Flexible heating with heat pumps and domestic thermal energy storage

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Aims of this work

Using real heat pump demands:

→ Consider how much thermal storage (or battery storage) a home requires to be self-sufficient

→ Estimate the peak HP demand reduction from a given level of thermal storage (or battery storage)

→ Estimate how much a given thermal store can reduce the capacity of heat pump installed

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Thermal Energy Storage (TES)

- Store energy as heat for use later

- Lots of materials (PCMs, TCES materials, hot water storage)

Sensible

- **Water tanks**
- **Aquifers**
- **Rocks**
- **Concrete**

Latent

- **Paraffins**
- **Salt-hydrate mixtures**
- **Sugar alcohols**
- **Salts (molten)**

Chemical

- **Salt hydration/ dehydration reactions**
- **Carbonate decomposition**
- **Redox reactions**

Already used widely for hot water storage in domestic buildings. 150L tank gives ~ 7 kWh storage.

Salt hydrates: Higher latent heat, thermal conductivity, small ΔV. Prone to supercooling, segregation and corrosive. Paraffins: Stable, low cost, low supercooling. Low λ_{cond}, inflammable, less well defined T_{fusion}.
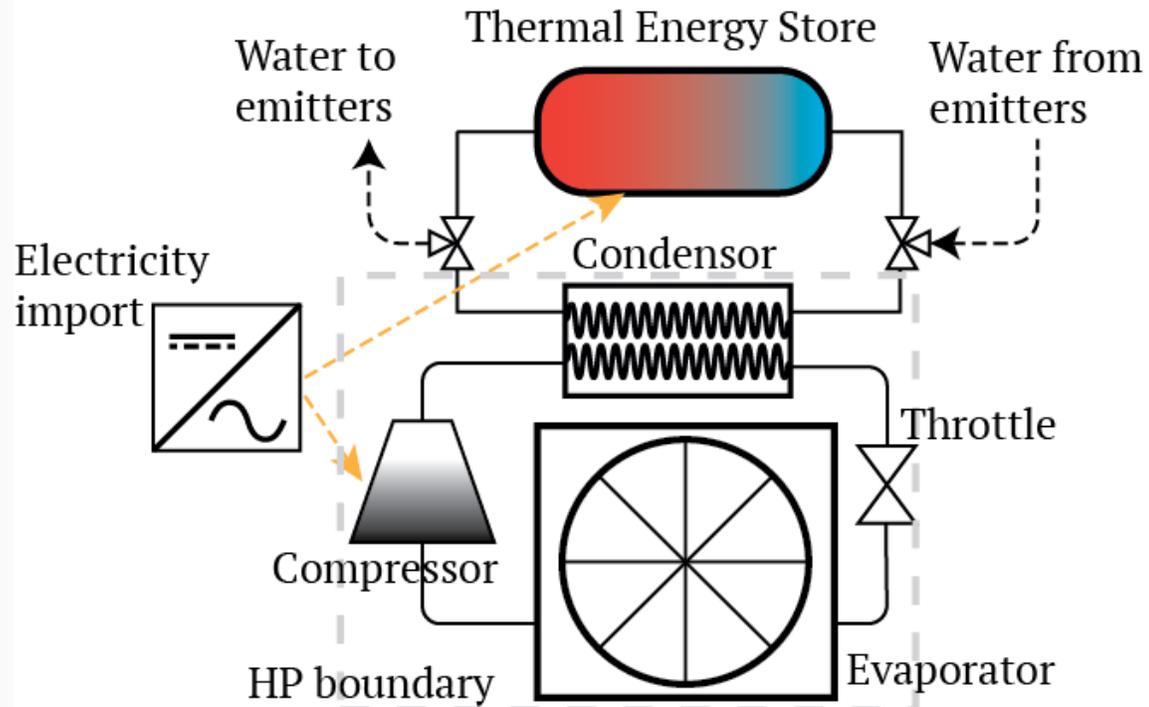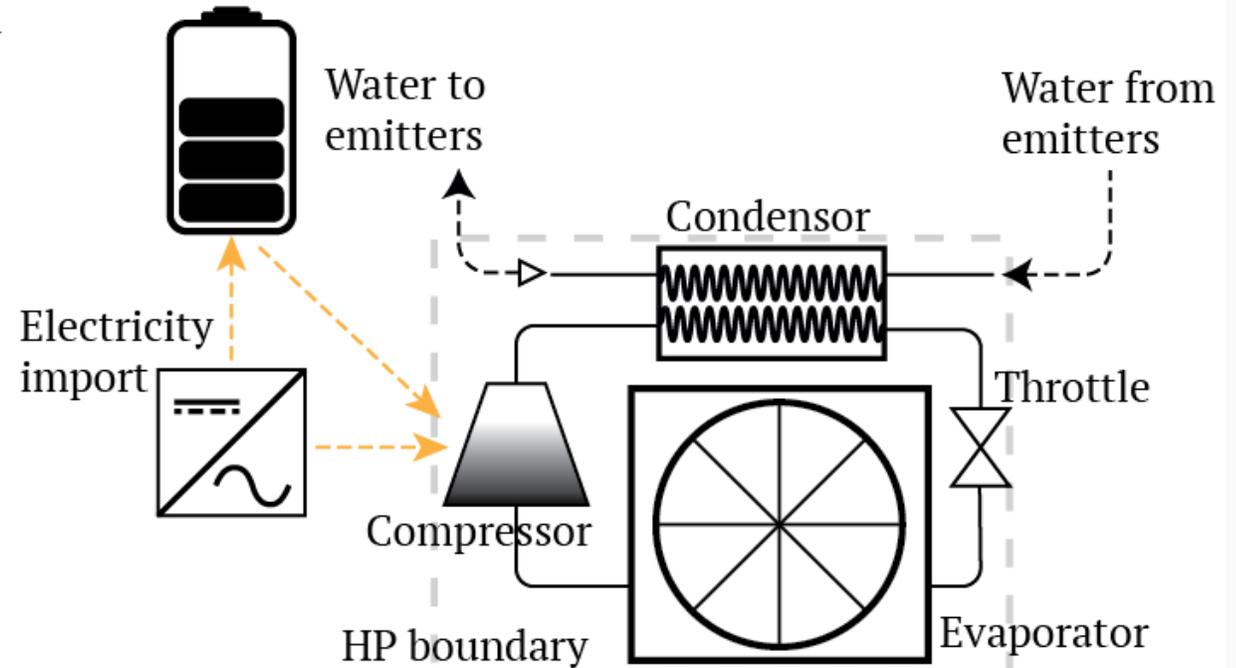
Uses thermochemicals, which have reversible chemical reactions. Highest energy density. Difficulty in controlling temperatures.

# Heat pumps with energy storage

(A) HP-TES system

Thermal Energy Store

Water to emitters

Water from emitters

Electricity import

Condensor

Throttle

Compressor

Evaporator

HP boundary

(B) HP with battery

Water to emitters

Water from emitters

Electricity import

Condensor

Throttle

Compressor

Evaporator

HP boundary

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Heat pump energy data

- Data from the Electrification of Heat (EoH) project[1]:
  - Heat flow (kWh per 2 min)
  - Electricity (kWh per 2 min)
  - Flow temperature
  - Return temperature
 - Internal temperature
  - External temperature
  - Meta data
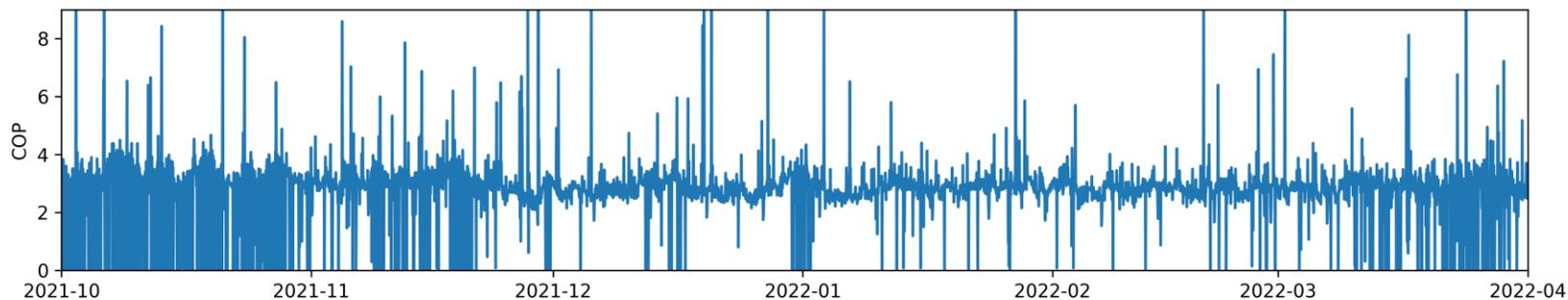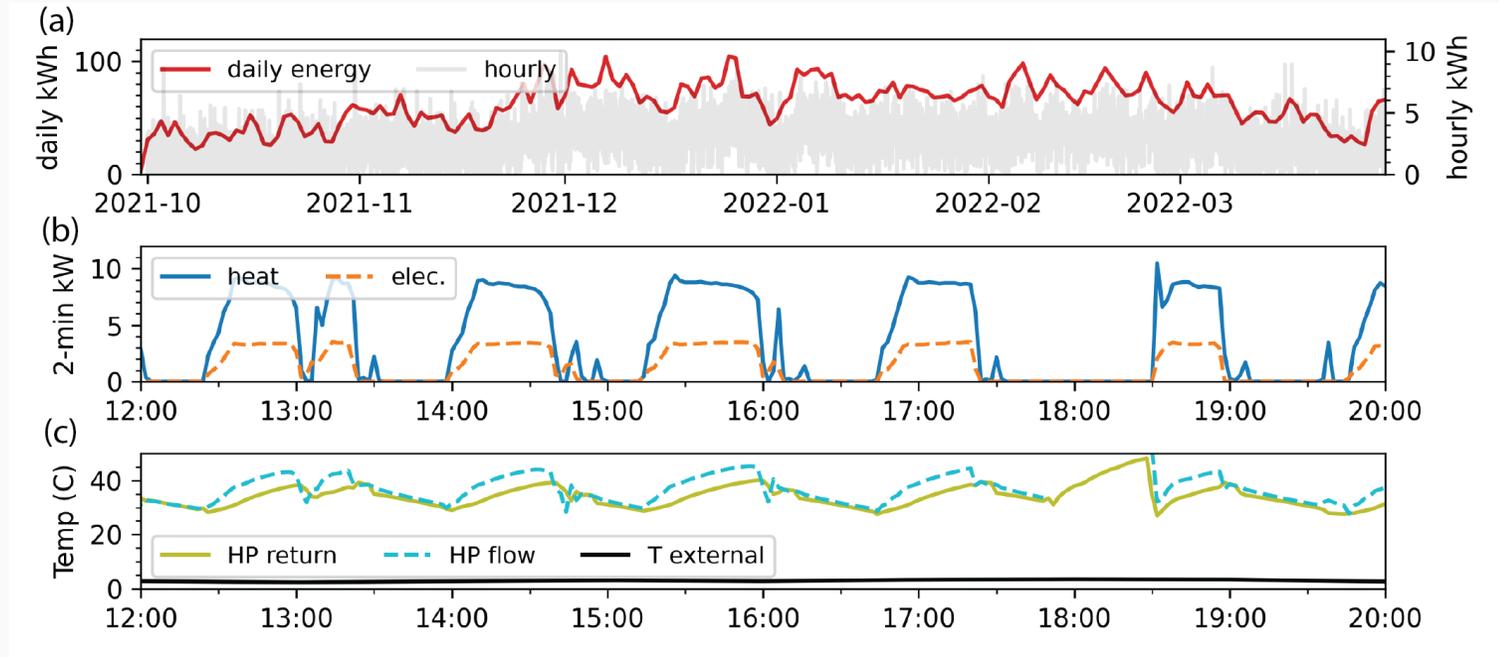
[1] Energy Systems Catapult. (2023). Electrification of Heat Demonstration Project: Heat Pump Performance Cleansed Data, 2020-2022. UK Data Service. SN: 9050, DOI: http://doi.org/10.5255/UKDA-SN-9050-1.

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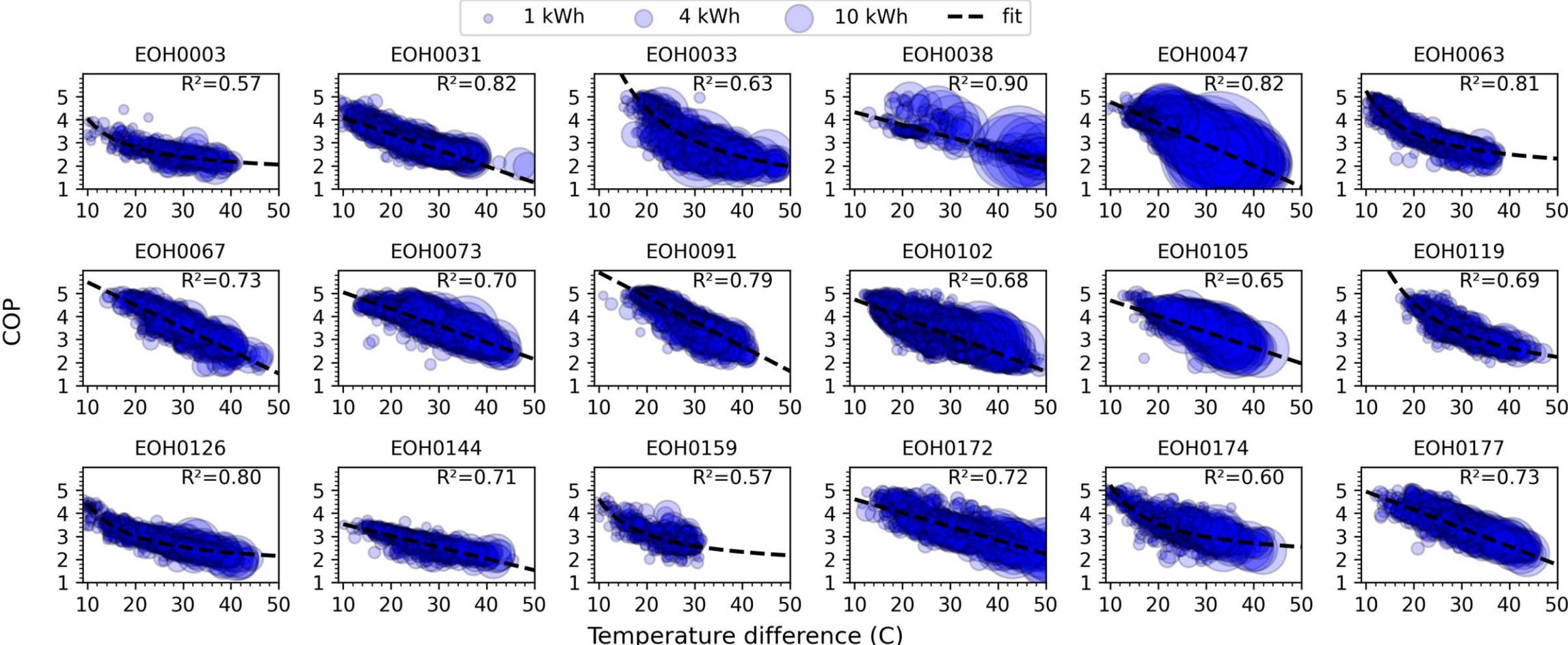
Heat pump performance model

- Extract 'heat events' from the data

- $COP_{event} = \dfrac{Q_{event}}{E_{event}}$

- In general, $COP = COP(\Delta T)$

- Assume $\Delta T = T_{return} - T_{ambient}$
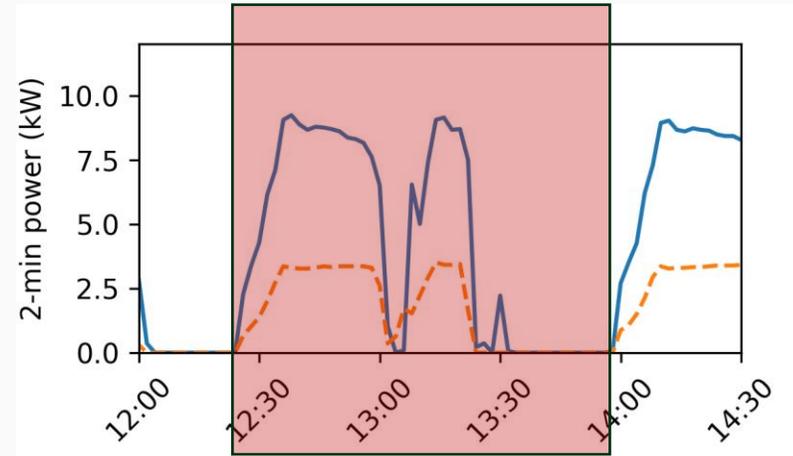
$$\boldsymbol{COP = \dfrac{A}{\Delta T} + B}$$
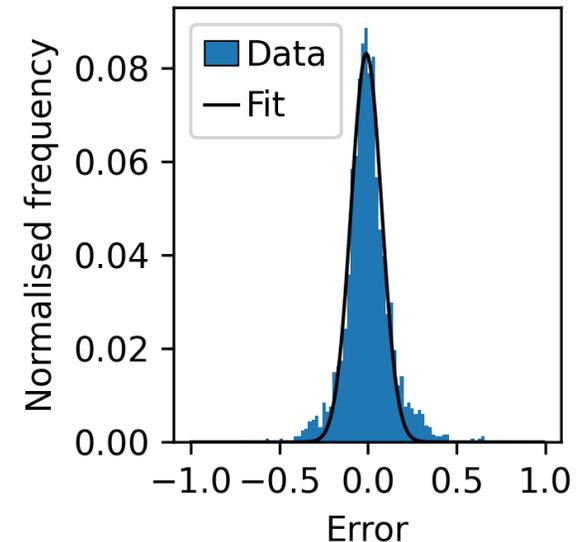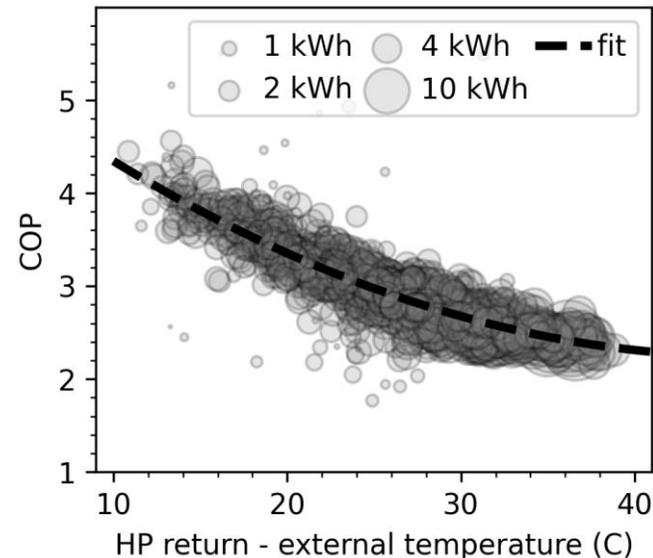
Heat pump performance model

Using heat pumps to minimise peak demand

$$MINIMIZE\left(\alpha MAX\{E_t^{Tot}\} + \beta \sum_t E_t^{Tot}\right)$$

$$Q_t^{dem} = Q_t^{HP} - Q_t^{-,TES} \qquad (1)$$

$$E_t^{Tot} = E_t^{HP} + E_t^{+,TES} \qquad (2)$$

$$Q_t^{+,TES} = E_t^{+,TES} \qquad (3)$$

$$E_t^{Tot} - E_t^{HP} = -\frac{Q_t^{-,TES}}{COP_t} \qquad (4)$$

Subject to:

$$0 \le SOC_t \le SOC^{MAX} \qquad (5)$$

$$0 \le Q_t^+ \le Q_t^{+,MAX} \qquad (6)$$

$$Q_t^{-,MIN} \le Q_t^- \le 0 \qquad (7)$$

$$SOC_t = \begin{cases} SOC_{t-1} + Q_t^+ + Q_t^- \;\; \forall t > 0 \\ 0 + Q_t^+ \qquad\qquad t = 0 \end{cases} \qquad (8)$$

Thermal storage

$$MINIMIZE\left(\alpha MAX\{E_t^{Tot}\} + \beta \sum_t E_t^{Tot}\right)$$

$$E_t^{Tot} = E_t^{HP} + \frac{E_t^+}{\eta_{chg}} + \eta_{dischg}E_t^- \qquad (9)$$

Subject to:

$$0 \le SOC_t \le SOC^{MAX} \qquad (10)$$

$$0 \le E_t^+ \le E_t^{+,MAX} \qquad (11)$$

$$E_t^{-,MIN} \le E_t^- \le 0 \qquad (12)$$

$$SOC_t = \begin{cases} SOC_{t-1} + E_t^+ + E_t^- \;\; \forall t > 0 \\ 0 + E_t^+ \qquad\qquad t = 0 \end{cases} \qquad (13)$$

Battery storage

- **LP optimized in python using pyomo[1] with CPLEX[2].**

[1]Hart, William E., Jean-Paul Watson, and David L. Woodruff. "Pyomo: modeling and solving mathematical programs in Python." Mathematical Programming Computation 3(3) (2011): 219-260.
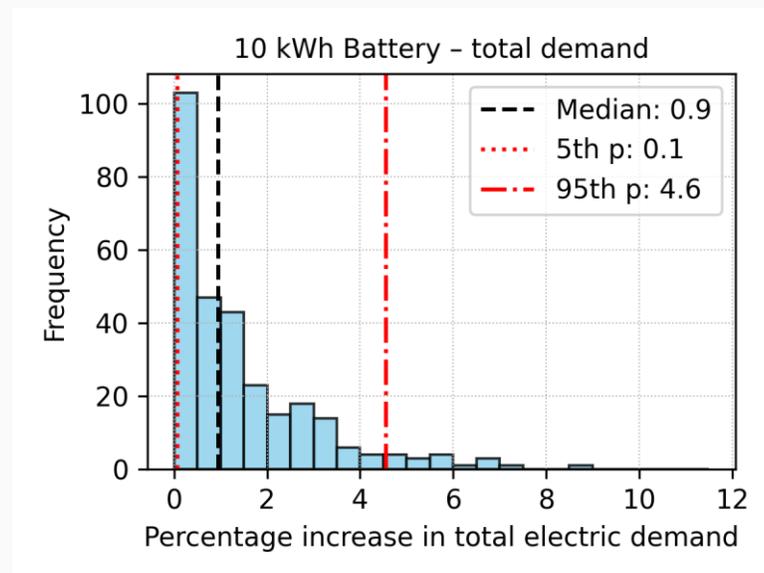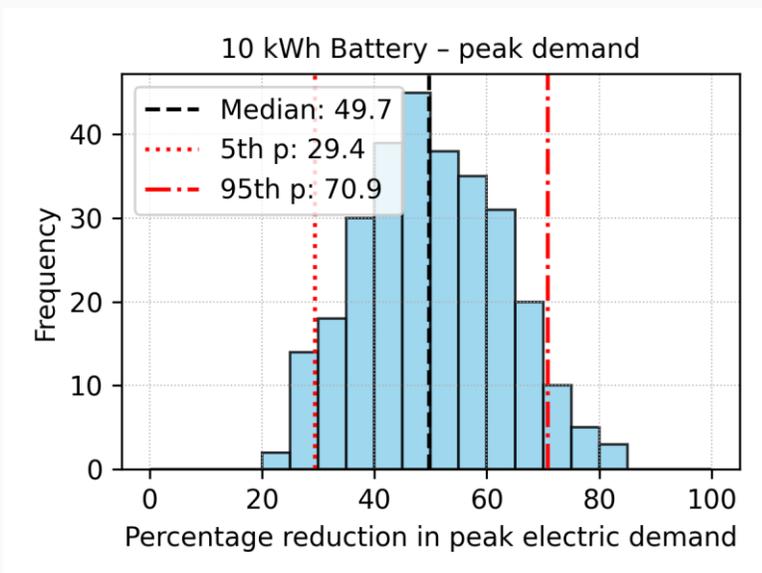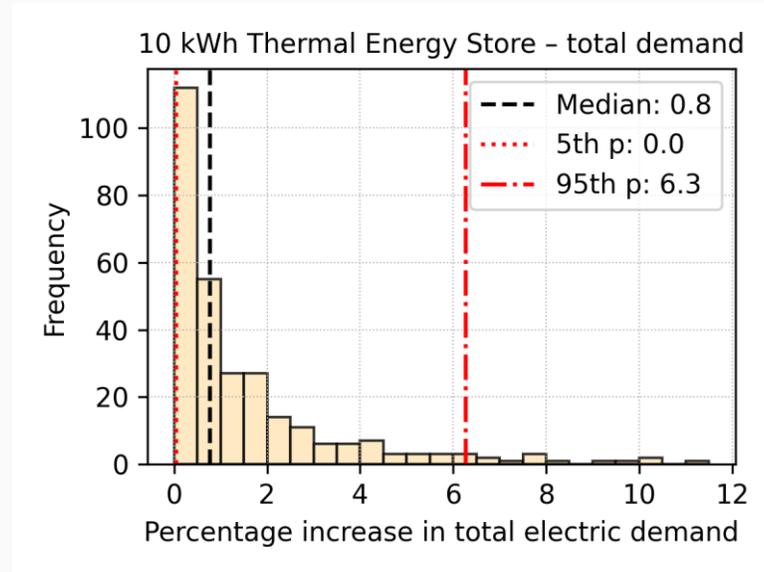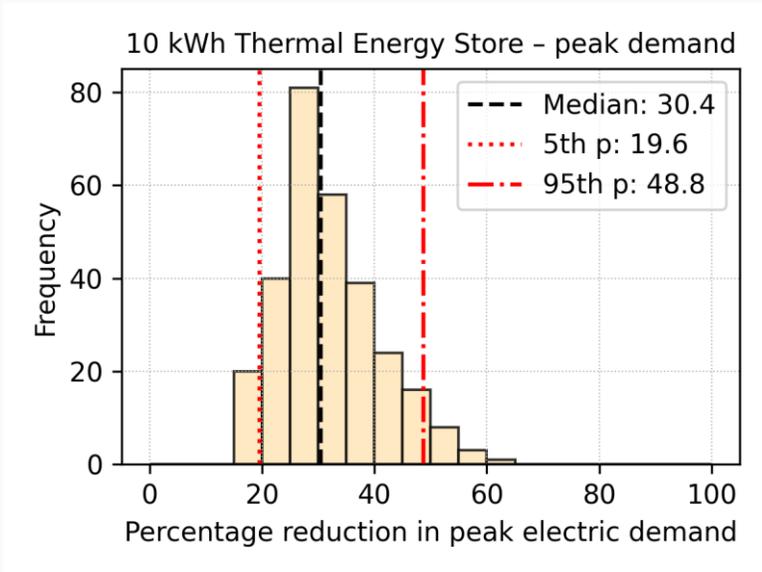[2]IBM. IBM ILOG CPLEX Optimization Studio v12.9. (2024), https://www.ibm.com/products/ilog-cplexoptimization-studio
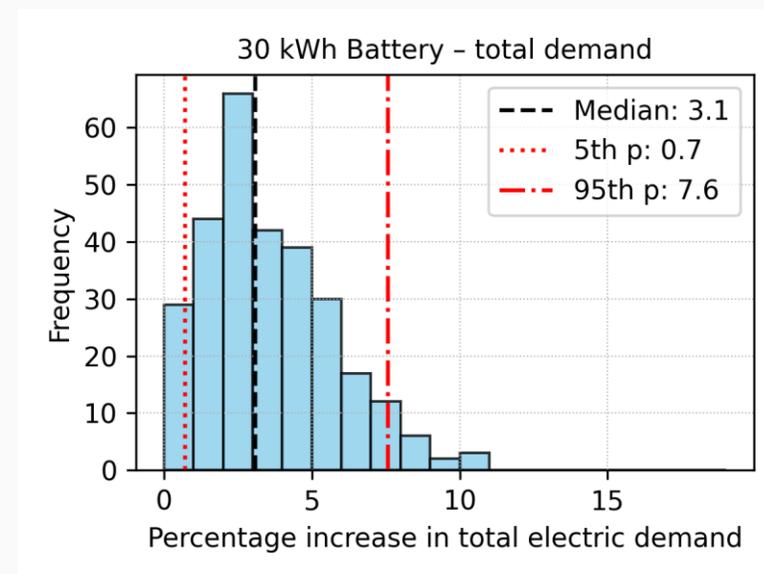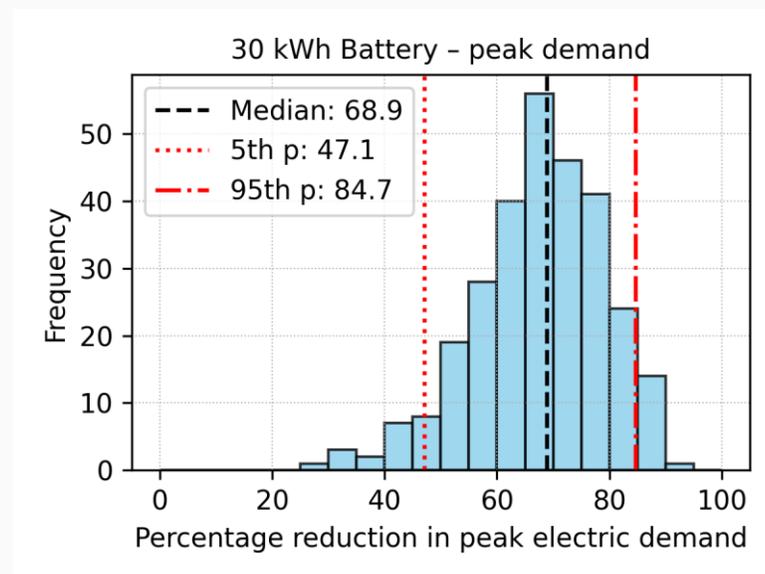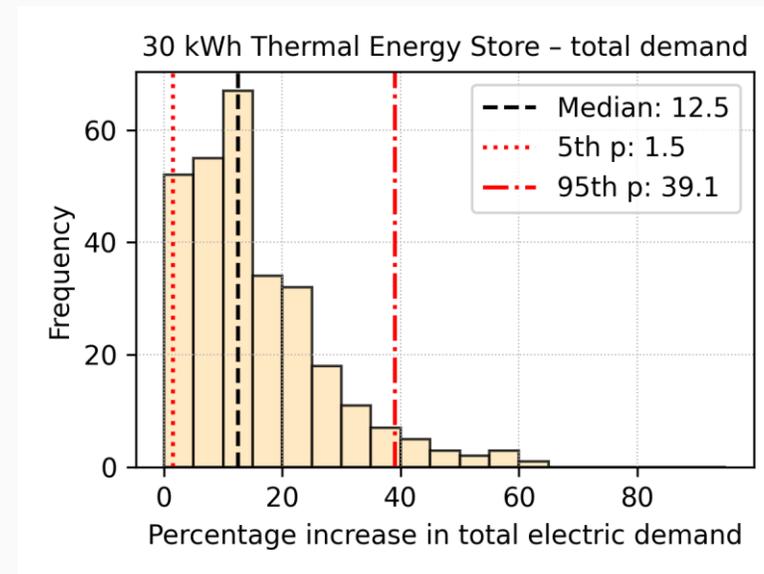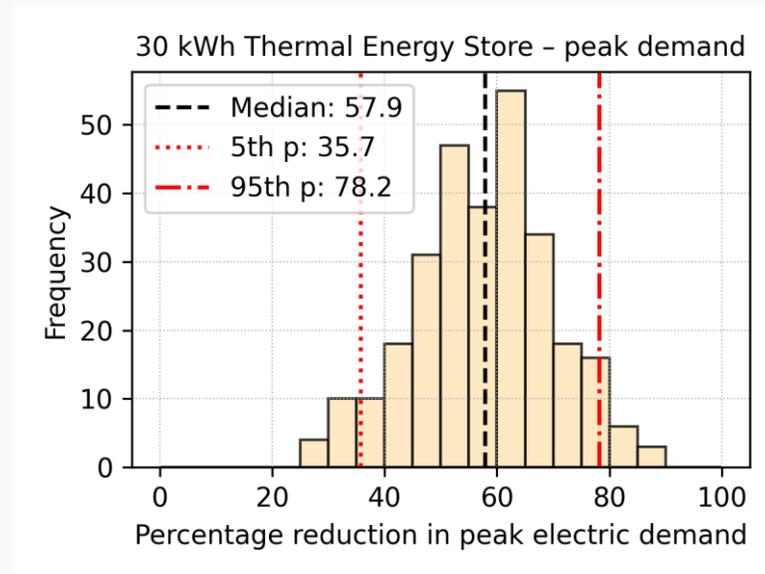
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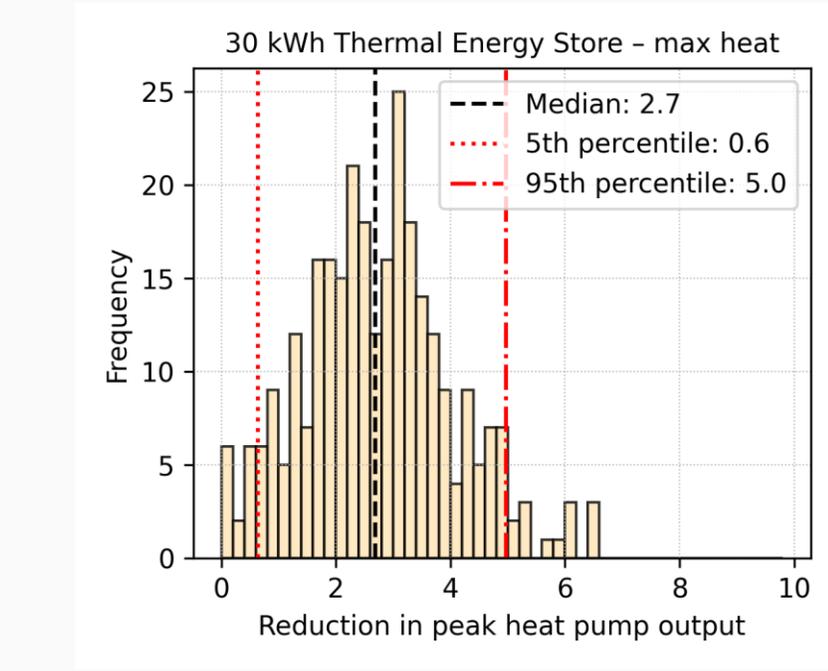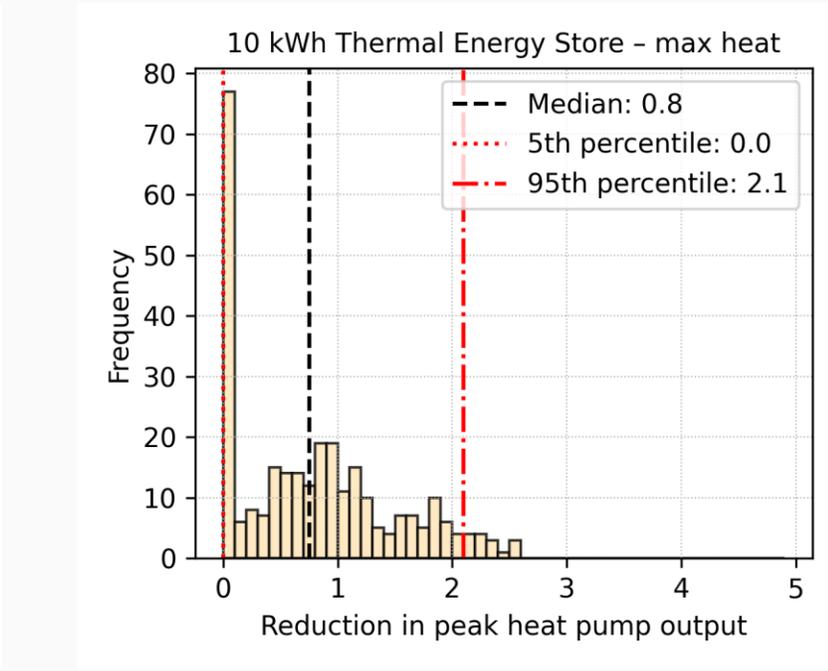# Results: heat/electric requirements for standalone operation
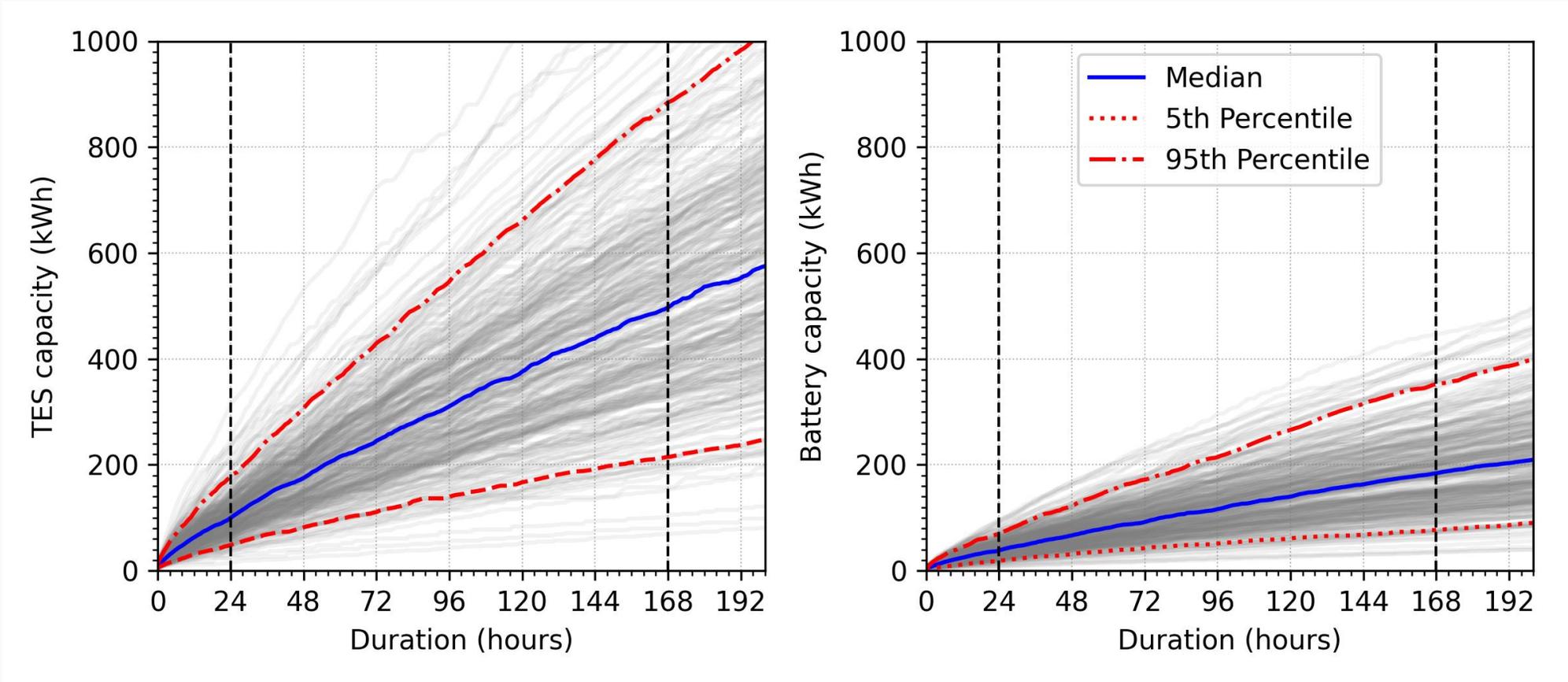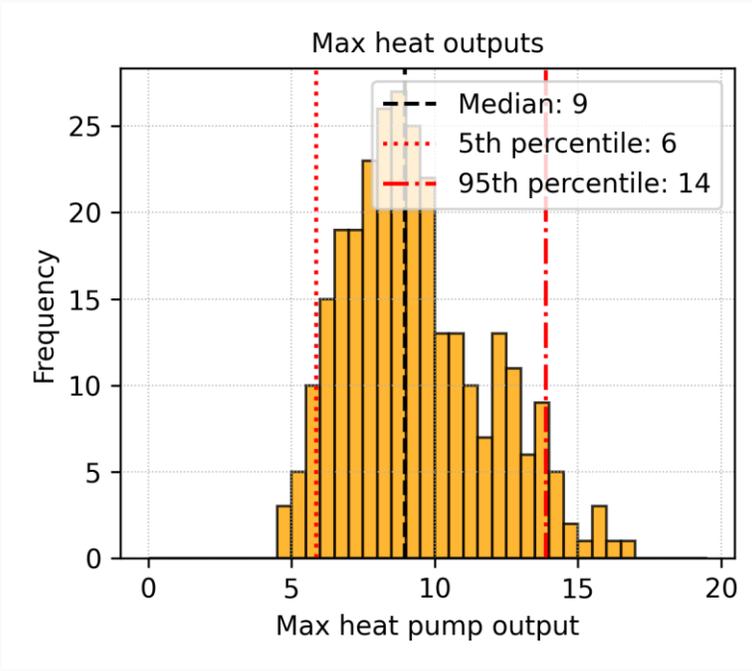
Results: peak electric demand minimisation (10 kWh)

Results: peak electric demand minimisation (30 kWh)

Results: reduction in peak heat pump output

Key conclusions

- For ***standalone operation***, large storage sizes are required, ***scaling approximately linearly with time up to 1 week***. The heat-to-electric ratio is around 2.7.

- For ***peak demand reduction***, both a modest battery and TES can provide considerable peak reduction.

- For the median house in our data, a ***30 kWh battery*** can reduce the peak by ***69%*** while a ***30 kWh TES*** can reduce the peak by ***58%***.

- ***Economics of TES*** will be ***challenging*** unless ***resistance charging*** is avoided.