Energy sector coupling: electric-thermal interaction through heat pumps

Tuesday 23th of October 2018

eurac research – *Institute for Renewable Energy*

NOI Tech Park, via A. Volta 13/A, Bolzano

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Using heat pumps to support electric distribution grids: opportunities and challenges

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Outline

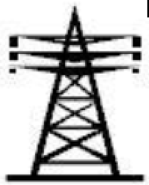
- Electric heat pumps management
  - Motivations
  - Case study 1: using thermal house inertia and customer flexibility
  - Case study 2: using thermal storage to provide flexibility
- Future scenarios and challenges
  - Ongoing and future activities
  - Challenges
  - Conclusions

Electric heat pumps management

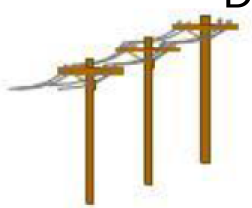
Electric grid scenario

Large generation

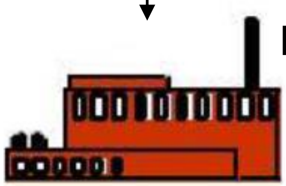
Transmission



Distribution → Distributed generation, Power electronics, Storage systems



End-user → Electric vehicles, Electric heating, More services



Higher complexity

Need for smart management

Demand Side Management concept

- Demand Side Management (DSM) is one of the solutions to enable the Smart Grid
  - modification of consumer demand for energy through various methods such as financial incentives and behavioral change through education

- DSM can be applied to *flexible loads*, namely appliances whose operation can be shifted, interrupted, or scheduled without generating a discomfort to the end-user

- Flexible loads: electric vehicles, water heaters, washing machines, air conditioning systems, **heat pumps**;

Why are heat pumps flexible?

↓

Thermal inertia of the house / slow dynamics

Possible flexibility from the customer on the accepted temperature

Possibility to have coupling with thermal storage

Demand Side Management objectives

- Goal of the optimal scheduling:
  - Power peak shaving in the electric distribution grid
  - Deliver the desired indoor temperature to the final customers

- Why power peak shaving??
  - Distribution grid benefits
    - Minimization power losses / better efficiency
    - Easier management of the grid having a flatter profile of the daily consumption
    - Postponements of investments for grid operated close to their limits
  - Transmission system benefits
    - Possibility to avoid the use of more expensive generators to cover power peaks
    - Reduction of the needed spinning reserve
  - Benefits for the customer
    - Less risks for contingencies / outages
    - Better efficiency translates in cheaper tariffs, which are finally also reflected in the price of energy for the end-user

Case study 1 –

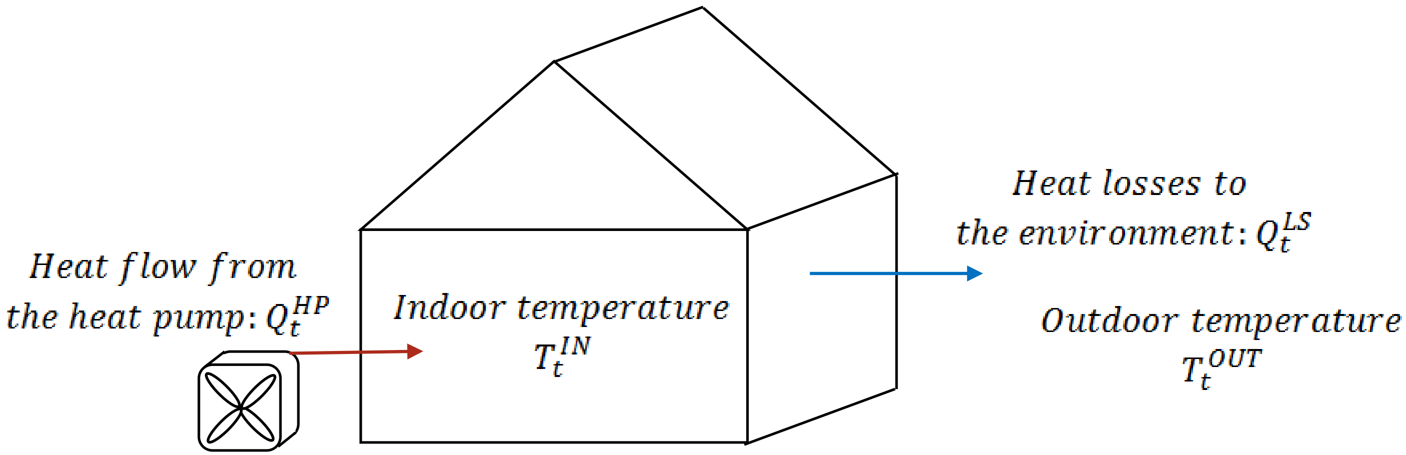
Using building thermal inertia and customer flexibility

Results from:

[1] J. Cremer, M. Pau, F. Ponci, A. Monti, "Optimal Scheduling of Heat Pumps for Power Peak Shaving and Customers Thermal Comfort", in *Proceedings of the 6th International Conference on Smart Cities and Green ICT Systems SMARTGREENS,* 23-34, 2017, Porto, Portugal

Case 1 - Thermal model of the house

- It describes the evolution of the thermal profile of the house



discretization time step

$$\textbf{Energy balance}: \; T_t^{IN} = T_{t-1}^{IN} + \frac{\Delta t}{\mu^{HS}\gamma^{AR}}\left(Q_t^{HP} - Q_t^{LS}\right)$$

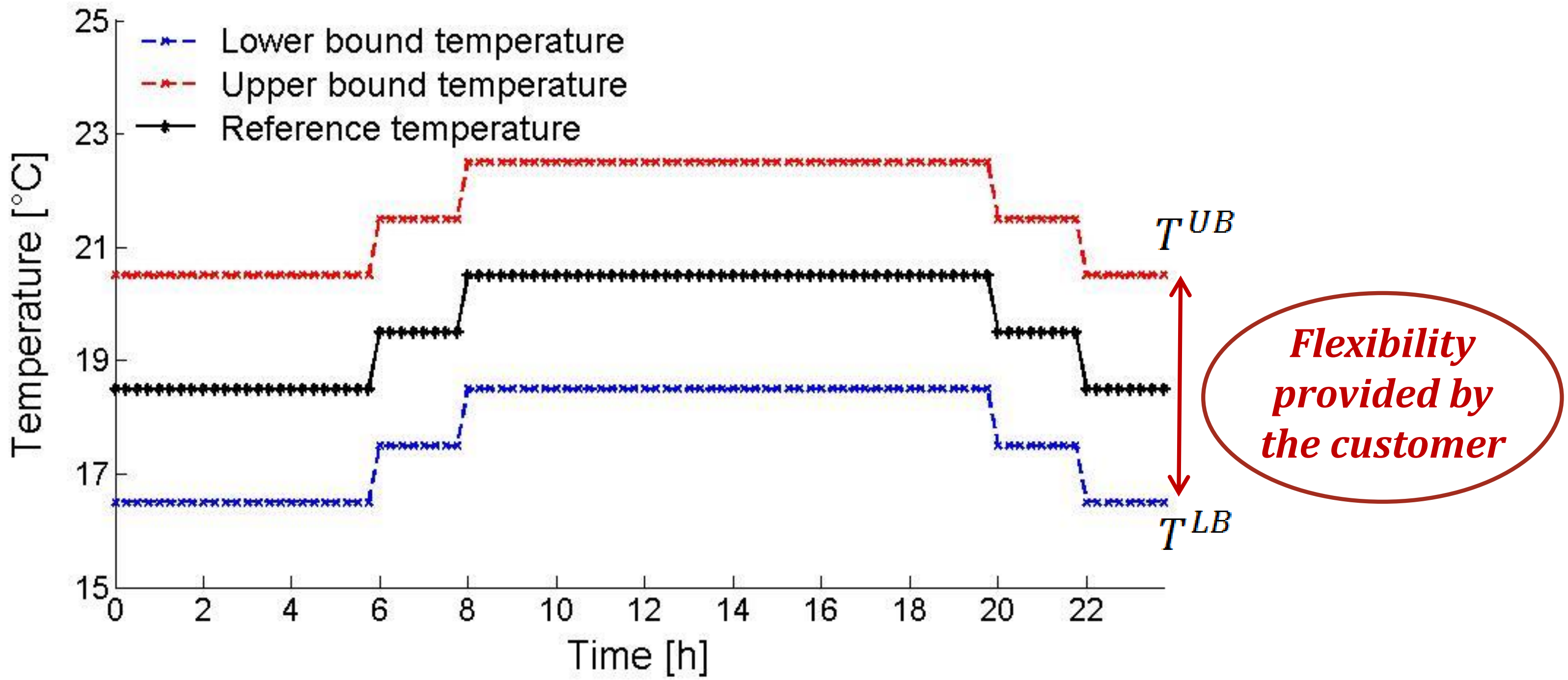
total air mass *air heat capacity*

$$\textbf{Heat losses}: \; Q_t^{LS} = \kappa^{HS}\left(T_{t-1}^{IN} - T_{t-1}^{OUT}\right)$$

Heat loss factor

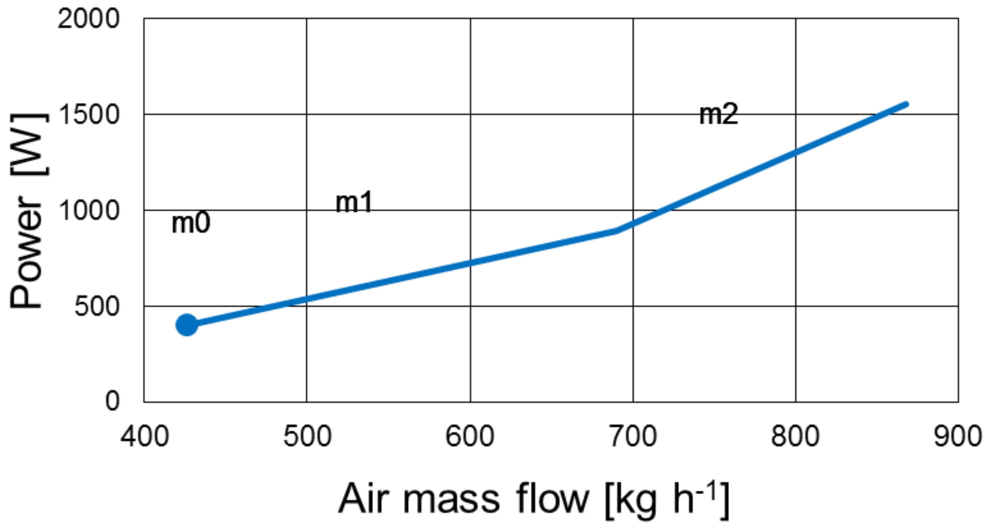
Case 1 - Thermal comfort constraints

- They allow delivering the temperature desired by the customers during the day



$$Comfort\ constraints: \begin{cases} T_t^{IN} \leq T_t^{UB} \\ T_t^{IN} \geq T_t^{LB} \end{cases}$$

- Continuous model of the heat pump



$$operating\ mode\ 0: \quad \Delta F_{0,t}^{HP} = y_t \cdot \phi_{m0}$$

$$operating\ mode\ i: \quad 0 \leq \Delta F_{i,t}^{HP} \leq \Delta \phi_{mi}^{UB}$$

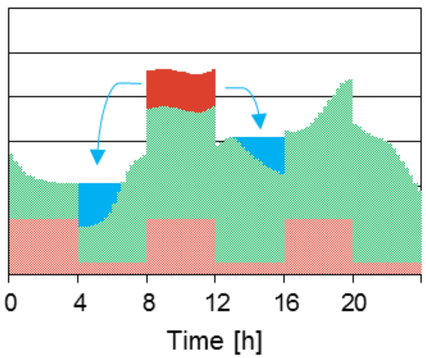
$$\boldsymbol{Heat\ from\ the\ heat\ pump}: Q_t^{HP} = \gamma^{AR} \sum_m \Delta F_{m,t}^{HP} (T^{HP} - T_{t-1}^{ref})$$

$$\boldsymbol{Power\ consumption\ of\ the\ heat\ pump}: P_t^{HP} = \sum_m \beta_m \Delta F_{m,t}^{HP}$$

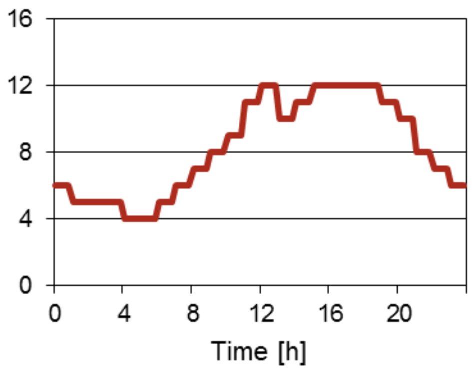
Case 1 - Day ahead scheduling of heat pumps

Forecasts of

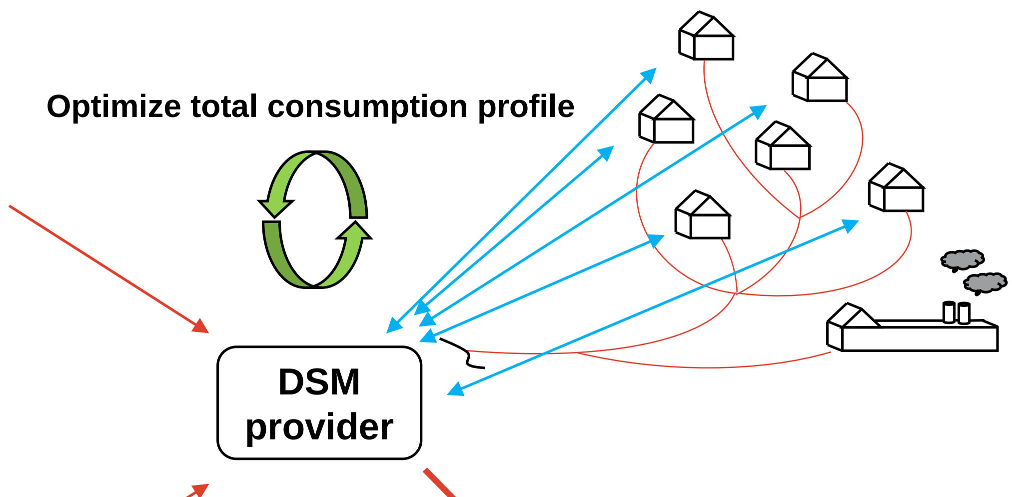
1. fixed power consumption



2. outdoor temperature [C]

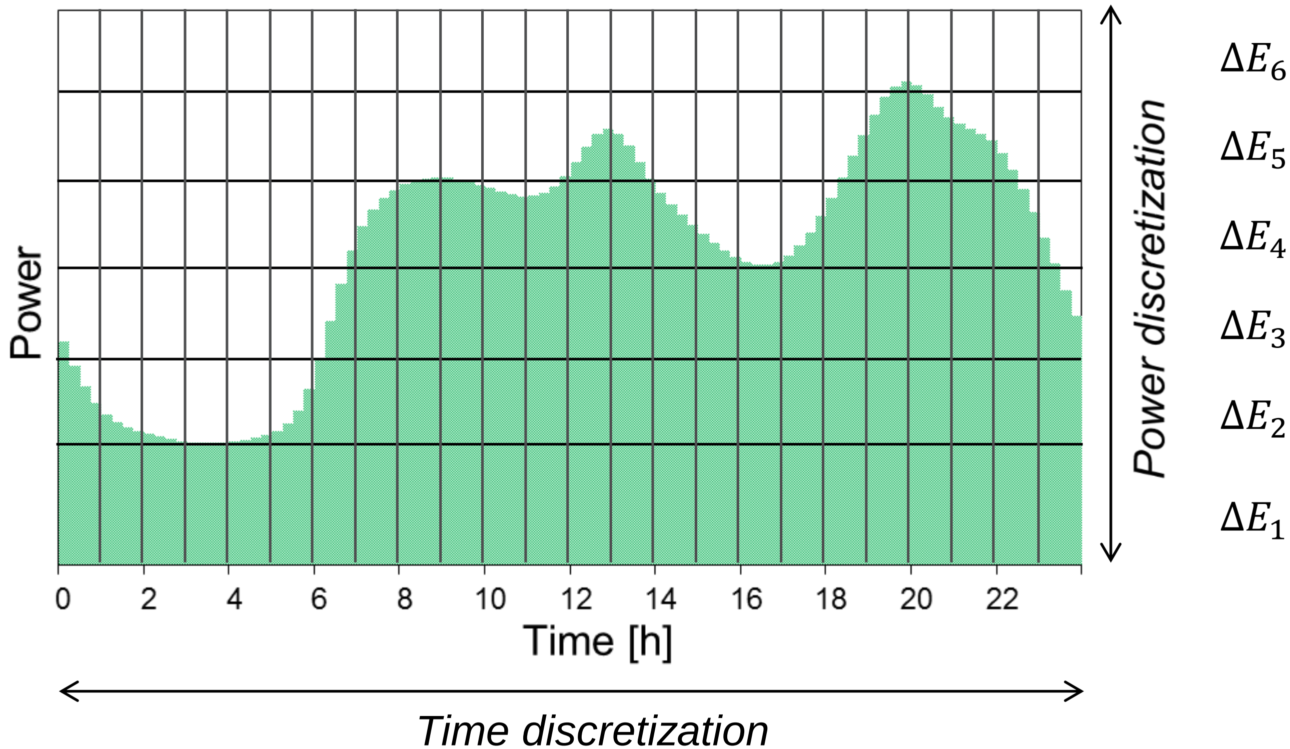


3. house characteristics



Centralized and coordinated smart scheduling of the heat pumps

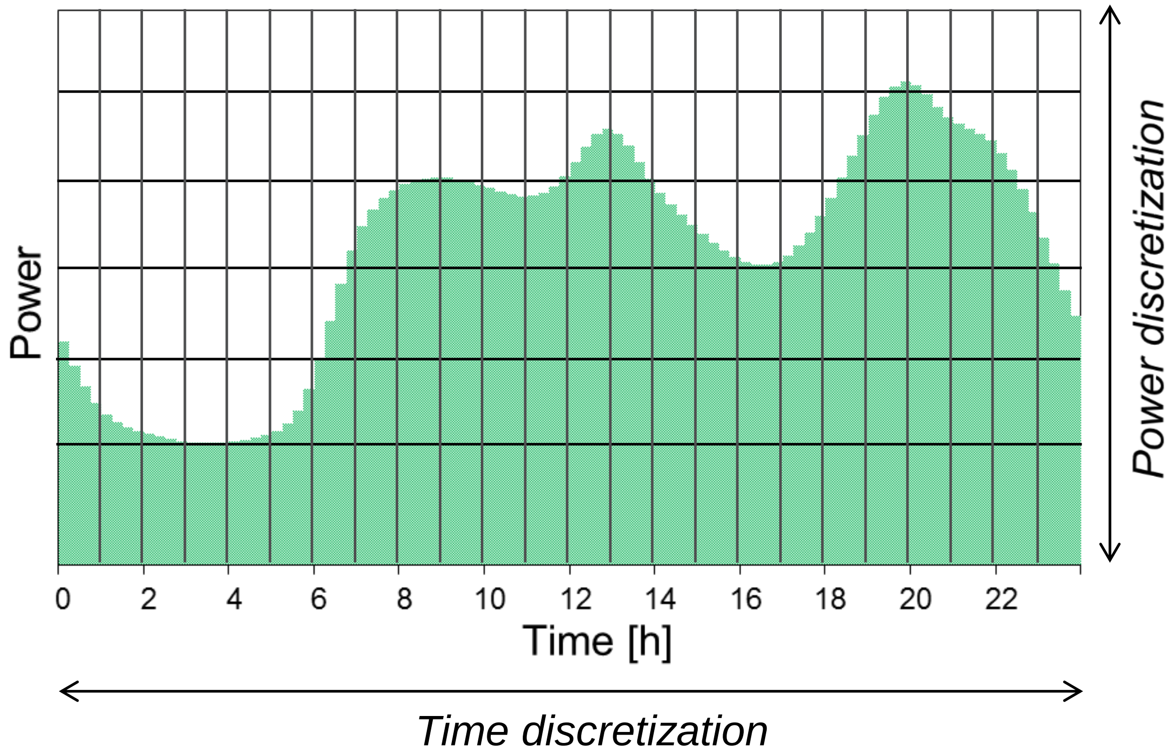
Case 1 - Optimization approach



Energy block constraints: $0 \leq \Delta E_{b,t} \leq \varepsilon_b^{UB}$

$$\sum_b \Delta E_b \geq \varepsilon_t^{GRID} + \sum_h P_{t,h}^{HP} \cdot \Delta t \qquad \forall t$$

Case 1 - Optimization approach



$\Delta E_6 \rightarrow \alpha_6$

$\Delta E_5 \rightarrow \alpha_5$

$\Delta E_4 \rightarrow \alpha_4$

$\Delta E_3 \rightarrow \alpha_3$

$\Delta E_2 \rightarrow \alpha_2$

$\Delta E_1 \rightarrow \alpha_1$

$\alpha_b > \alpha_{b-1}$

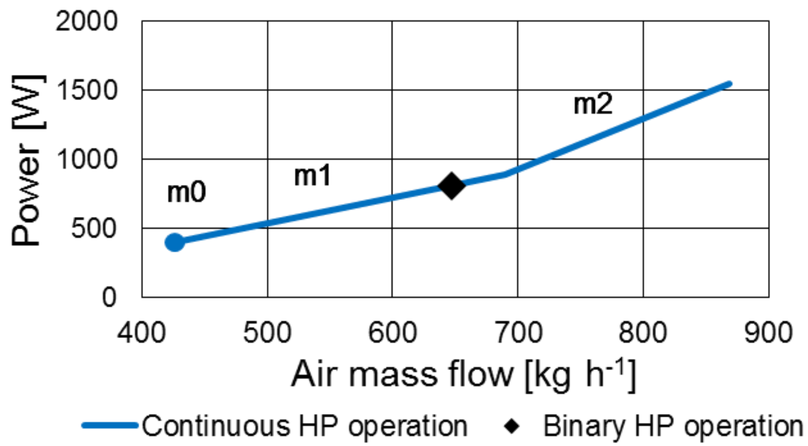
Objective function: minimize $\left(\sum_b \sum_t \alpha_b \, \Delta E_b \right)$

Linear problem, optimization with Mixed Integer Linear Programming

Case 1 - Results evaluation

- Proper operation of the proposed algorithm
  - Check of results at aggregated level
  - Check of the temperature evolution within the houses

- Performance comparison with respect to heat pumps with binary operation



For the binary mode:

$$\text{operating mode } 0: \quad \Delta F_{0,t}^{HP} = y_t \cdot \phi_{m0}$$

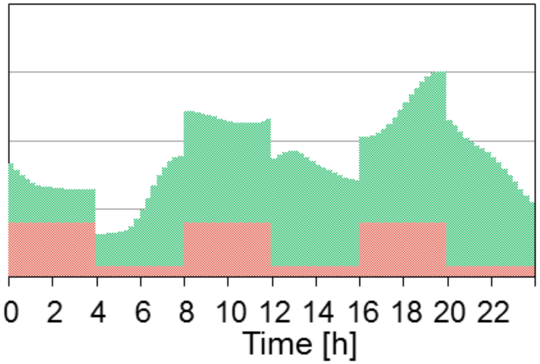
- Performance comparison with respect to case without DSM

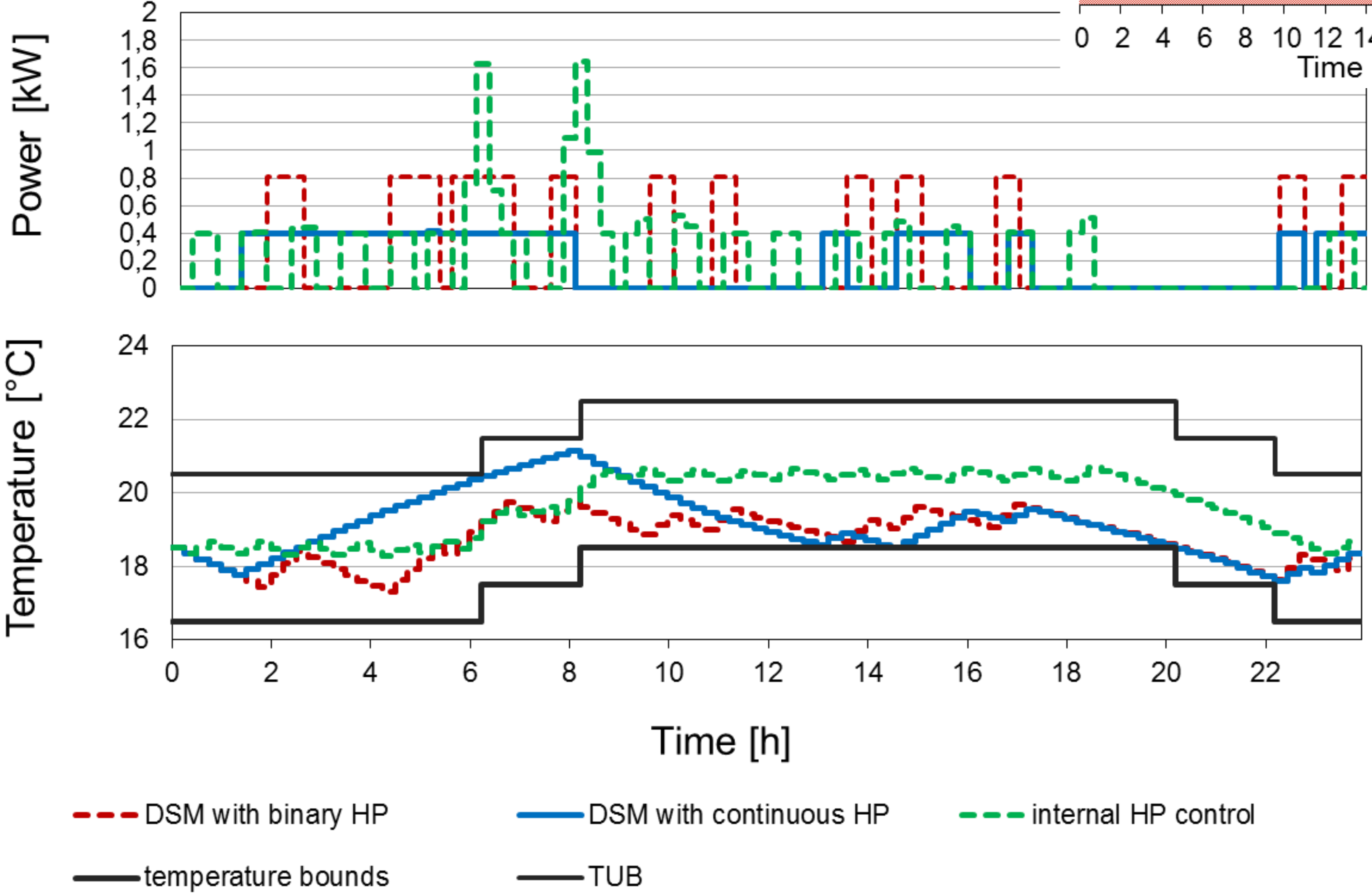
Objective function HP control without DSM:

$$\text{minimize} \sum_t \left(T_t^{IN} - T_t^{ref}\right)^2 \quad \forall h$$

Case 1 - Simulation results 1st scenario

- 60 houses, all with electric heat pumps, day in May





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Case 1 - Simulation results 1st scenario

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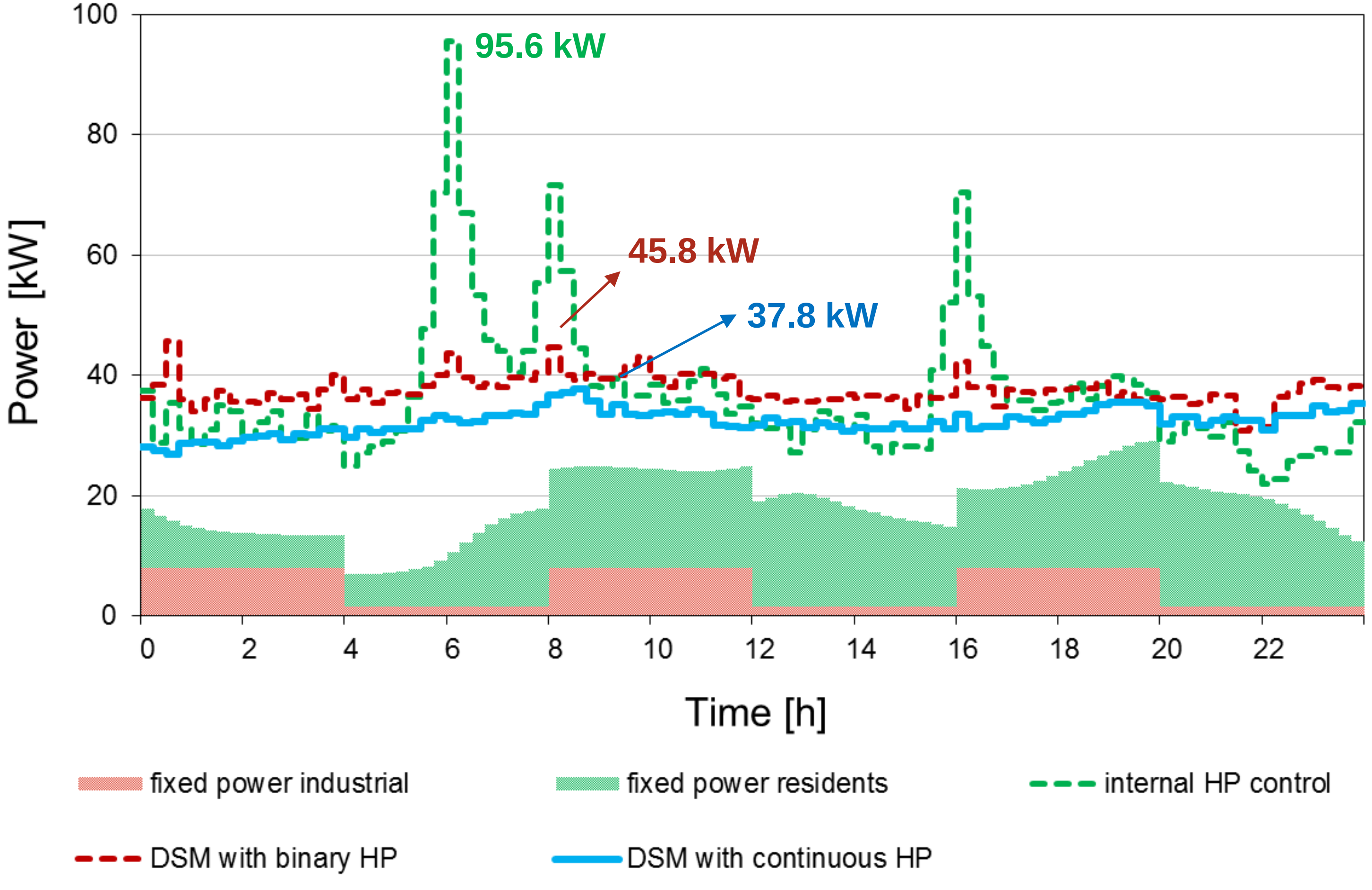
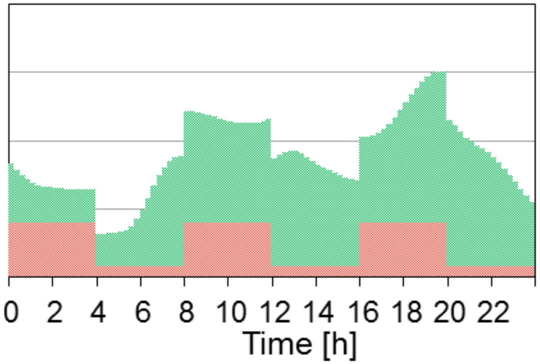
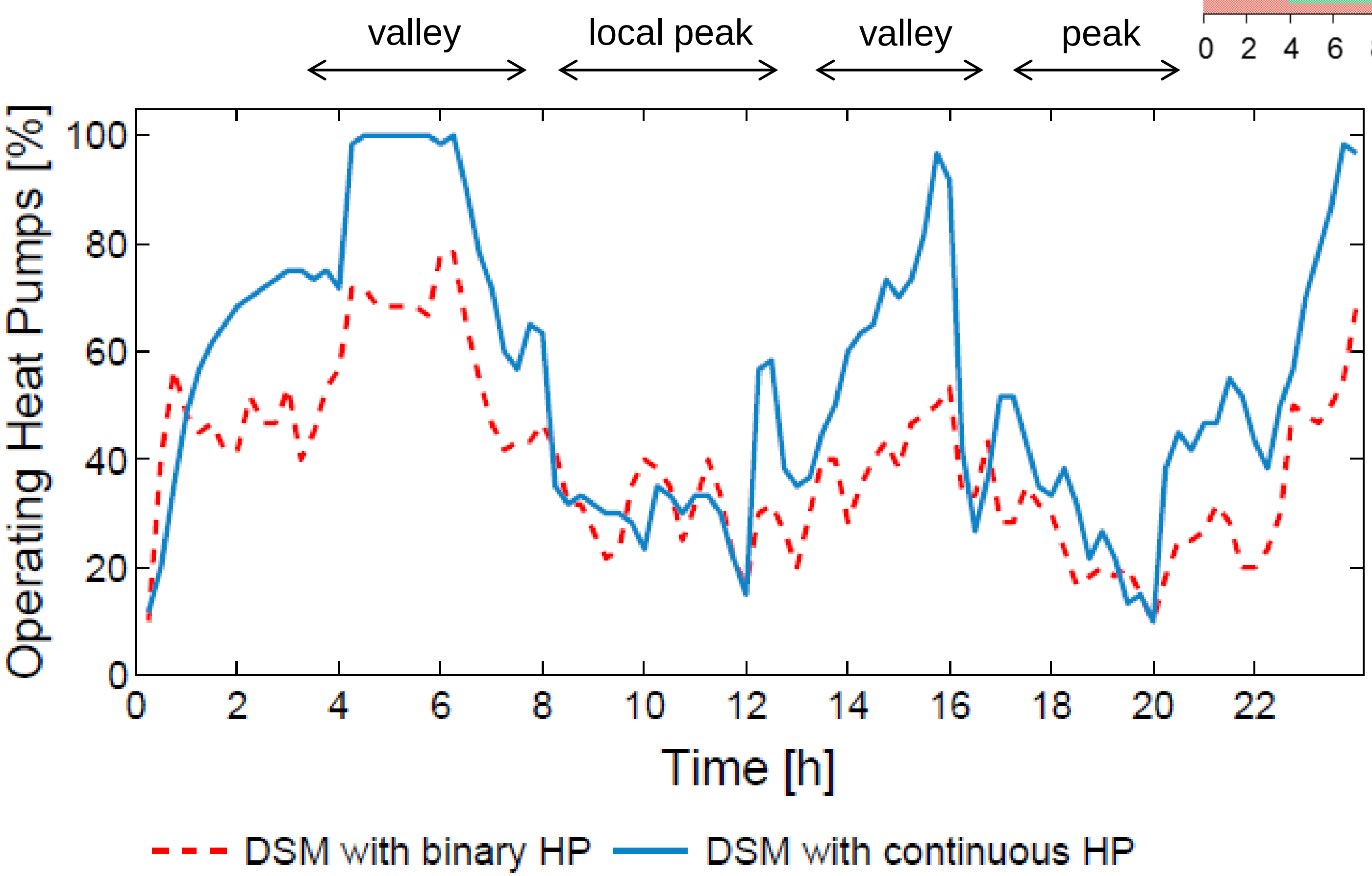


- with the continuous HP operation, almost 75% of heat pump consumption is reallocated during the peak time

Case 1 - Simulation results 2nd scenario

- 240 houses, 60 have electric heat pumps, day in May

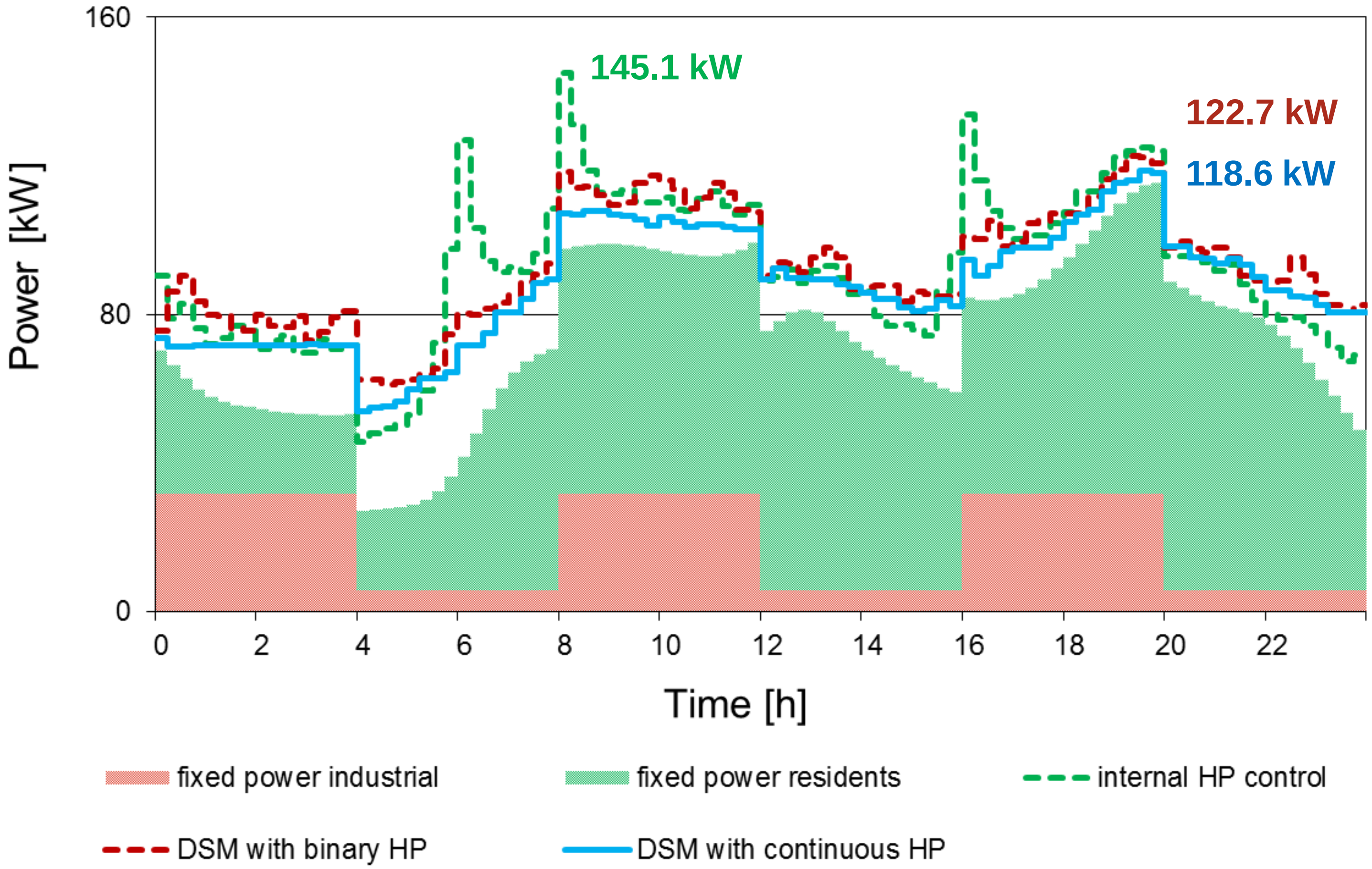




- Energy saving with the continuous HP operation: more than 30%

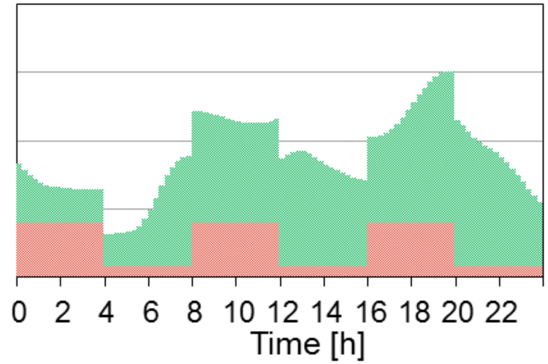
Case 1 - Simulation results 2nd scenario

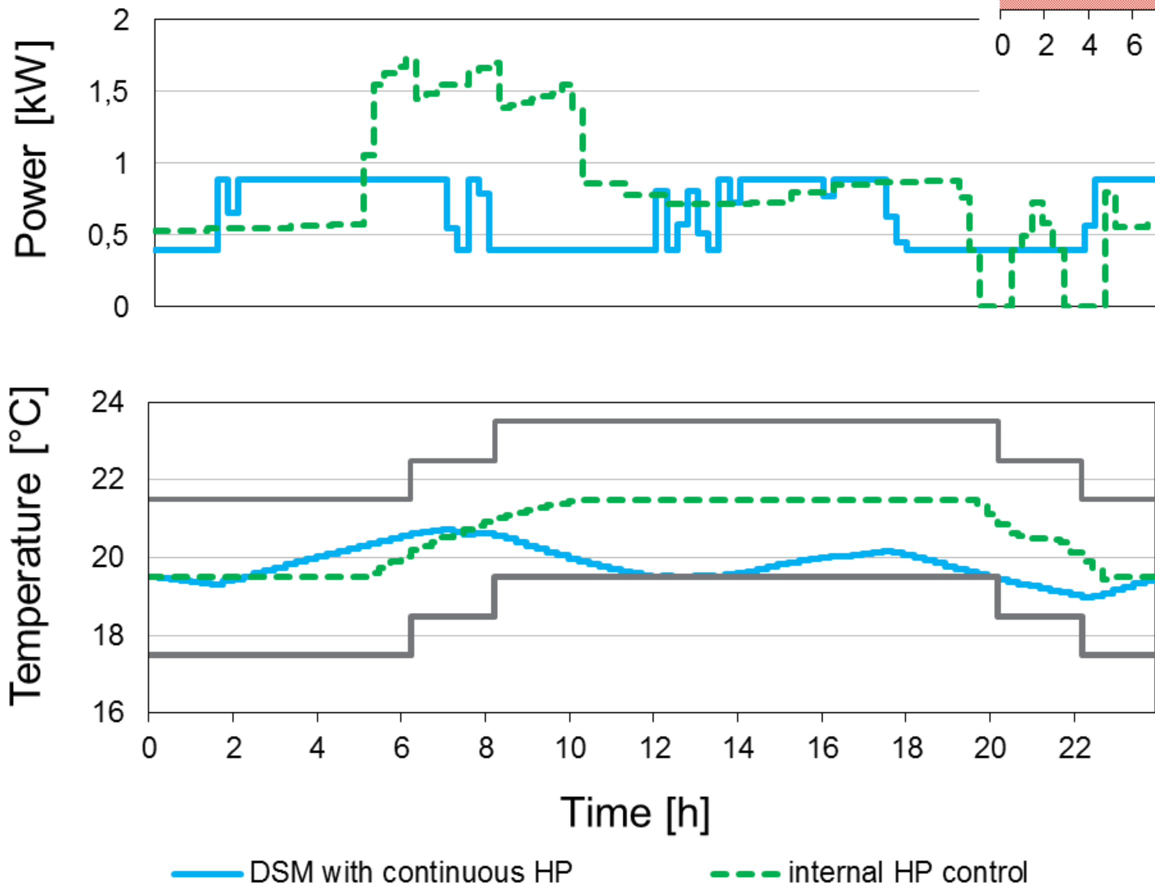
- 240 houses, 60 have electric heat pumps, day in May



Case 1 - Simulation results 3rd scenario

- 240 houses, 60 have electric heat pumps, day in Decembe

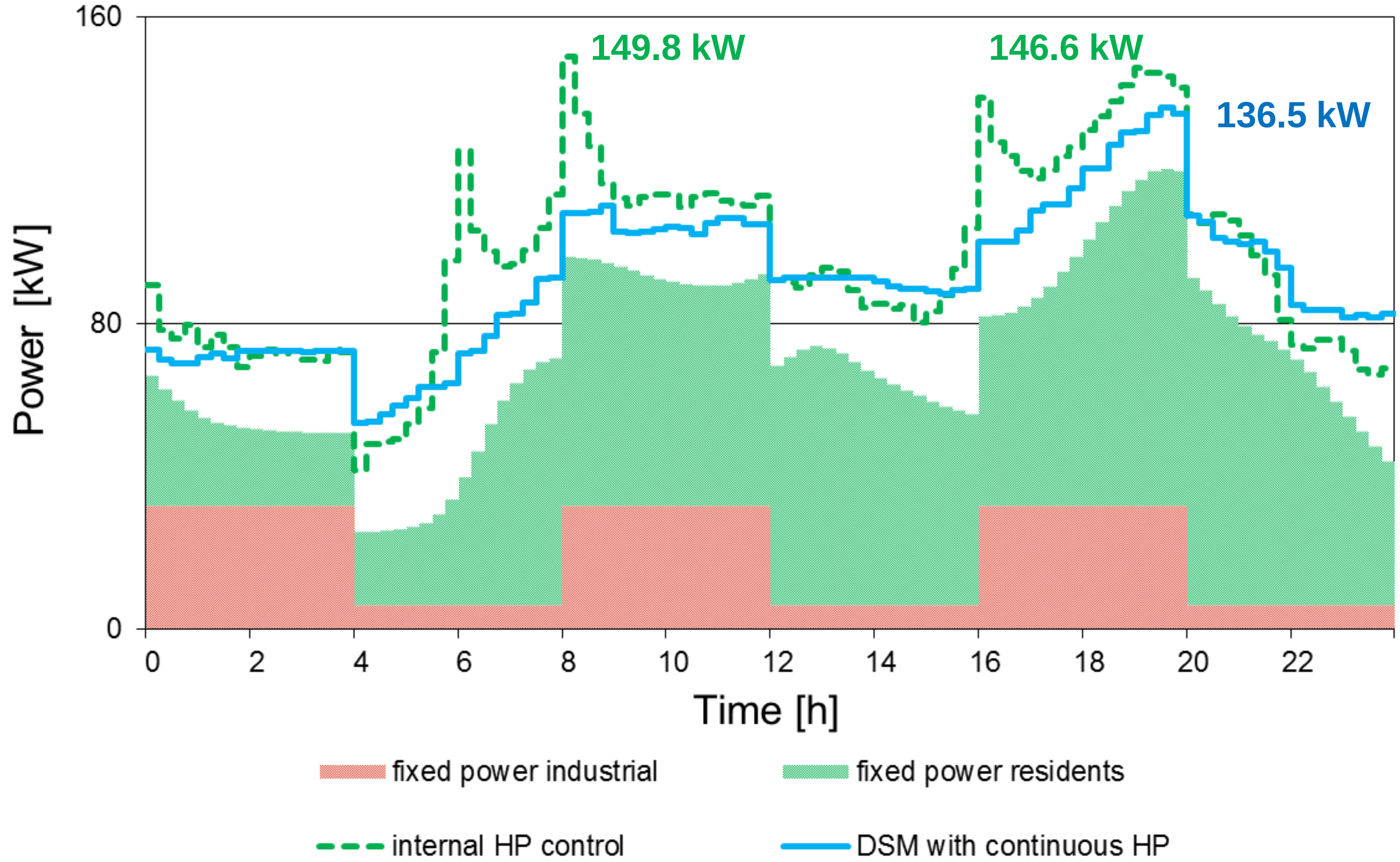




- Continuous HP: 5 houses with HP always ON; 13 houses with HP ON for 23 hours

Case 1 - Simulation results 3rd scenario

- 240 houses, 60 have electric heat pumps, day in December



- Binary operation mode does not converge in this scenario!!

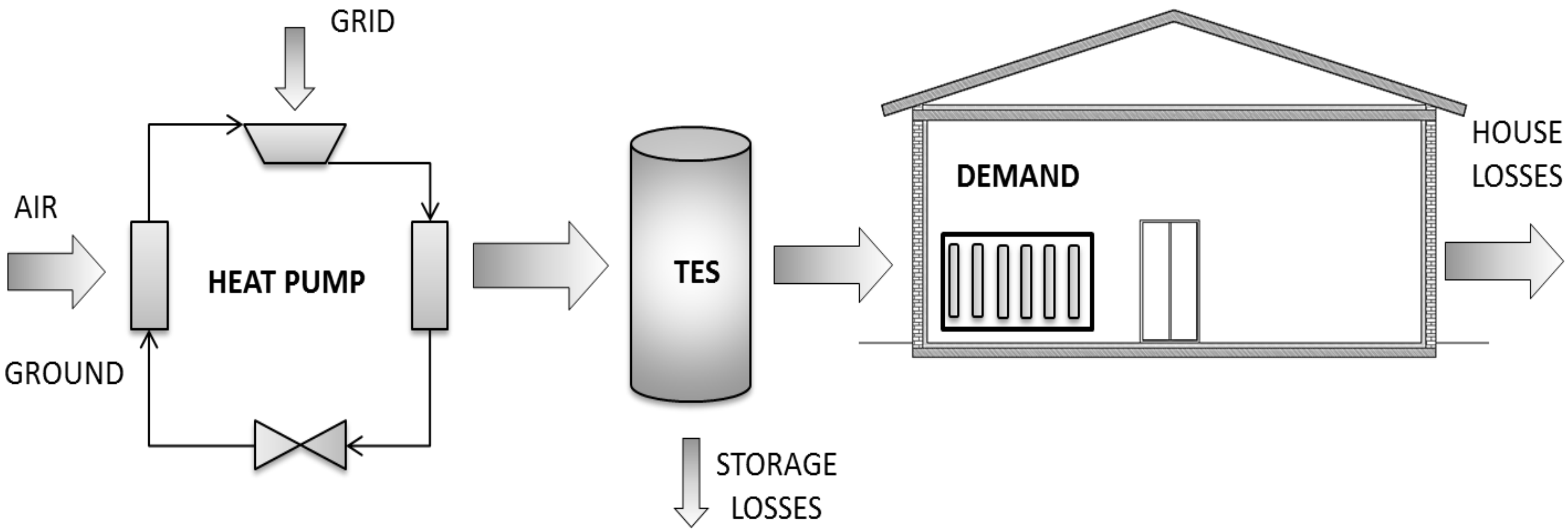
Case study 2 –

Using thermal energy storage to provide flexibility

Results from:

[2] M. Pau, F. Cunsolo, J. Vivian, F. Ponci, A. Monti, "Optimal Scheduling of Electric Heat Pumps Combined with Thermal Storage for Power Peak Shaving"**,** in *2018 IEEE International Conference on Environment and Electrical Engineering and 2018 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe),* 1-6, 2018, Palermo, Italy

Case 2 – Overview electro-thermal components

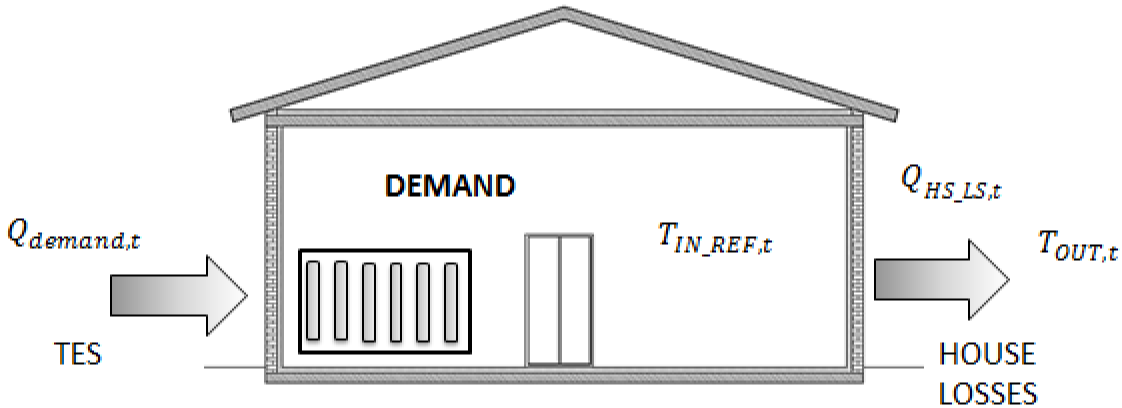


HEAT PUMP → HEAT GENERATION

THERMAL STORAGE → BUFFER

BUILDING → HEAT DEMAND

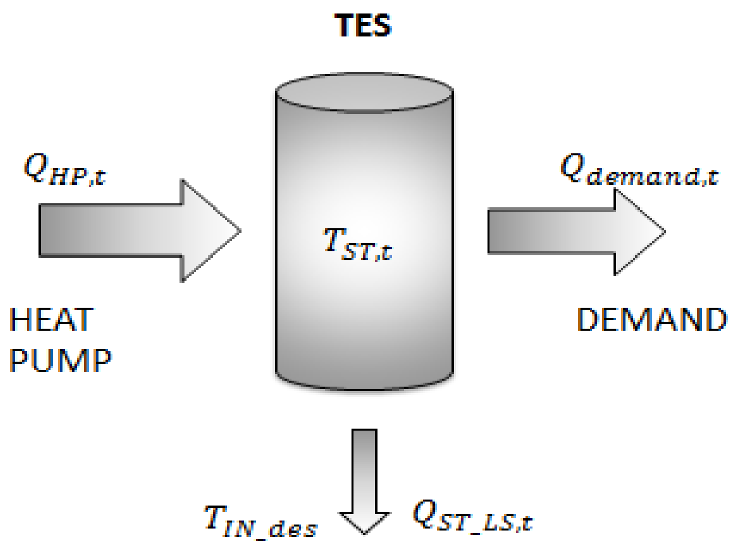
Case 2 - Building thermal model



- Building thermal parameters
- Occupancy pattern
- Outdoor temperature
- Desired indoor temperature

→ 5R1C Model (ISO 13790) → HEAT DEMAND

Case 2 - Storage thermal model



Energy balance:

$$T_{ST,t} = T_{ST,t-1} + \frac{\Delta t}{m_{ST} \cdot c_w}\left(Q_{HP,t-1} - Q_{demand,t-1} - Q_{ST\_LS,t-1}\right) \qquad [°C]$$

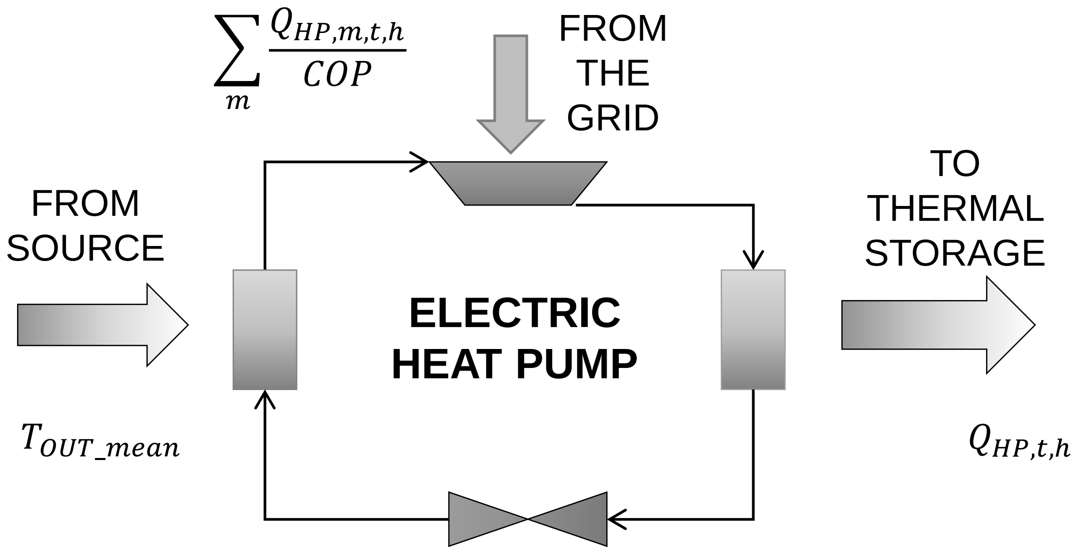
Energy losses:

$$Q_{ST\_LS,t} = k_{ST} \cdot \left(T_{ST,t} - T_{IN\_des}\right) \qquad [W]$$

Temperature constraints:

$$T_{ST,min} < T_{ST,t} < T_{ST,max} \qquad [°C]$$

Case 2 - Heat Pump model



Heat pump operation:

$$Q_{0,t}^{HP} = y_t^{HP} \cdot Q_{LB,t}^{HP}$$

$$0 \leq \Delta Q_t^{HP} \leq y_t^{HP} \cdot (Q_{UB,t}^{HP} - Q_{LB,t}^{HP})$$

$$Q_t^{HP} = Q_{0,t}^{HP} + \Delta Q_t^{HP}$$

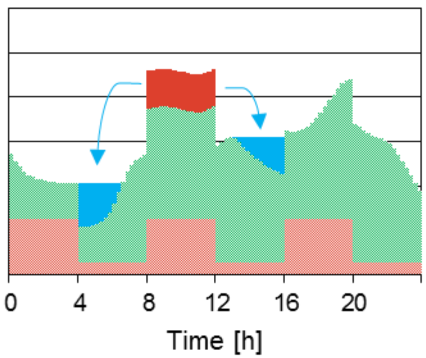
Heat pump power consumption:

$$P_t^{HP} = \frac{Q_t^{HP}}{COP}$$

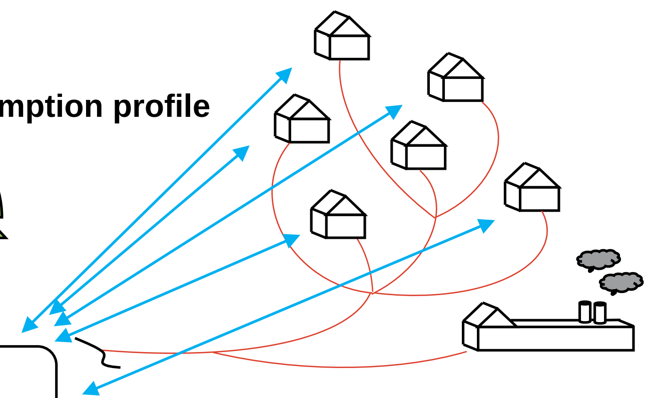
Case 2 - Day ahead scheduling of heat pumps

Forecasts of

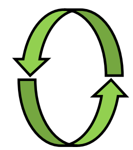
1 fixed power consumption



3 house characteristics

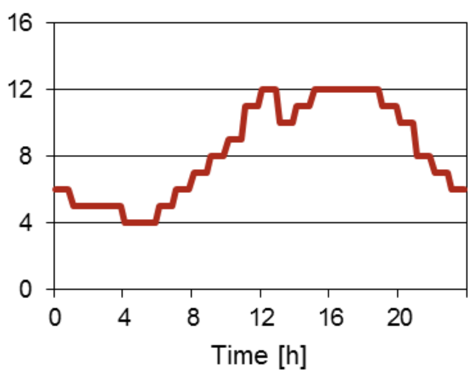


Optimize total consumption profile



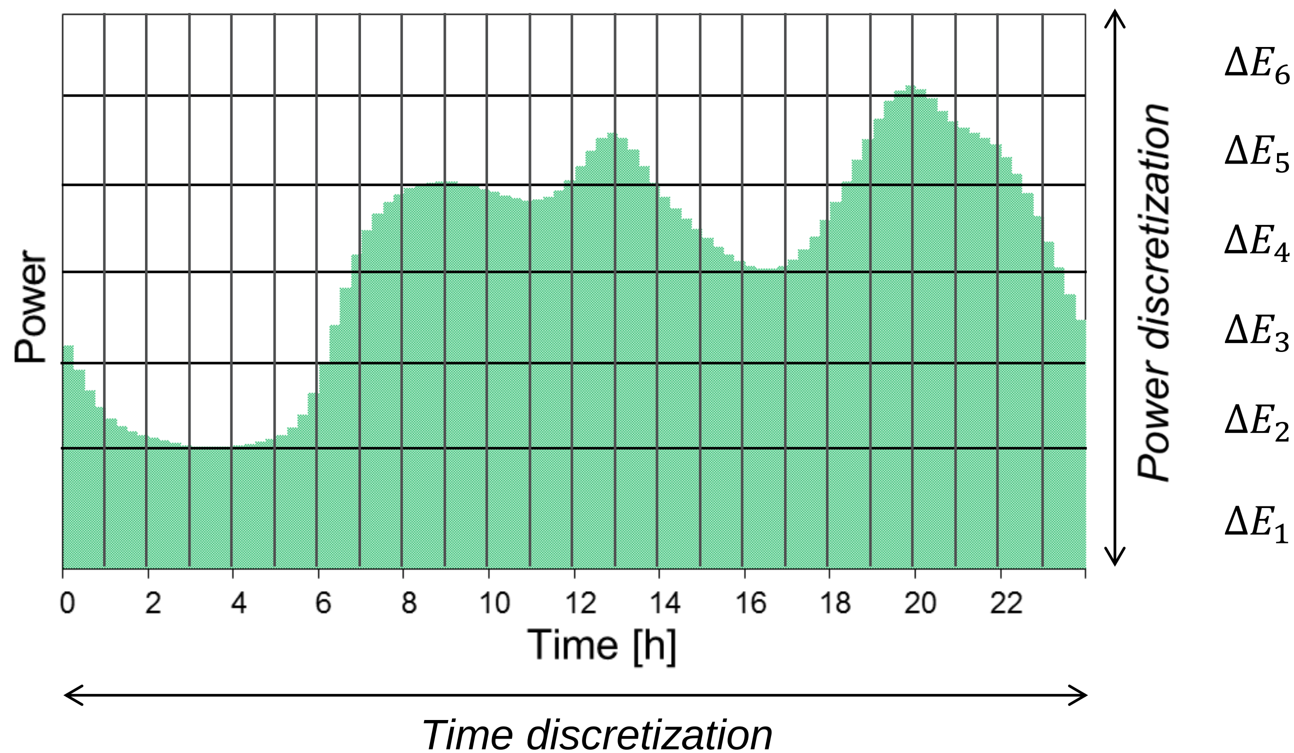
DSM provider

2 outdoor temperature [C]



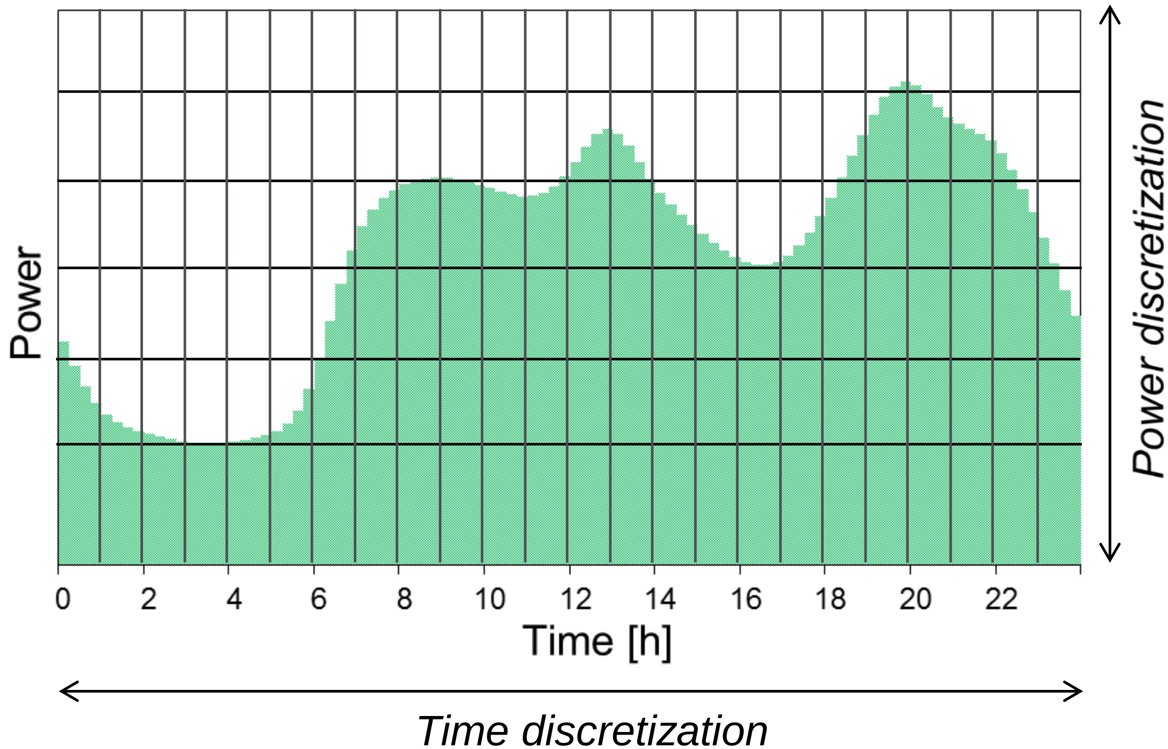
Centralized and coordinated smart scheduling of the heat pumps

Case 2 - Optimization approach



Energy block constraints: $0 \leq \Delta E_{b,t} \leq \varepsilon_b^{UB}$

$$\sum_b \Delta E_b \geq \varepsilon_t^{GRID} + \sum_h P_{t,h}^{HP} \cdot \Delta t \qquad \forall t$$



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$\Delta E_2 \rightarrow \alpha_2$

$\Delta E_1 \rightarrow \alpha_1$

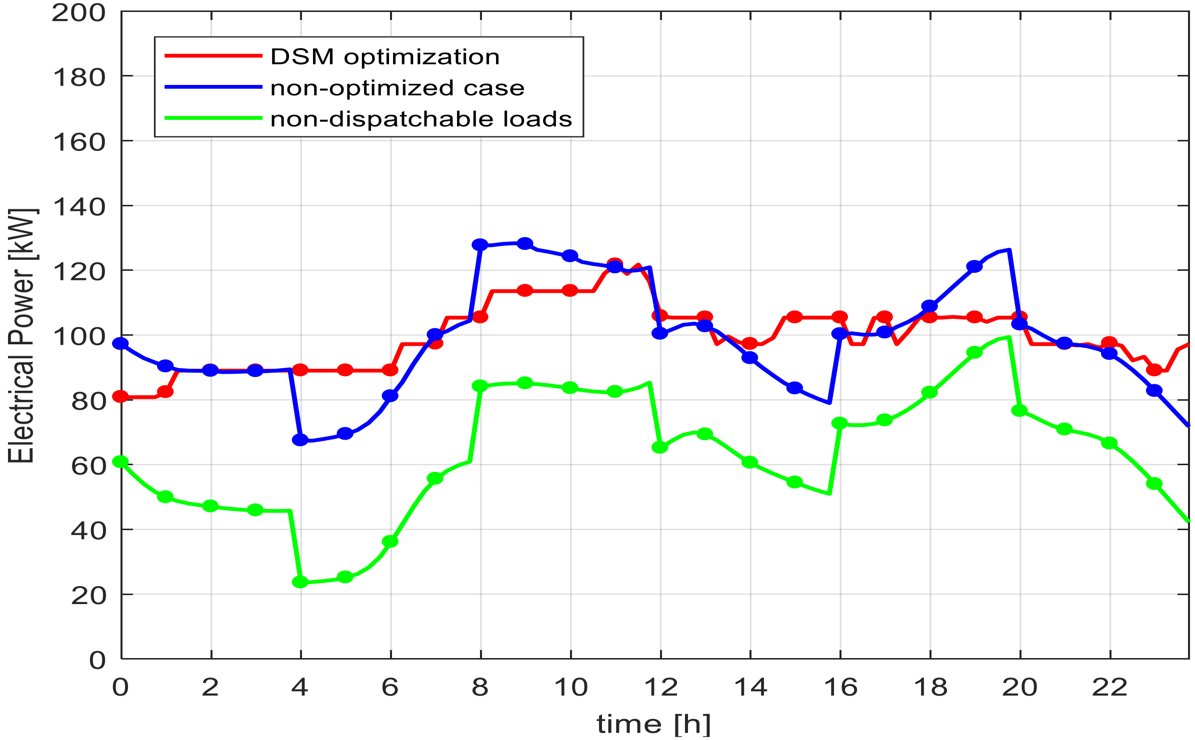
$\alpha_b > \alpha_{b-1}$

Objective function: minimize $\left(\sum_b \sum_t \alpha_b \, \Delta E_b \right)$

Linear problem, optimization with Mixed Integer Linear Programming

Case 2 - Simulation results: May temperature

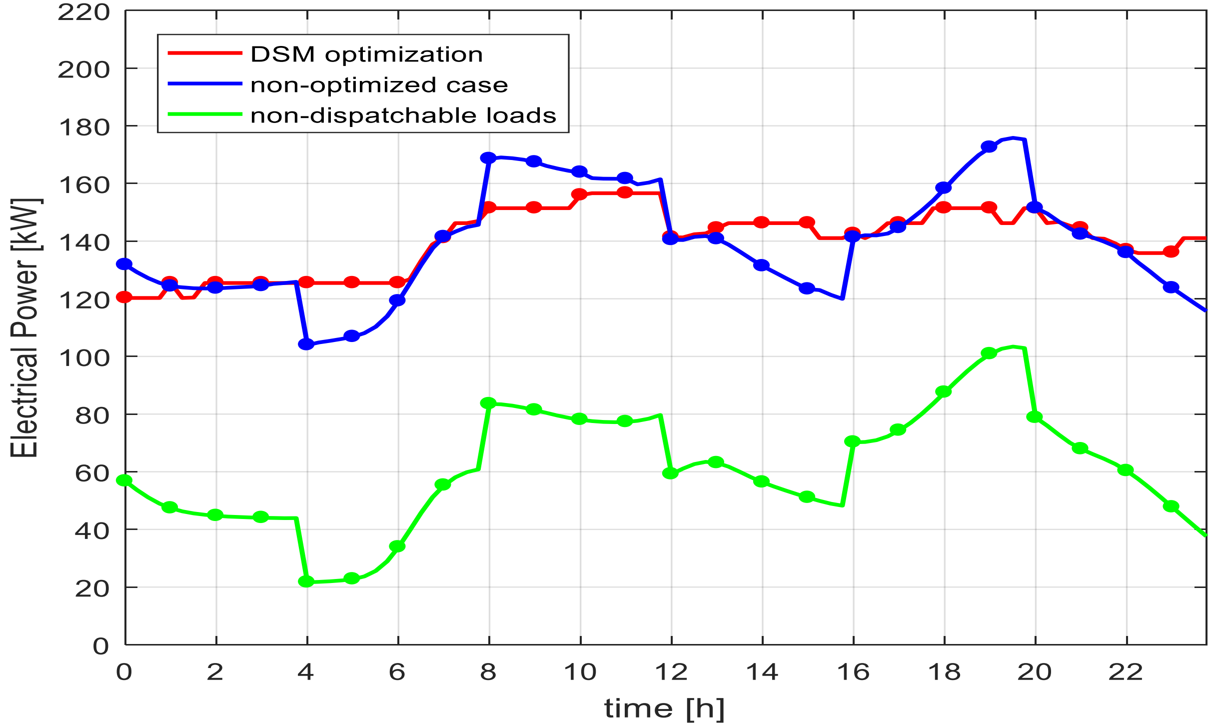
- 100 houses, 20 have electric heat pumps, day in May



Case	Load factor [%]	Maximum Gap [kW]	Power peak [kW]
Inflexible power	63.7	75.8	99.4
EHP with no optimization	76.8	61.0	128.3
EHP with optimization	81.8	40.9	121.7

Case 2 - Simulation results: December temperature

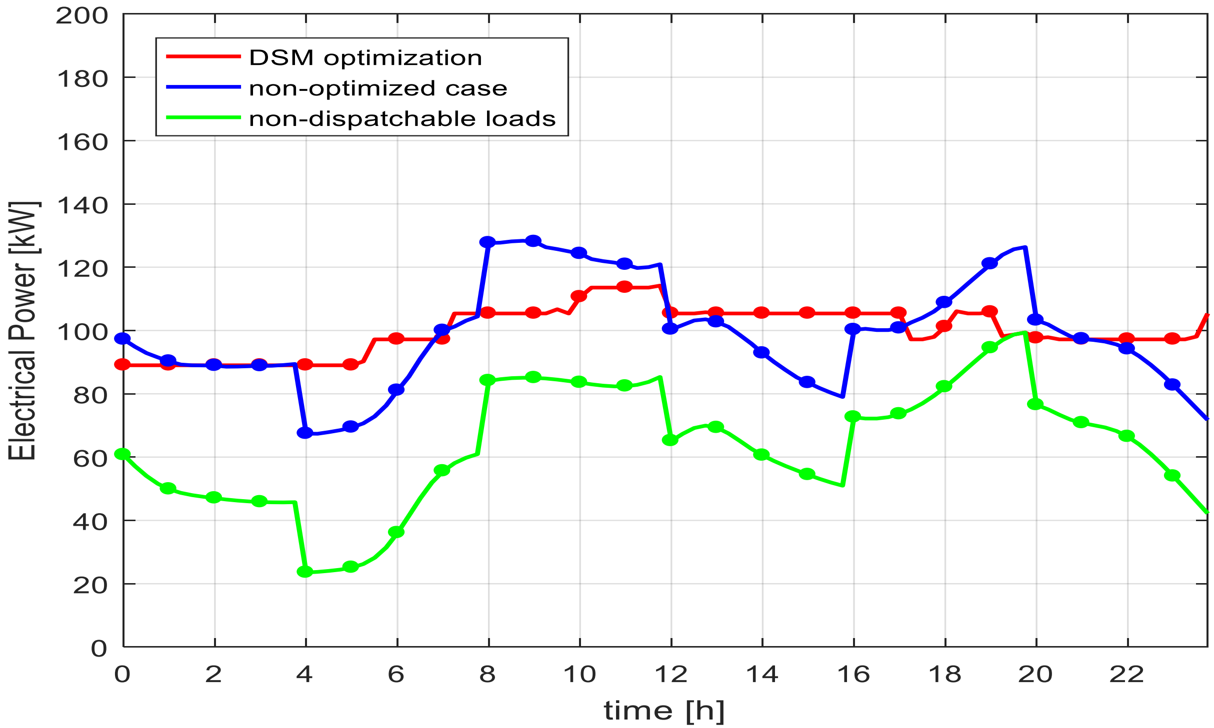
- 100 houses, 20 have electric heat pumps, day in December



Case	Load factor [%]	Maximum Gap [kW]	Power peak [kW]
Inflexible power	63.7	75.8	99.4
EHP with no optimization	79.2	71.9	175.8
EHP with optimization	89.6	36.3	156.6

Case 2 - Simulation results: storage size variation

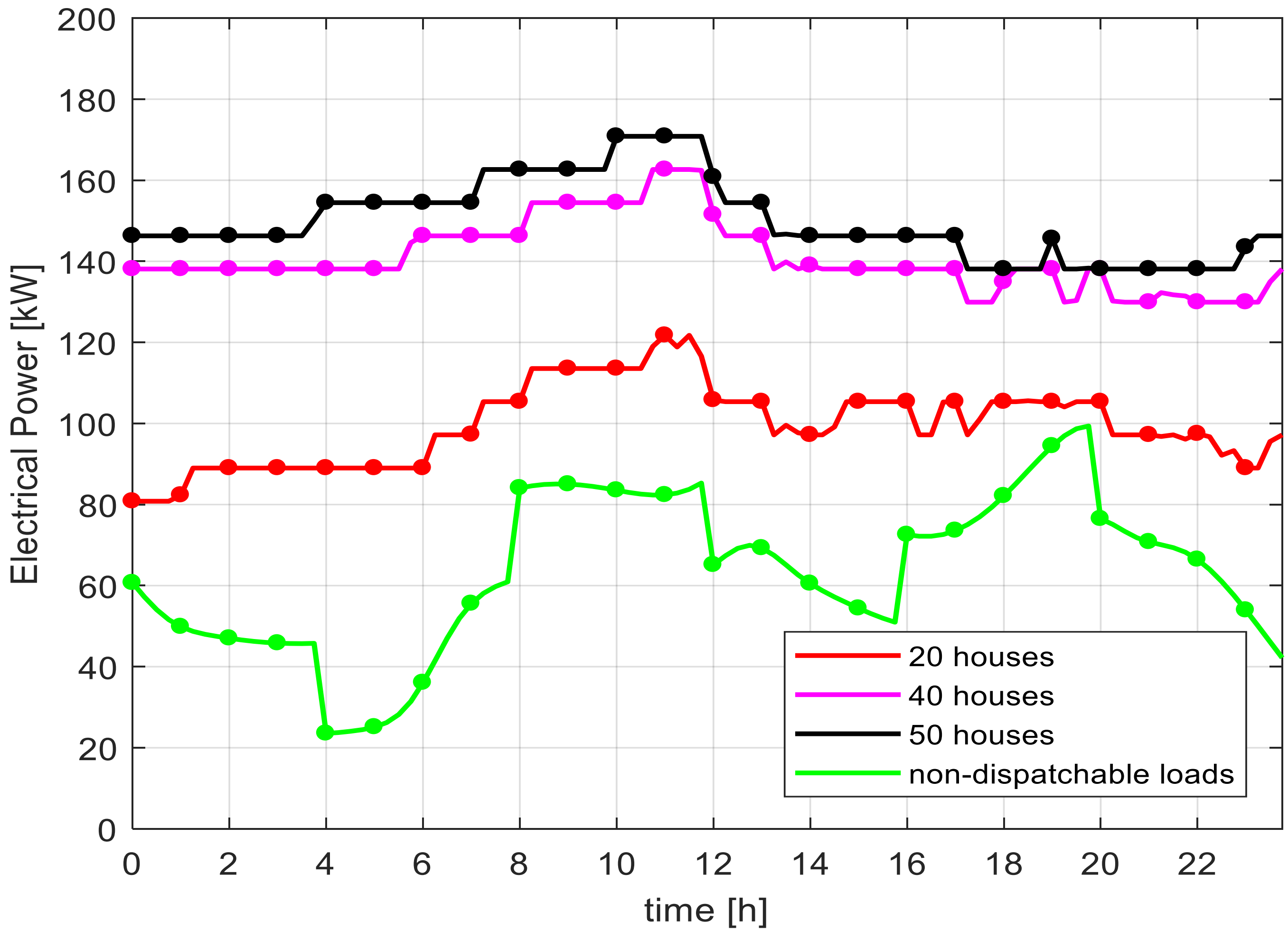
- 100 houses, 20 have electric heat pumps, day in May



Case	Load factor [%]	Maximum Gap [kW]	Power peak [kW]
Inflexible power	63.7	75.8	99.4
EHP with no optimization	76.8	61.0	128.3
EHP with optimization (25l/kW)	81.8	40.9	121.7
EHP with optimization (40l/kW)	87.6	25.2	114.1

Case 2 - Simulation results: number of houses variation

- 100 houses, 20 have electric heat pumps, day in May



Future scenarios and challenges

Outgoing and future activities in ACS Institute

- Ongoing activities
  - Use of electric heat pumps for quasi real-time demand response
  - Implementation of a distributed version of the optimization to reduce computation time and improve optimization results
- Future work
  - Impact of uncertainties on optimization results
  - Inclusion of domestic hot water demand in the optimization model
  - Testing of more detailed thermal models via distributed optimization framework
  - Definition strategies for on-line adaptation of the scheduling in case of significant deviations for the forecast thermal profile

Challenges for heat pumps management

- Technical challenges
  - Still poor level of observability for most of the distribution grids
  - Remote controllability for the electric heat pumps
  - Availability of accurate models for the buildings
- Regulatory/market challenges
  - DSOs are not motivated to push in this direction (investments on copper are still the best solution in case of problems)
  - Despite general interest in DSM and DR, there is no clear regulatory framework supporting their development
  - Who is offering the DSM service (DSO, aggregator, retailers, other?) and how to define business interfaces while preserving the technical objectives?
  - Which compensation scheme should apply for customers offering flexibility?
  - Differences among EU countries could represent an additional obstacle to diffusion of DSM schemes
- Society challenges
  - Acceptance of customers to be involved in DSM programs

Conclusions

- Smart management of EHPs could be a solution to deal with potential issues emerging at electric distribution level and to achieve a much more efficient operation of the grid
- Technical solutions already exist or can be developed tailored to specific scenarios in order to give the expected technical benefits
- Main issue is to determine how to combine technical benefits with business opportunities for the different parts involved in the DSM scheme
- Regulatory framework needs important updates to motivate all stakeholders to look more concretely to DSM solutions

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