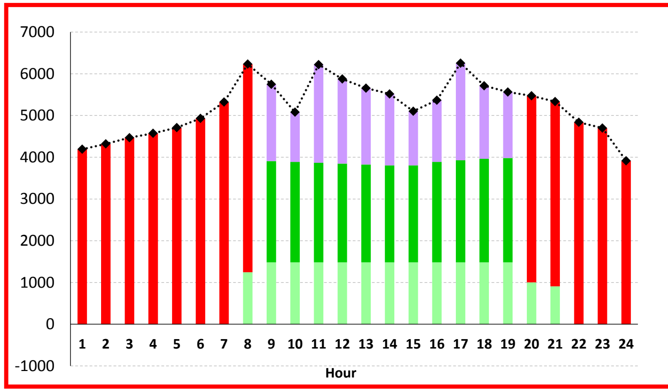
El.Cost [€/kWh]	$9^{th}19^{th}$	8^{th}; $20^{th}23^{th}$	$24^{th}7^{th}$
Purchase	0,158	0,116	0,088
Sale	0,126	0,093	0,070

Fuel Cost [€/kWh]	0-24h
Prime Movers	0,06
Boilers	0,06

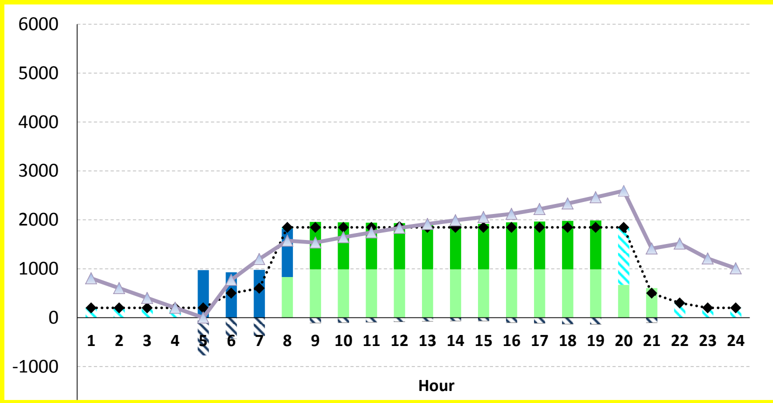
Test Case, 20 intervals – Electric Energy [kWh]



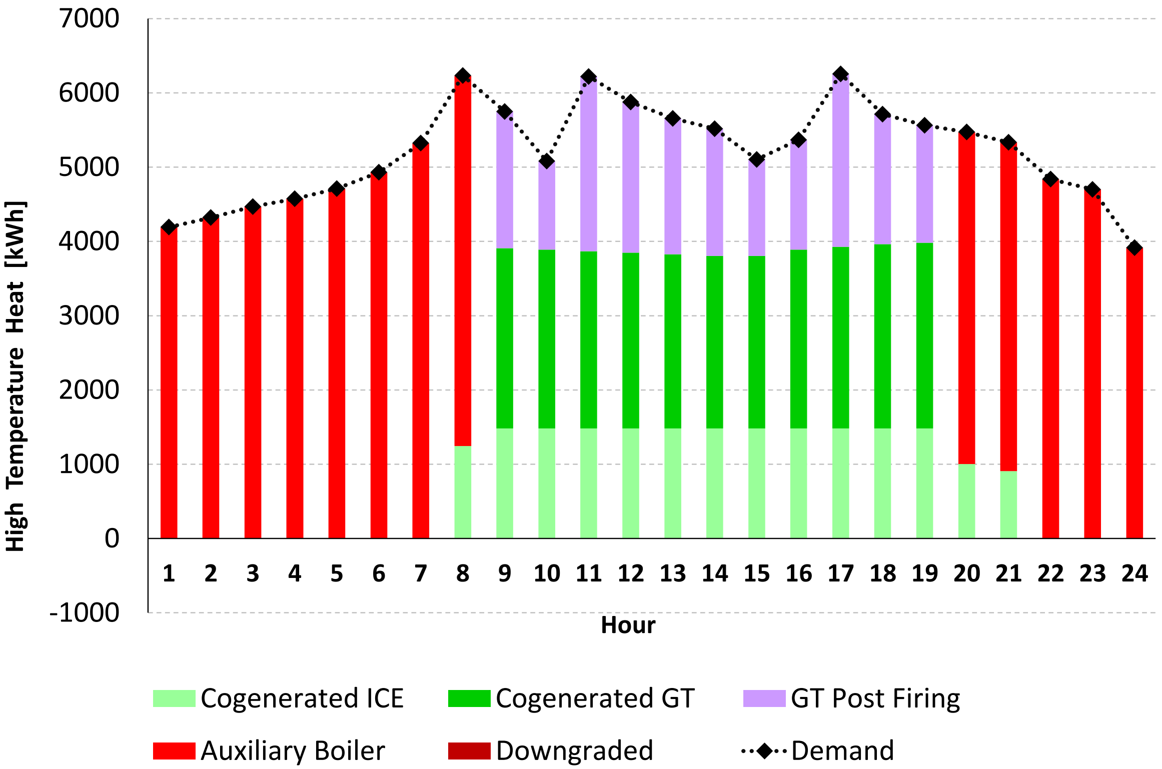
High Temperature Heat [kWh]



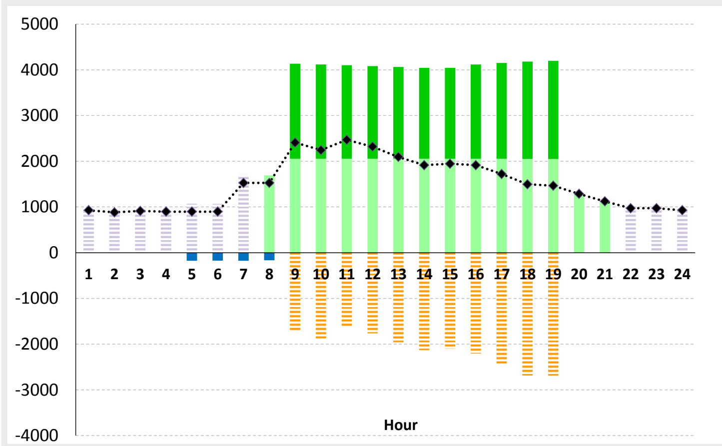
Low Temperature Heat [kWh]



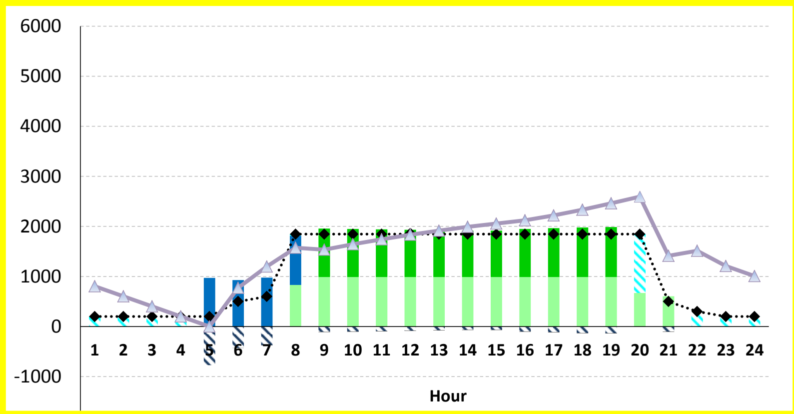
Test Case, 20 intervals – High Temperature Heat [kWh]



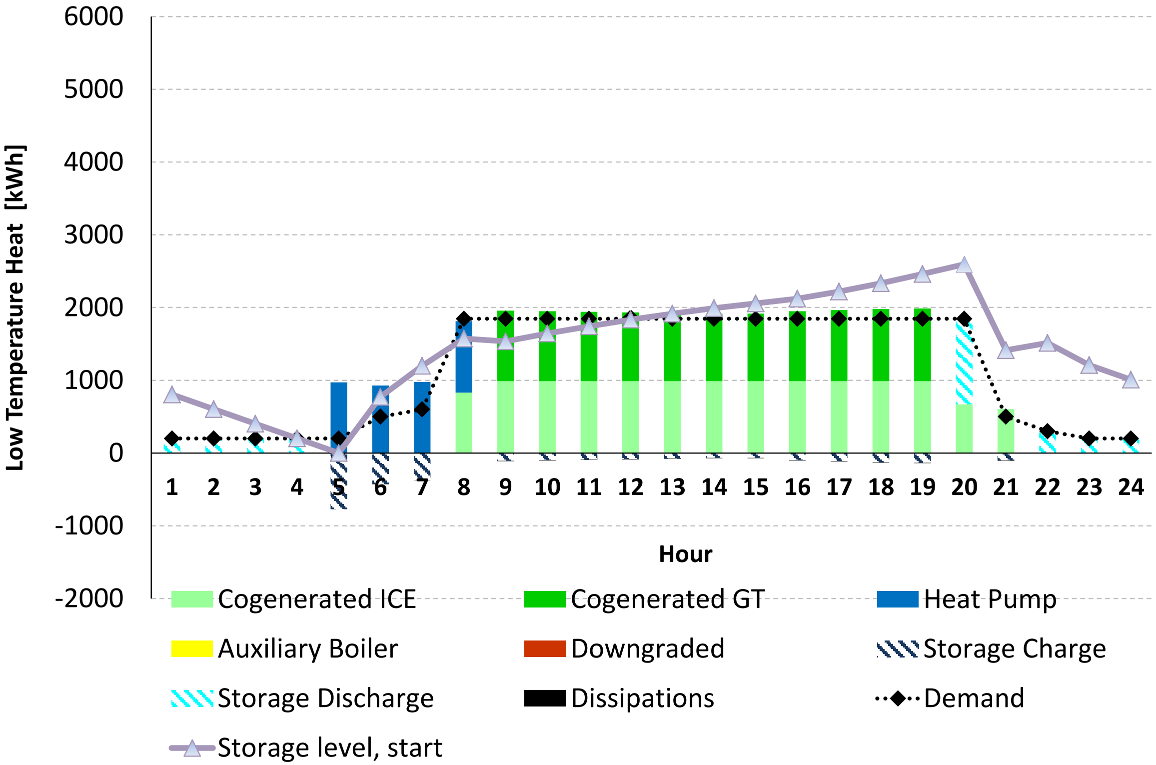
Electric Energy [kWh]



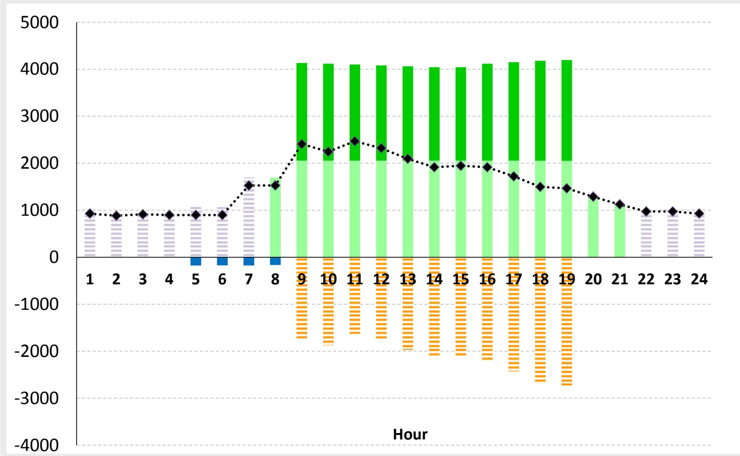
Low Temperature Heat [kWh]



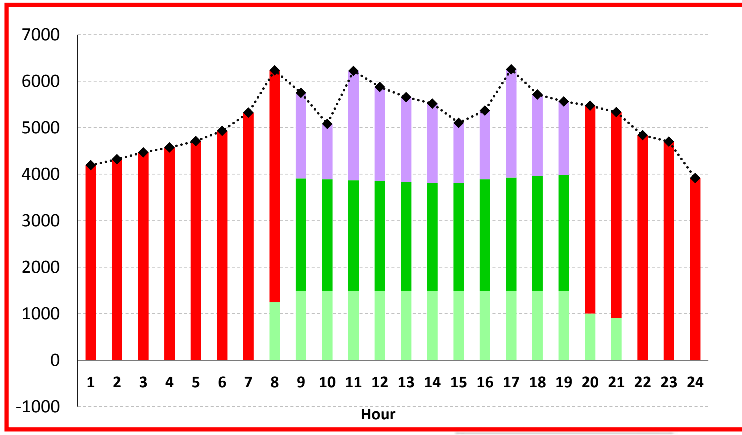
Test Case, 20 intervals – Low Temperature Heat [kWh]



Electric Energy [kWh]



High Temperature Heat [kWh]



Results summary

Discretization Intervals▸	5 intervals	10 intervals	20 intervals
Number of binary variables*	1944	6144	21744
Total number of variables	5712	13512	39912
Number of constraints	4685	8285	19085
Computational time (s)	22.69	68.28	293.86
Relative MILP gap (%)	9E-3	9E-3	9E-3
Objective function value (€)	14059.19	14055.43	14054.55

0,009% gap from the global optimum corresponds to ~ 1,2€ out of 14060€ in the worse case scenario
Excluding "macro mistakes"!!

**Without the «second-degree-of-freedom», post firing, the total number of variables goes down to about 2400 (5 intervals) ÷ 6000 (20 intervals)!!*

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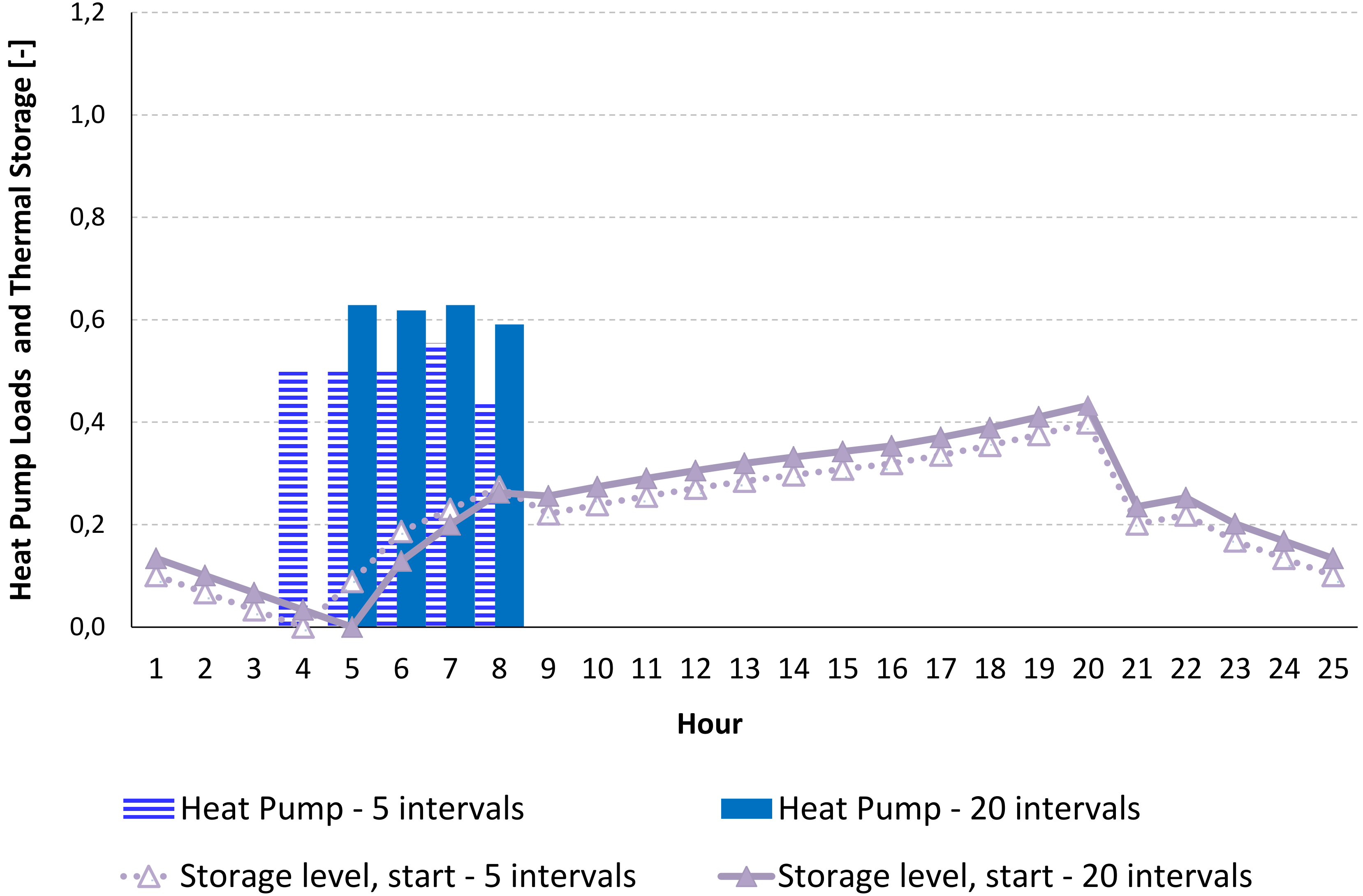
Short term differences, 20 intervals vs. 5 intervals



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