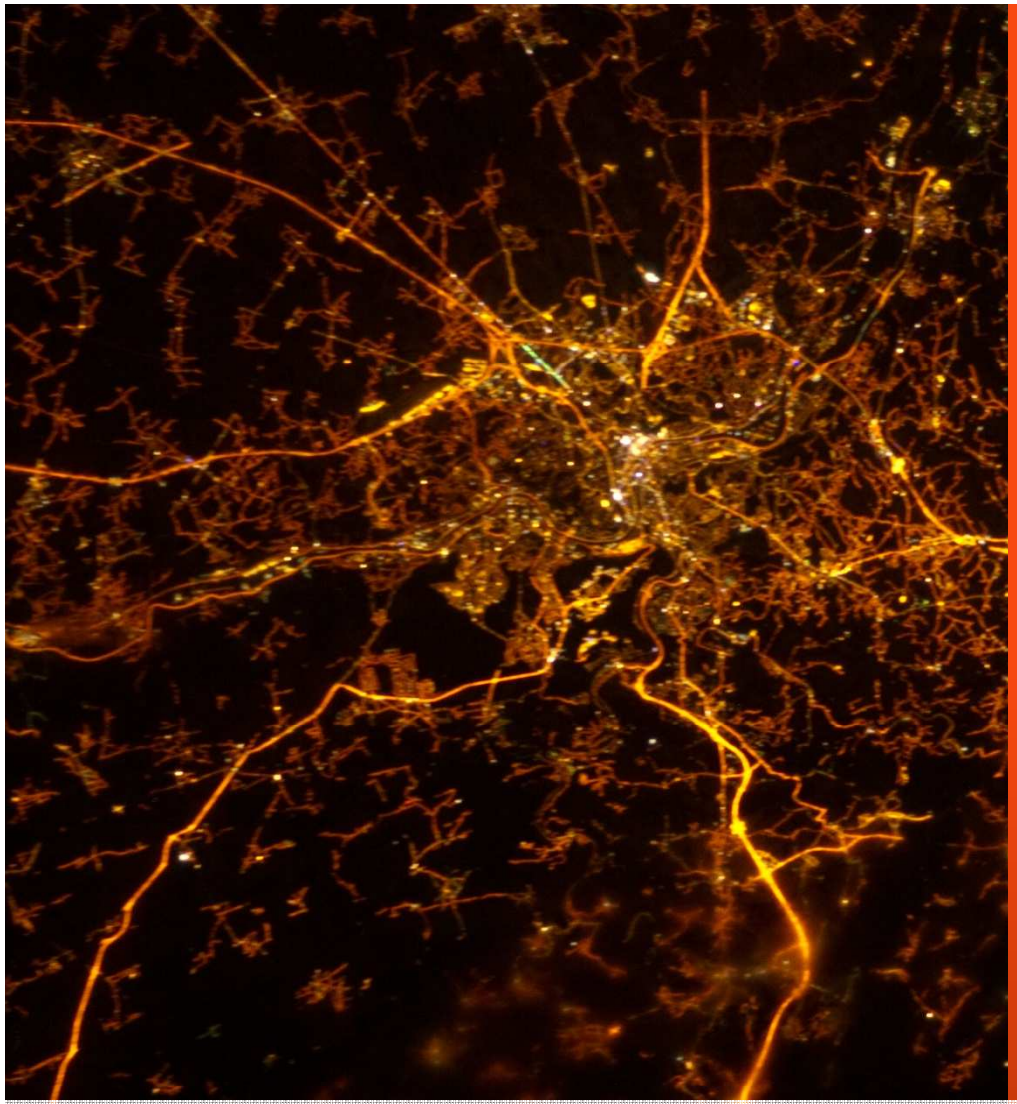

Load modulation strategies of residential heat pumps for demand-response programs with different thermal storage options

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UNIVERSITY of LIÈGE

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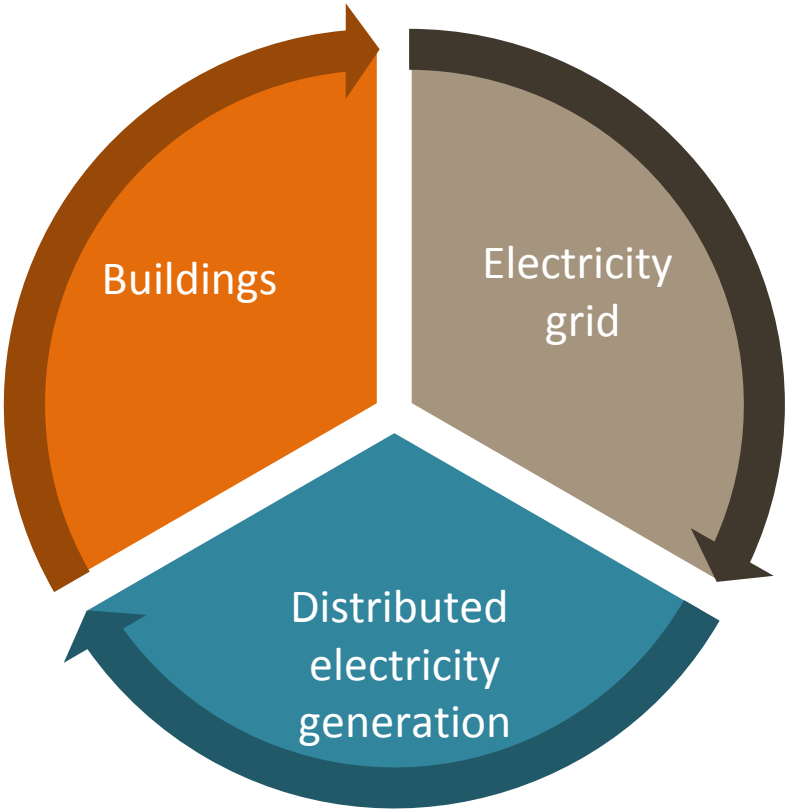
Introduction

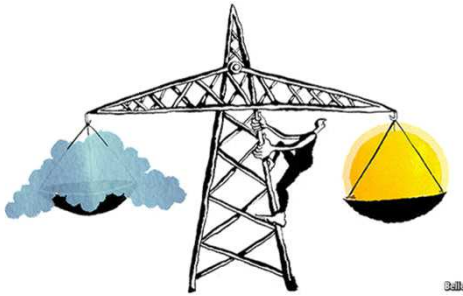
Electrification
- Heat pumps
- Air-conditioning
- Electric vehicles

Active Demand Response (ADR)

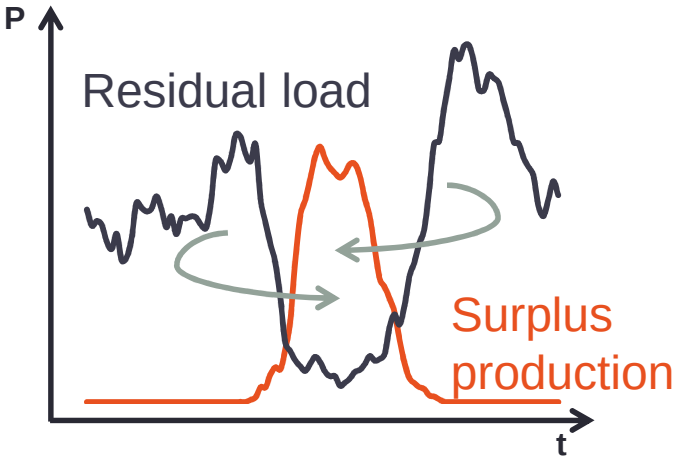


Constraints
- Voltage
- Power

- Intermittent production
- Grid balancing



Introduction



Suitable load modulation strategy/incentive?

Building stock

Heterogeneous set

Best thermal storage option?

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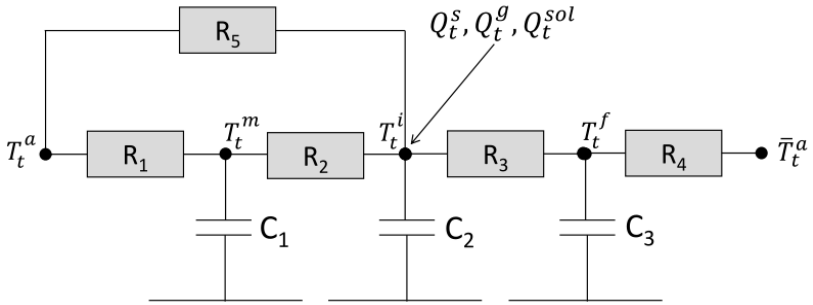
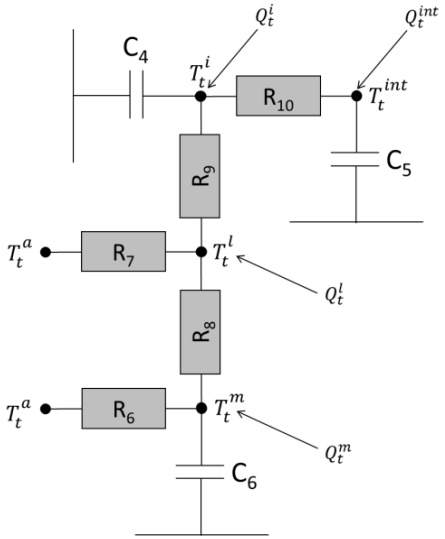
Thermal models and storage options

- Freestanding buildings

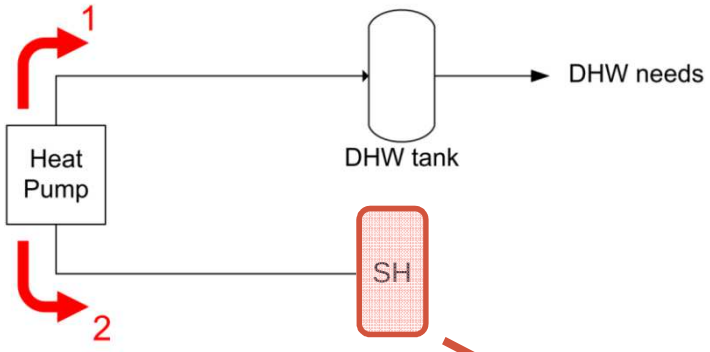
Year of construction	N# of floors	Heated volume [m³]	Ground floor area [m²]	Average U value [W/m²K]	Design heat demand @ - 10°C [kW]	Nominal HP temperatures A/W [°C]	Auxiliary heater [kW]
2007-2014 (A)	2	457	75	0.31	6.5	7/45	3
1991-2006 (B)	2	457	75	0.46	8.0	7/45	3
1971-1990 (C)	1	423	148.5	1.24	17.0	7/65	5
1971-1990 (D) Retrofit	1	423	148.5	0.77	12.0	7/45	5

- Grey-box models





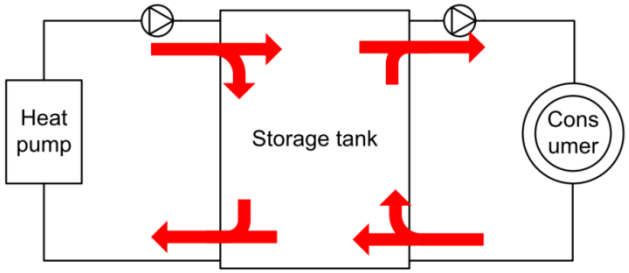
Thermal models and storage options



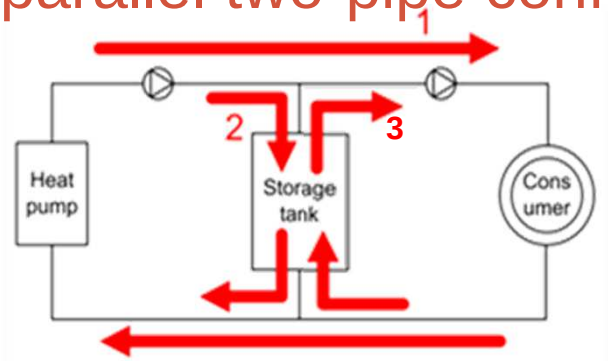
DHW tank

+

- Storage in the building envelope
- SH tank: parallel four-pipe configuration



- SH tank : parallel two-pipe configuration



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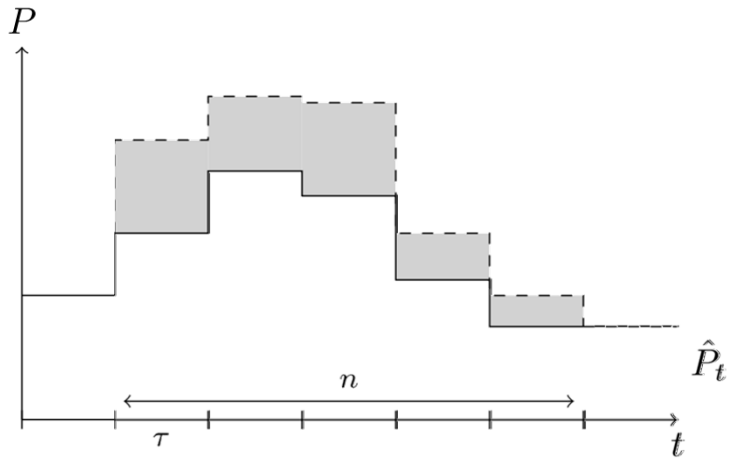
Load modulation strategies

- Define reference consumption = baseline
  - Cost-optimal
  - Minimum energy consumption
  - Other

- From the baseline, perform a load modulation to increase the consumption over a time interval



- To provide a flexibility service
  - load following
  - secondary reserve

- To increase self consumption

Load modulation strategies

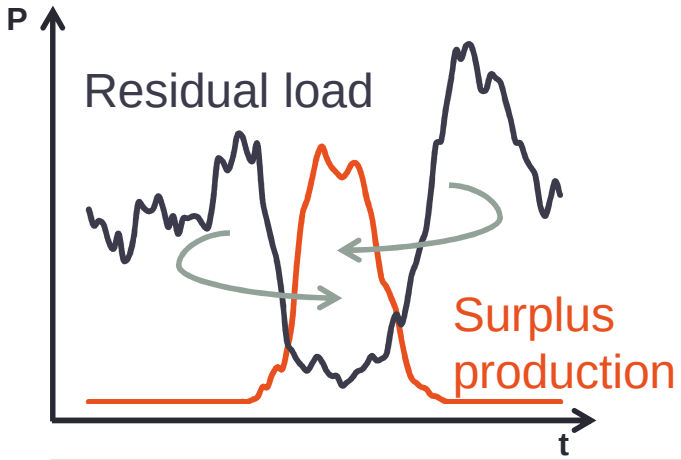
- Thermal state transition model and constraints summarized by

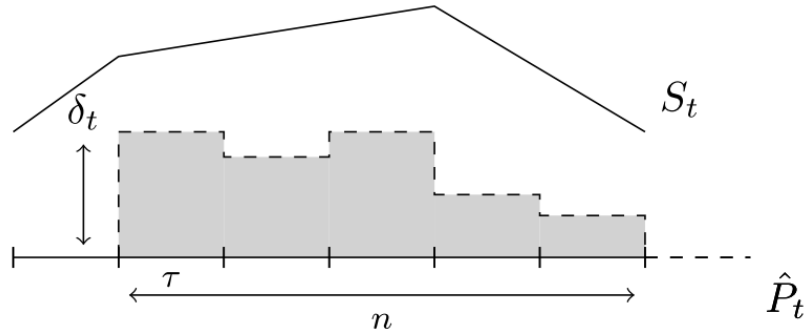
$$\boldsymbol{x}_{t+1} = f(\boldsymbol{x}_t, \boldsymbol{u}_t, \boldsymbol{w}_t)$$
$$x_t^{min} \leq x_t \leq x_t^{max}$$
$$u_{i,t}^{min} \leq u_t \leq u_{i,t}^{max}$$
$$u_{i,t} + u_{j,t} \leq \max(u_{i,t}, u_{j,t})$$

Where

- $\boldsymbol{x}_t$ state variables, i.e. temperatures
- $\boldsymbol{w}_t$ model disturbances, i.e.: climate conditions, heat gains,…
- $\boldsymbol{u}_t$ control variables: heat pump power

Load modulation strategies





Upward modulation (ADR#1)

Max I_{mod}

s.t.

$R \geq \delta_t \geq I_{\text{mod}} \quad t \in [\tau, \tau + n - 1]$

state constraints

power limitations

Self-consumption (ADR#2)

Min

$$\sum_{t=\tau}^{\tau+n-1} \left(\max(\delta_t - S_t, 0) + \min(\delta_t - S_t, 0) \alpha_{bb,t} \right)$$

<<<

s.t.

state constraints

power limitations

Table of content

Results for a single house

- Load matching for 3 storage options
  - House B with ADR#2

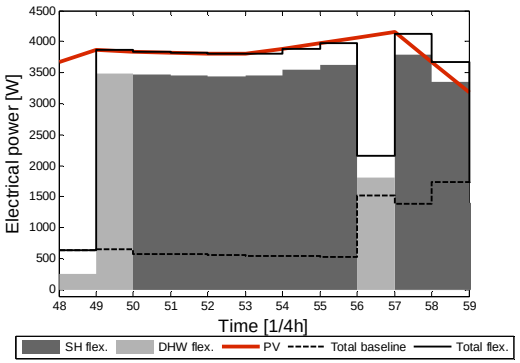
DHW

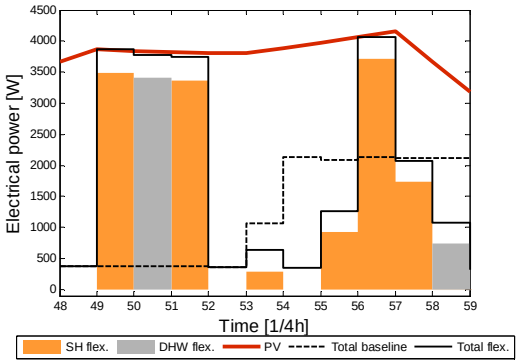
+

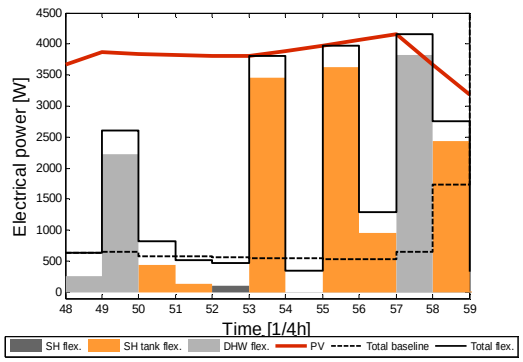
SH

in building structure – in SH tank – in SH tank

direct supply 4-pipe 2-pipe/direct supply



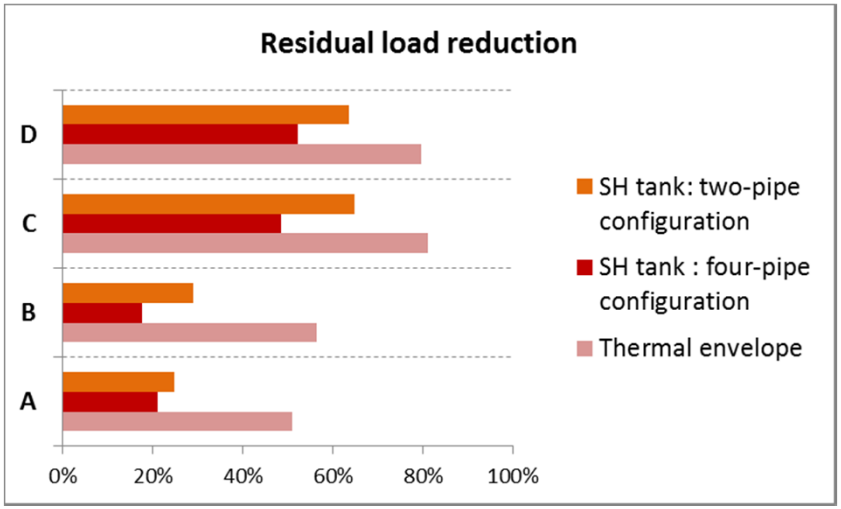




Results - ranking

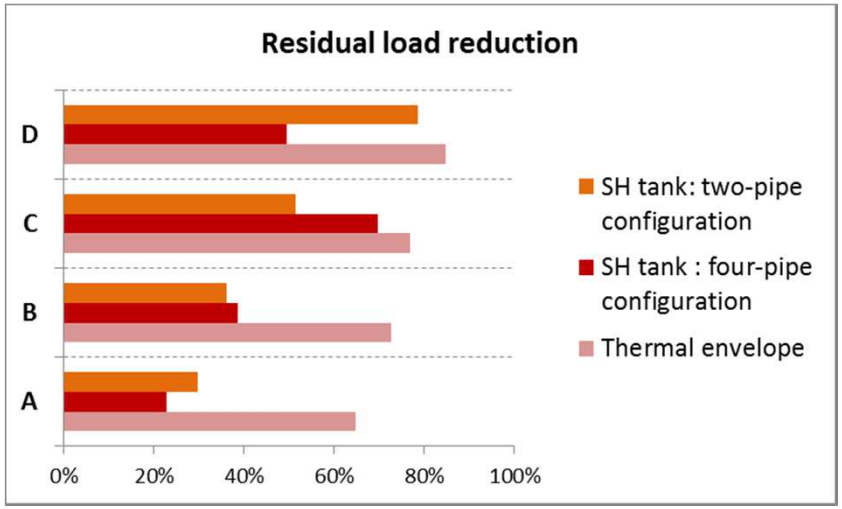
- Selection criterion: residual load

Upward modulation (ADR#1)



1. Thermal envelope
2. SH tank with 2-pipe config.
3. SH tank with 4-pipe config.

Self-consumption (ADR#2)



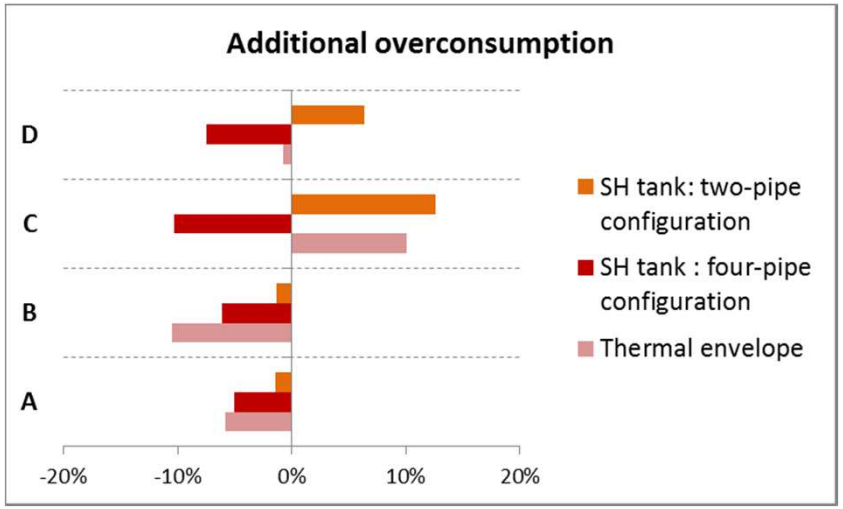
1. Thermal envelope
2. *well-insulated houses*:
   SH tank with 2-pipe config.
   poorly insulated houses:
   SH tank with 4-pipe config.

Results - ranking

- Selection criterion: residual load + additional overconsumption

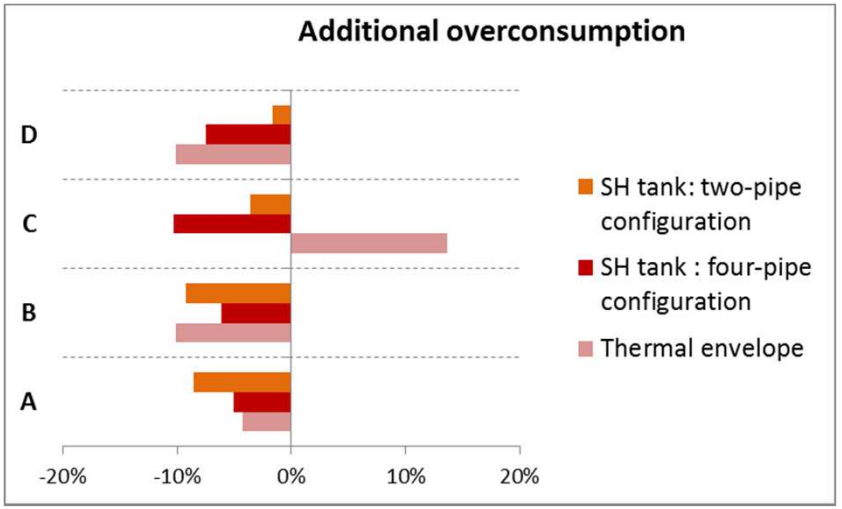
(= overconsumption entailed after the modulation interval)

Upward modulation (ADR#1)



- ✓ *Well-insulated houses*: thermal envelope
- ✓ *poorly-insulated houses*: SH tank with 4-pipe config.
- X SH tank with 2-pipe config.

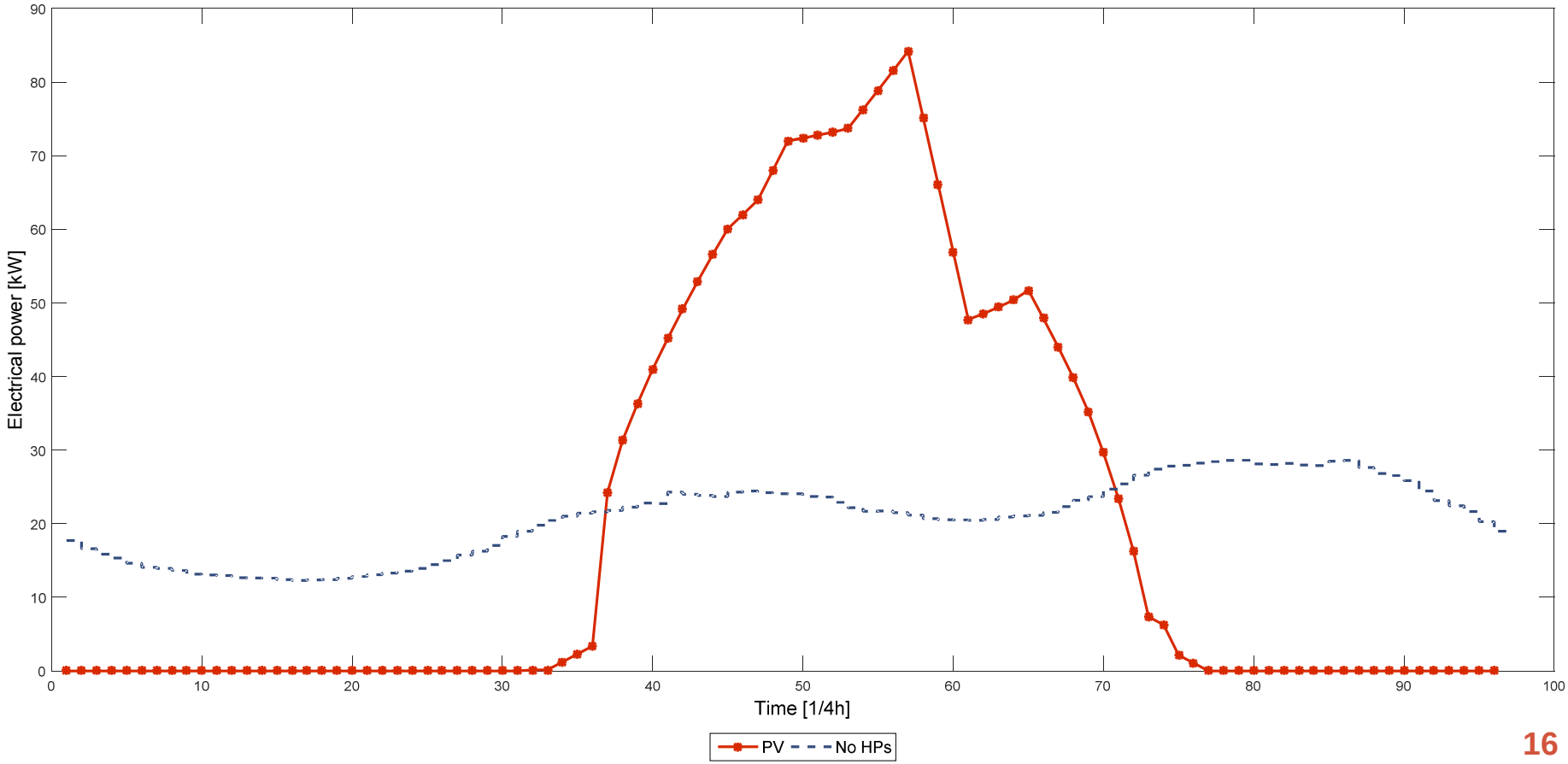
Self-consumption (ADR#2)



- ✓ *Well-insulated houses*: thermal envelope / tank with 2-pipe config.
- ✓ *Poorly insulated houses:* *4-pipe configuration*

Rsults – semi-urban feeder

- 63 houses
- 50% PVs
- 20% HPs
- suitable thermal storage



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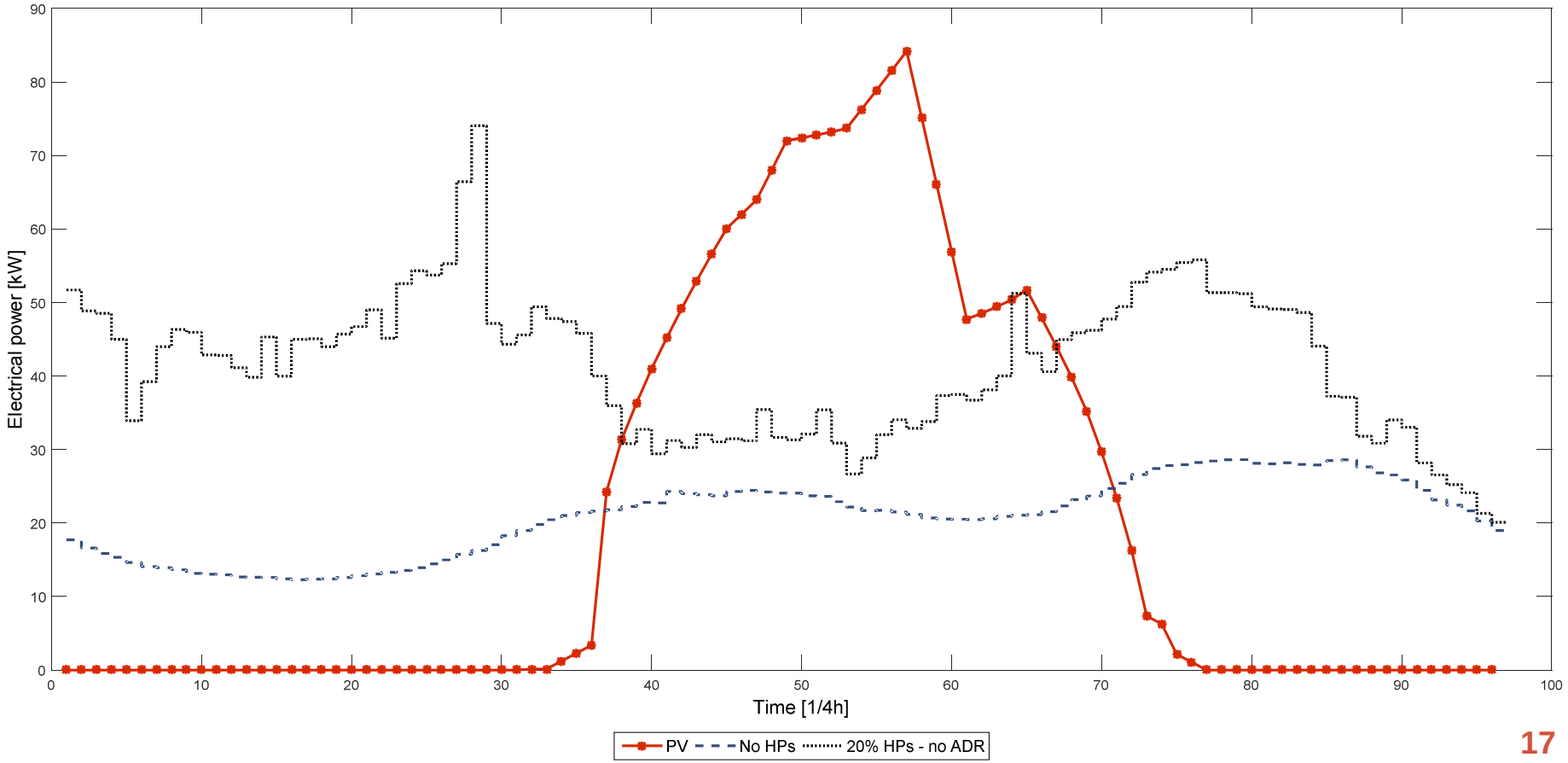

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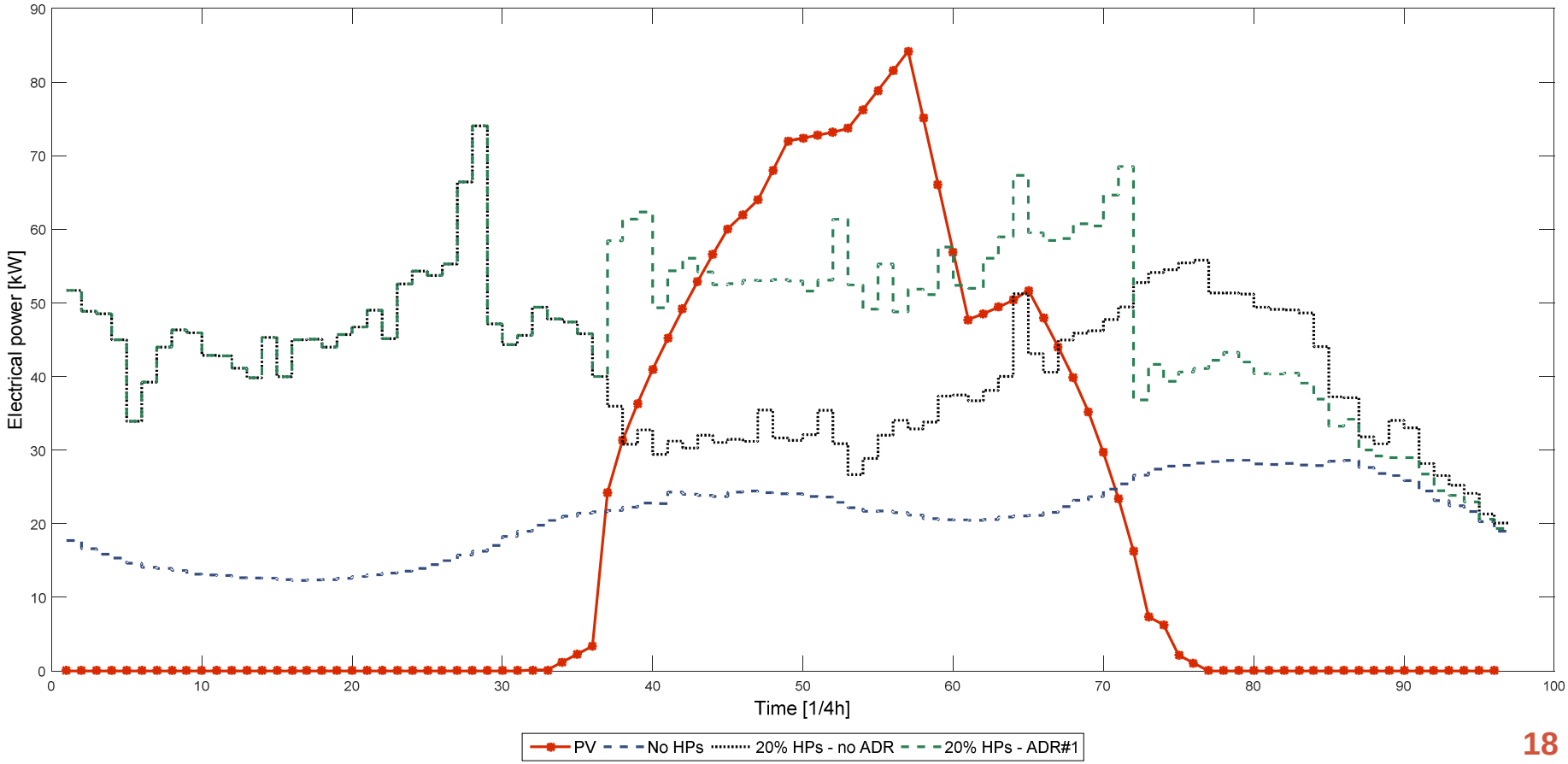

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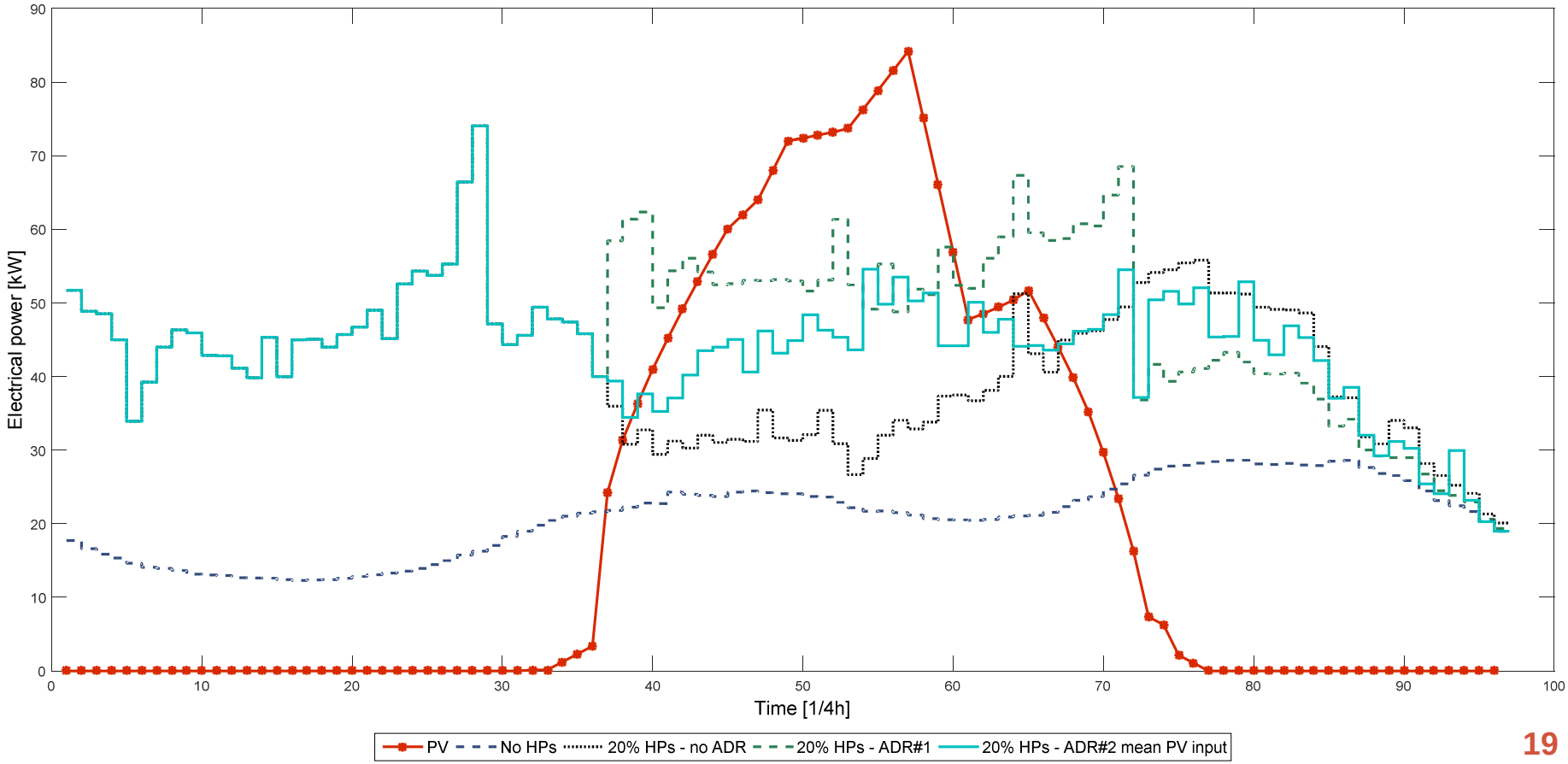

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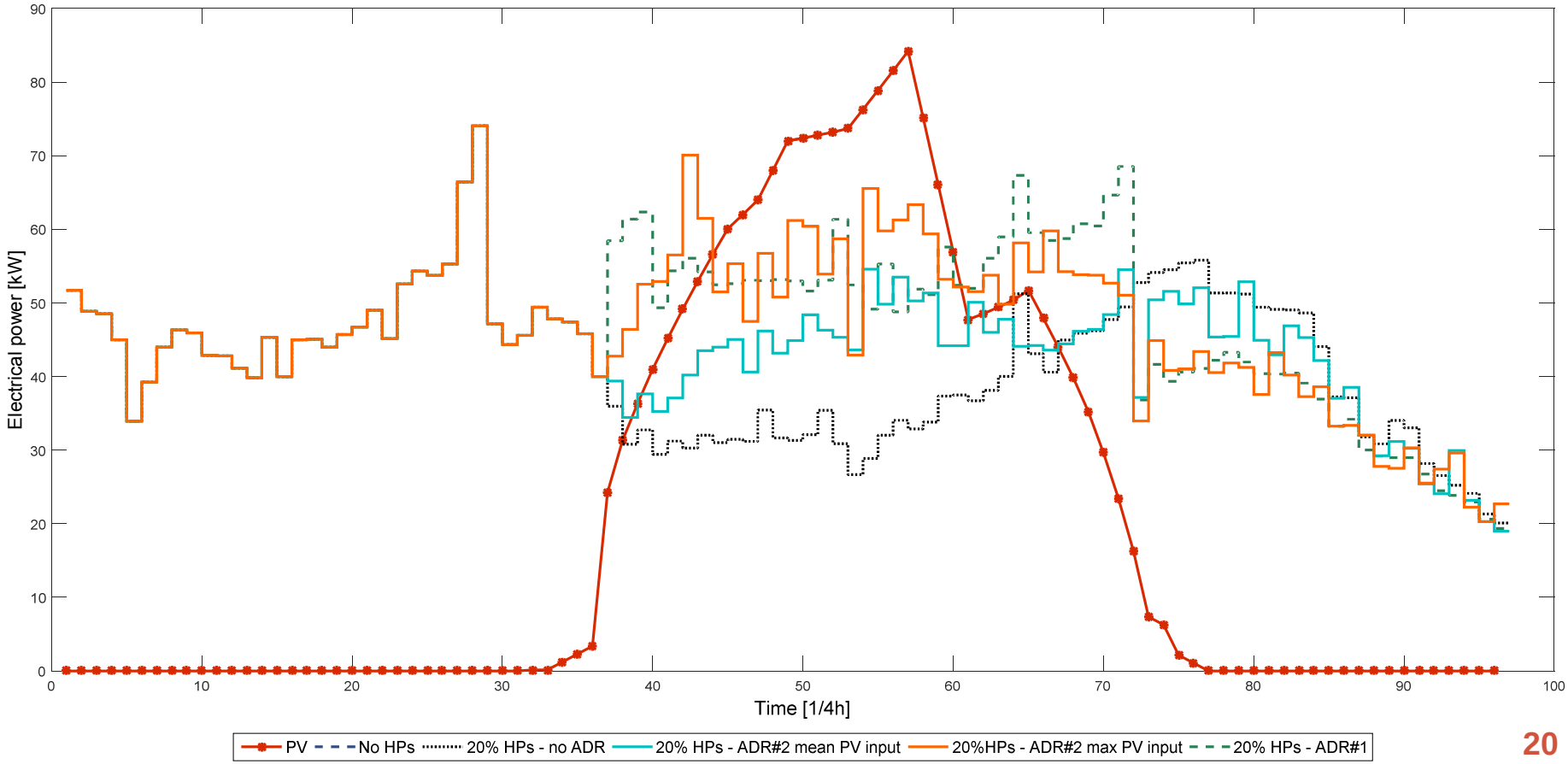

Conclusions

- Comparison of
  - two optimal control formulations for load shifting strategies with residential heat pumps (ADR#1 and ADR#2)
  - three storage options combining a DHW tank and either the thermal envelope of the building or a SH tank with two hydraulic configurations
  - four typical Belgian houses with different insulation levels

⇒ Ranking of the most suitable storage options

- Application to a feeder of 63 houses with 50% PVs and 20% HPs

⇒ Residual load reduced by 28 to 73.4%

⇒ ADR#1 better suited for short time intervals and constant modulation amplitude

⇒ ADR#2 allows to better limit the additional overconsumption

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