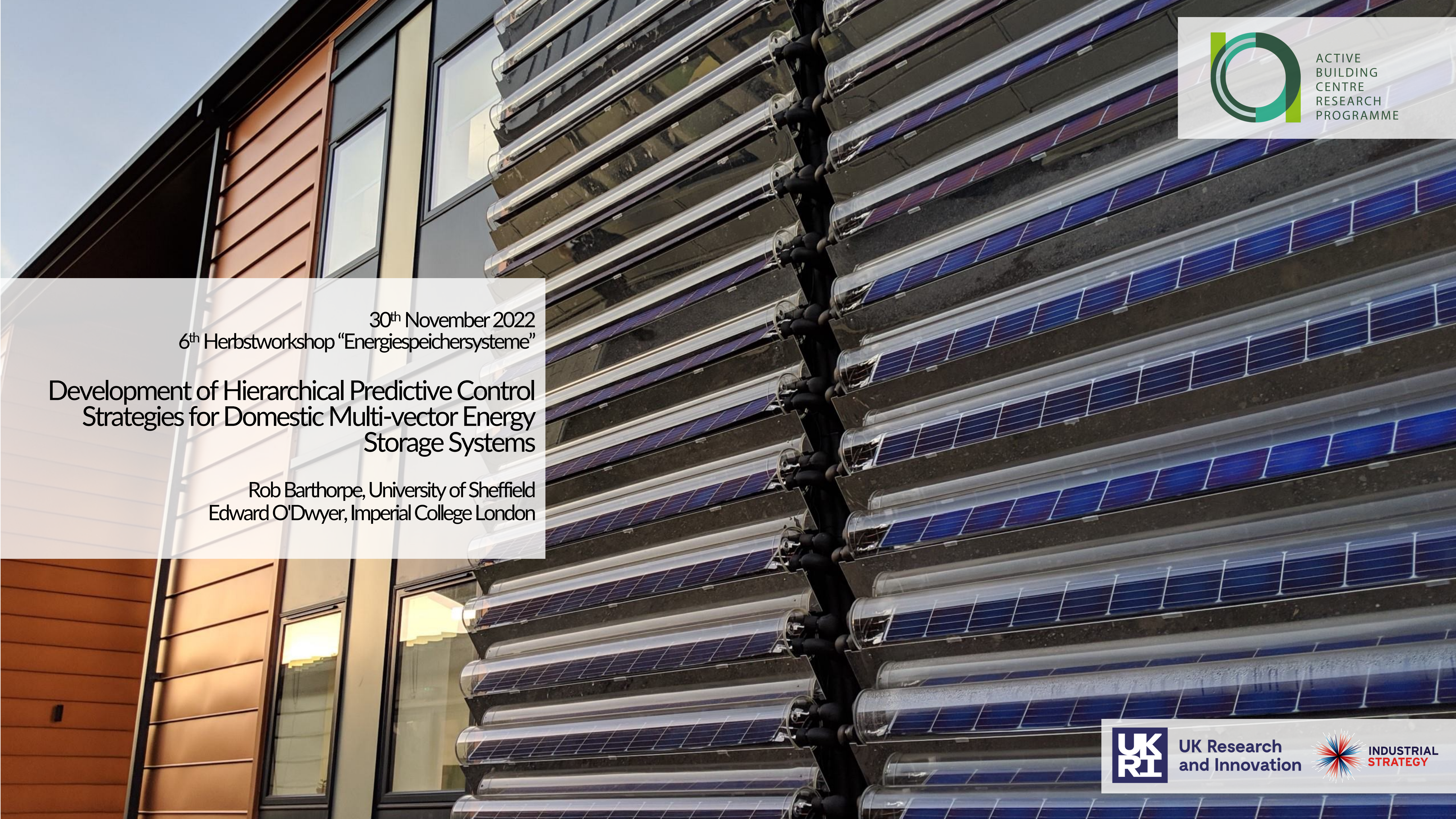

30th November 2022
6th Herbstworkshop “Energiespeichersysteme”

Development of Hierarchical Predictive Control Strategies for Domestic Multi-vector Energy Storage Systems

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Motivation

Motivation

- Decarbonisation of domestic heat offers both huge opportunities and challenges.
- Increased penetration of renewable energy generation allied to the electrification of domestic heating systems is expected to create substantial grid balancing issues.
- Imbalances in inter-seasonal supply and demand present a particular challenge, promoting interest in long-duration electrical and thermal energy storage.

Multi-Vector Energy Storage

- Storing electrical and thermal energy at point-of-use within domestic dwellings offers benefits over alternatives such as large-scale grid-level storage, not least that issues arising from local network distribution constraints may be overcome.
- However, efficient, practicable control of domestic multi-vector systems remains an open problem, and particularly so in cases where longer-duration storage - such as that offered by emerging thermochemical technologies - is combined with shorter-duration storage.

Motivation

The ideal control strategy for such a scenario would display several key characteristics:

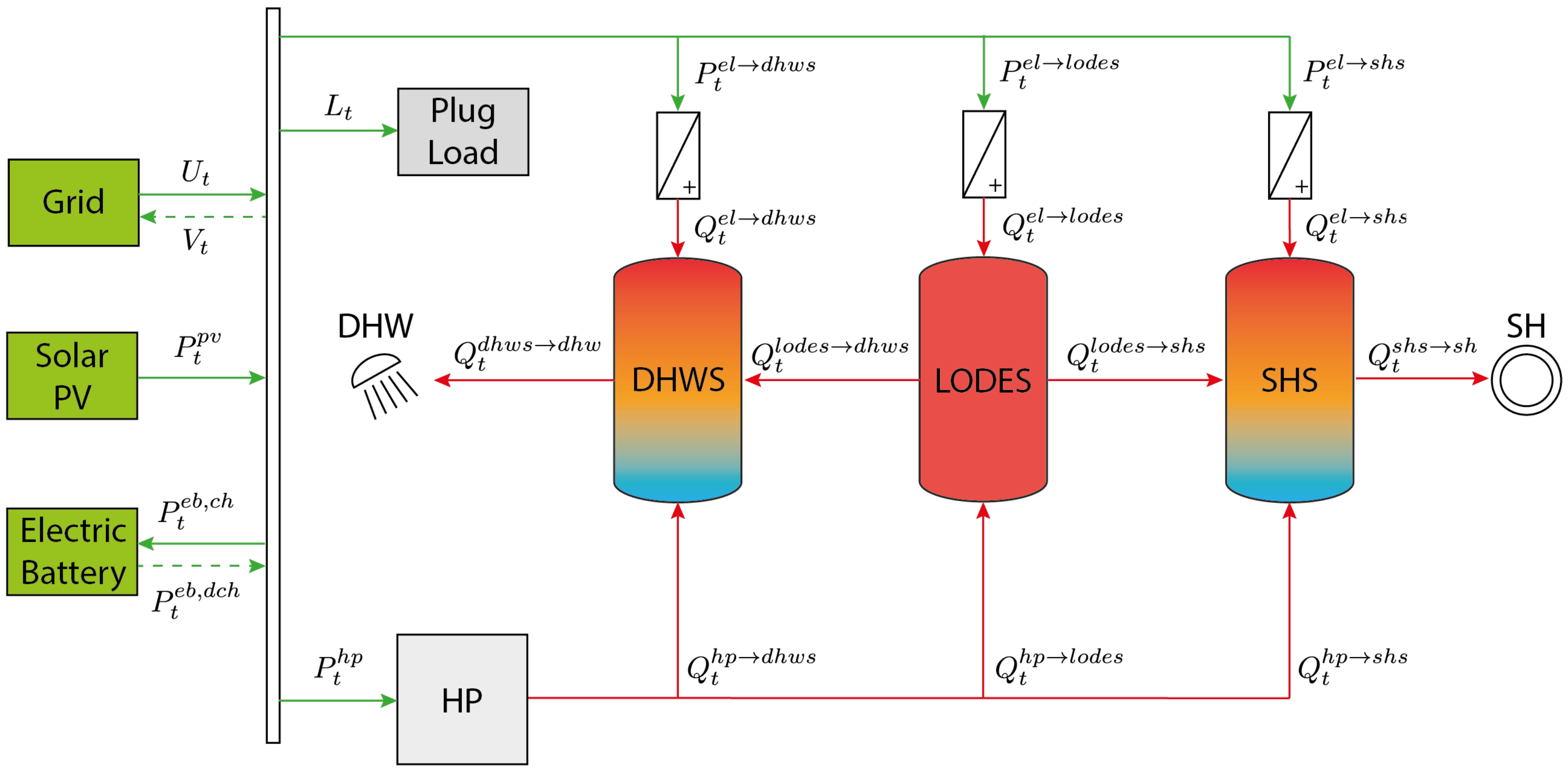
- Should be scalable, predictive and grid-aware
- Should require minimal user input and installer tuning
- Should be capable of servicing both occupier and network needs by balancing multiple, potentially competing objectives.

Applications of developed control scheme:

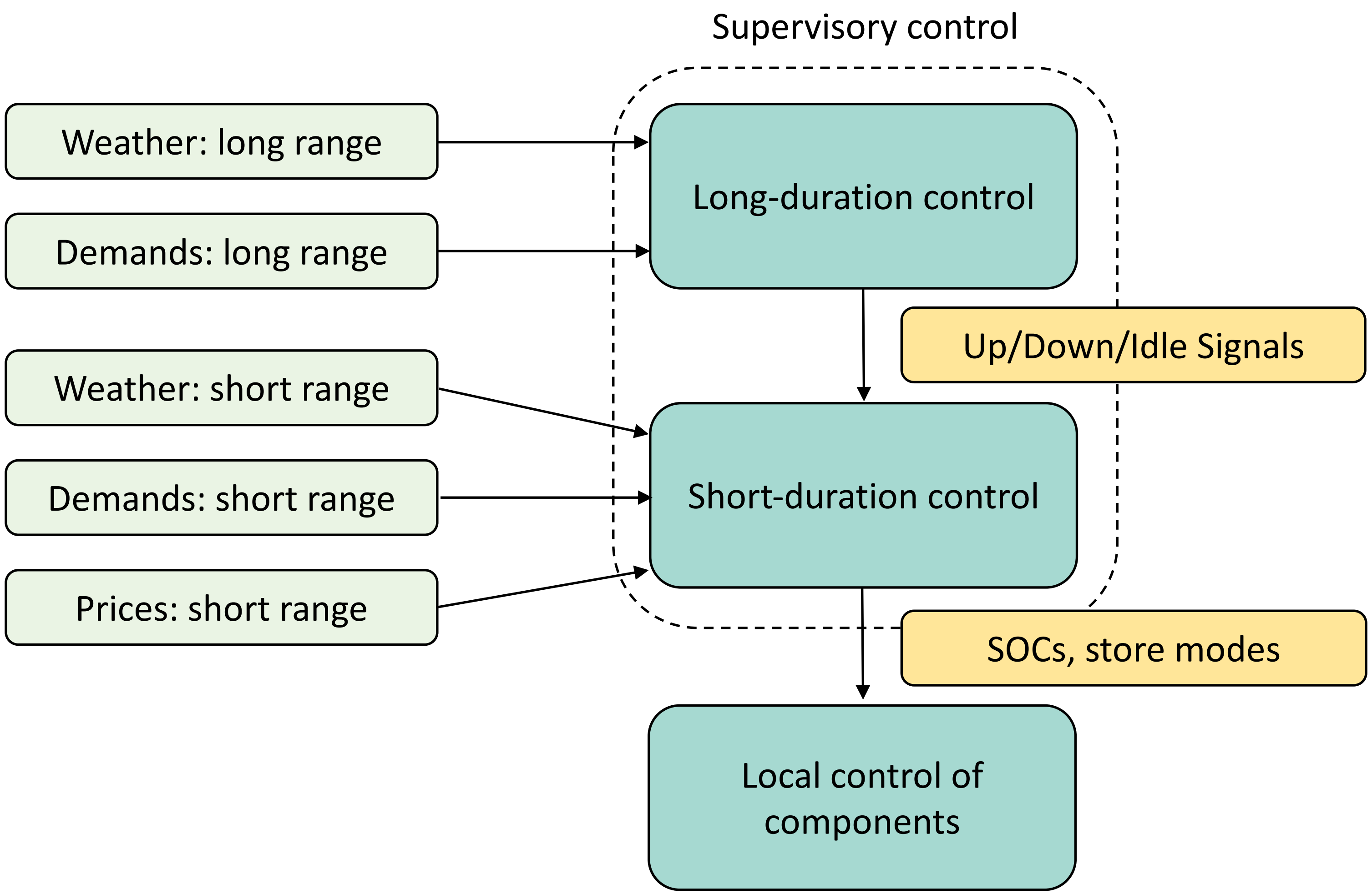
- Primary:
  1. Practical dwelling-level control
- Secondary:
  2. Tool for evaluating impact of different interventions, given data/model
  3. Basis for other analyses, multi-dwelling control etc

Methodology: Hierarchical predictive control

What kind of system are we trying to control?



Methodology: Hierarchical predictive control

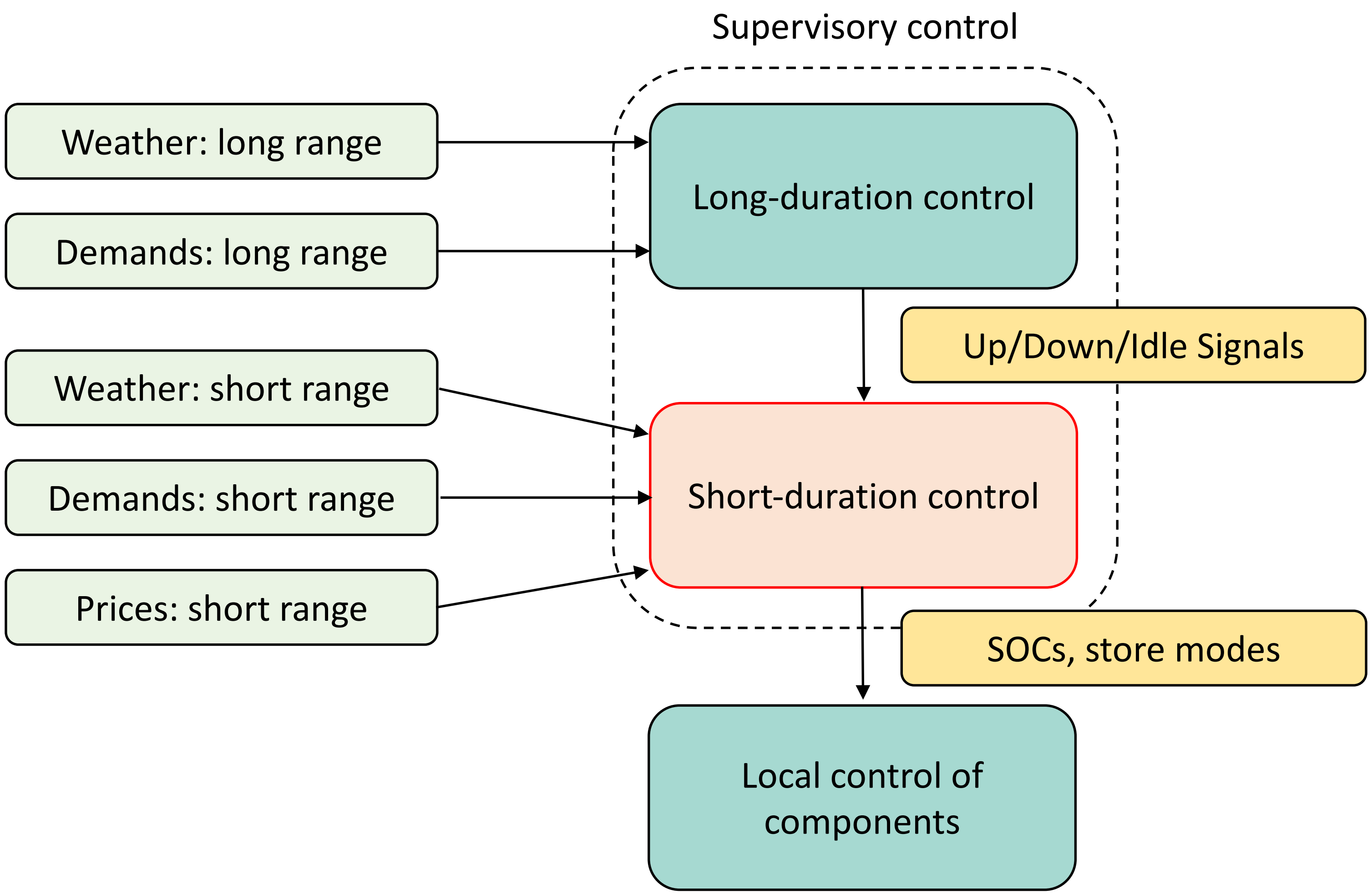


Δt = days, weeks
Time horizon = weeks, months

Δt = minutes
Time horizon = hours

Δt = seconds
Time horizon = seconds

Methodology: Hierarchical predictive control



Δt = days, weeks
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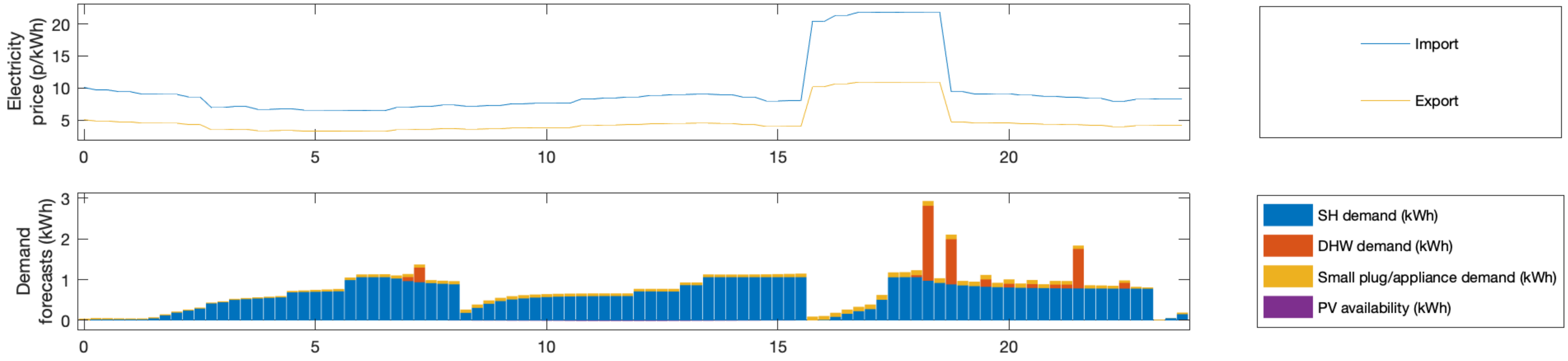
Methodology: Short duration control

Model Predictive Control (MPC)



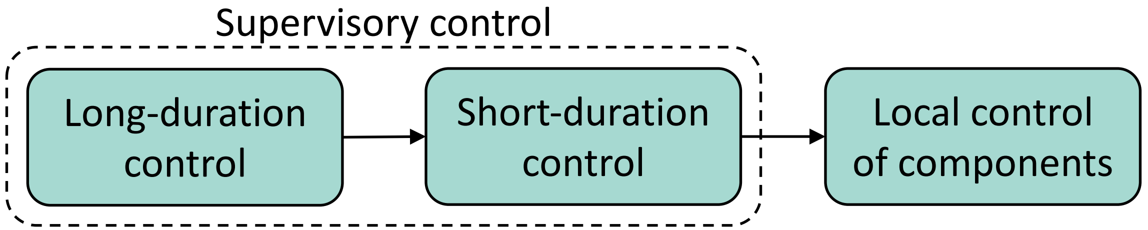
Methodology: Short duration control

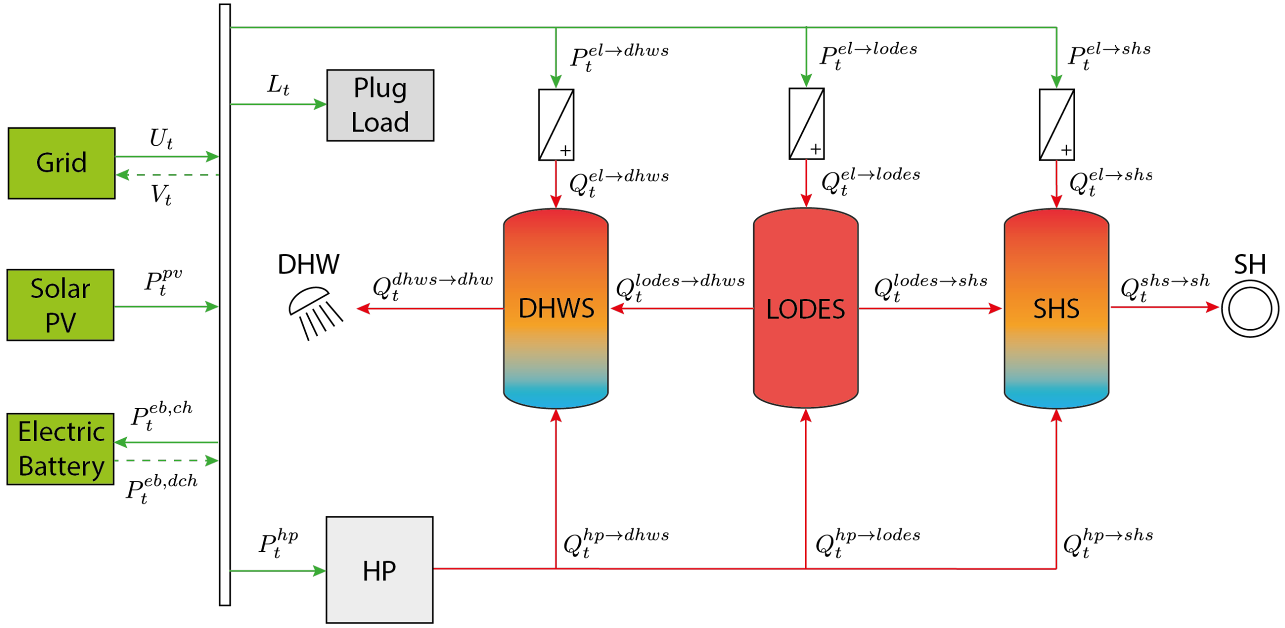
Model Predictive Control (MPC)

Forecasts variables: known/predicted system inputs/outputs.
- Energy tariffs
- Weather
- Energy demands
- Long-duration control signals

Decision variables: known/predicted system inputs/outputs.
- Storage states of charge (SoCs)
- Storage and HP Modes of operation
- Energy flows to/from grid
- Electrical input, etc.

Objective function: mathematical statements of how we would like the system to behave.
- Minimise energy cost
- Minimise carbon usage
- Combination of above





Methodology: Short duration control

Forecast and Decision Variables

Forecast Variables

Electricity Price	Import [p/kWh]
	Export [p/kWh]
Demands	Space Heating (SH) [kWh]
	Domestic Hot Water (DHW) [kWh]
	Small Plug/Appliance (SPA) [kWh]
Local Generation	Solar PV [kWh]
Weather	Ambient Temperature [°C]
Flexibility Services	Turn up/turn down signal {1, 0, -1}
TCS charge mode	Charge/idle/discharge signal from long-duration control {1, 0, -1}

Decision Variables

Power from Grid	Imported [kWh]
	Exported [kWh]
Electrical battery	Electrical energy in [kWh]
	State of Charge [0,1]
Heat pump (HP)	Mode 1: Charge TCS store [0,1]
	Mode 2: Charge DHWS store [0,1]
	Mode 3: Charge SHS store [0,1]
	HP input energy [kWh]
	HP output energy [kWh]
SH store (SHS)	Electrical energy in [kWh]
	Thermal energy to building [kWh]
	State of Charge [0,1]
Phase change material store (PCM)	Electrical energy in [kWh]
	Thermal energy to building [kWh]
	State of Charge [0,1]
Thermochemical store (TCS)	Electrical energy in [kWh]
	Mode 1: Charge SHS store [0,1]
	Mode 2: Charge DHWS store [0,1]
	TCS output energy [kWh]
	State of Charge [0,1]

Objective Function

$$J(t) = \sum_{i=1}^{T} U_i u_i - V_i v_i$$

i denotes future time steps up to the control horizon T

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Methodology: Short duration control

Constraints

1. **State of Charge (SoC) updates for each store**. The change in SoC is equal to the net sum of inward and outward energy flows, minus standing losses.

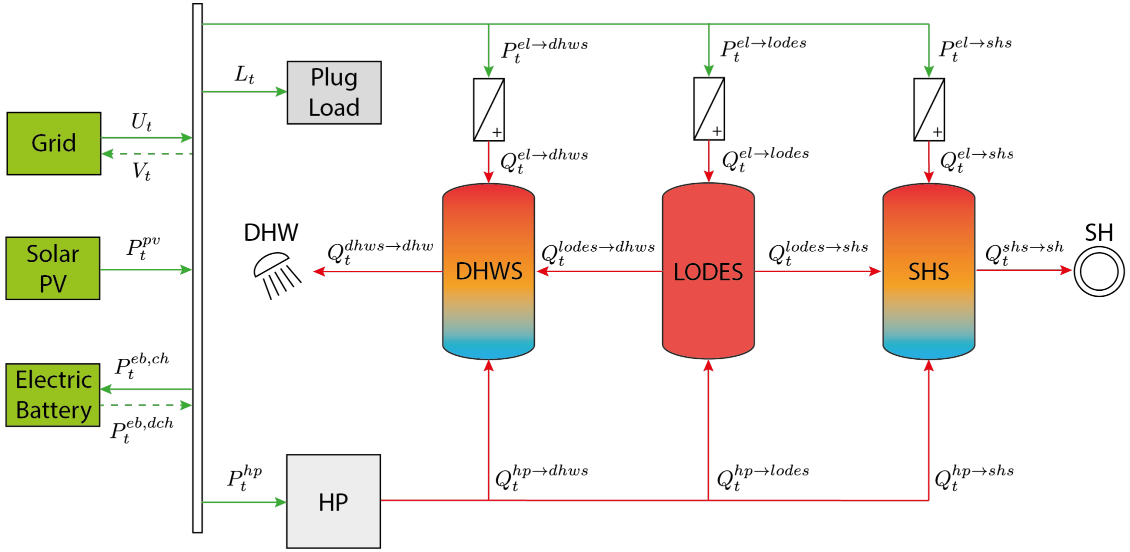
   - General

$$E_t = E_{t-1}(1 - \Lambda \Delta t) + \eta_{ch} Q^{in} \Delta t - \eta_{dch} Q_t^{out} \Delta t$$

$$E_t = \overline{E} \cdot SOC_t$$

$$\Lambda = E^{loss} / \overline{E}$$

$$E_0 = E_T$$



   - Example: SHS

$$E_t^{shs} = E_{t-1}^{shs}(1 - \Lambda^{shs} \Delta t) + \eta_{ch}^{shs}(Q_t^{hp \to shs} + Q_t^{el \to shs} + Q_t^{lodes \to shs}) \Delta t - \eta_{dch}^{shs} Q_t^{shs \to sh} \Delta t$$

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Methodology: Short duration control

Constraints

2. **Electrical energy balance.** The total electricity import/export must sum to zero for all timepoints.

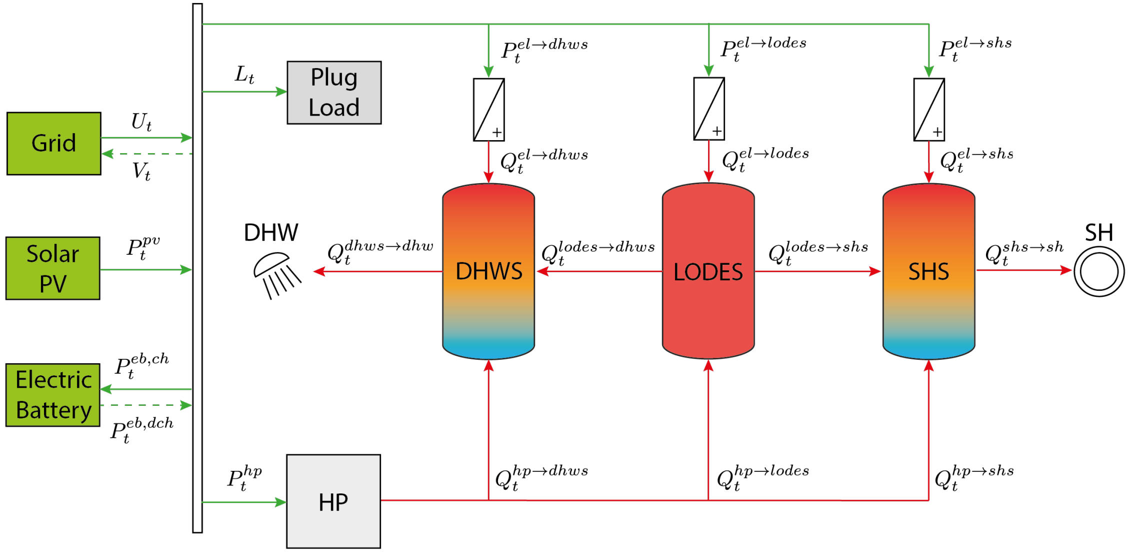
$$[U_t - V_t] - P_t^{eb} - P_t^{hp} - [P_t^{el \to shs} + P_t^{el \to dhws} + P_t^{el \to lodes}] = L_t - P_t^{pv}$$

3. **Complementarity constraint**. One of either grid import or export must equal zero for each timepoint.

$$0 \leq U_t \leq (1 - z_t)\overline{U}$$

$$0 \leq V_t \leq z_t \cdot \overline{V}$$

$$z_t \in \{0, 1\}$$



Methodology: Short duration control

Constraints

4. **HP output energy balance.** Total thermal output during the time step must equal the sum of output energies for all operation modes.

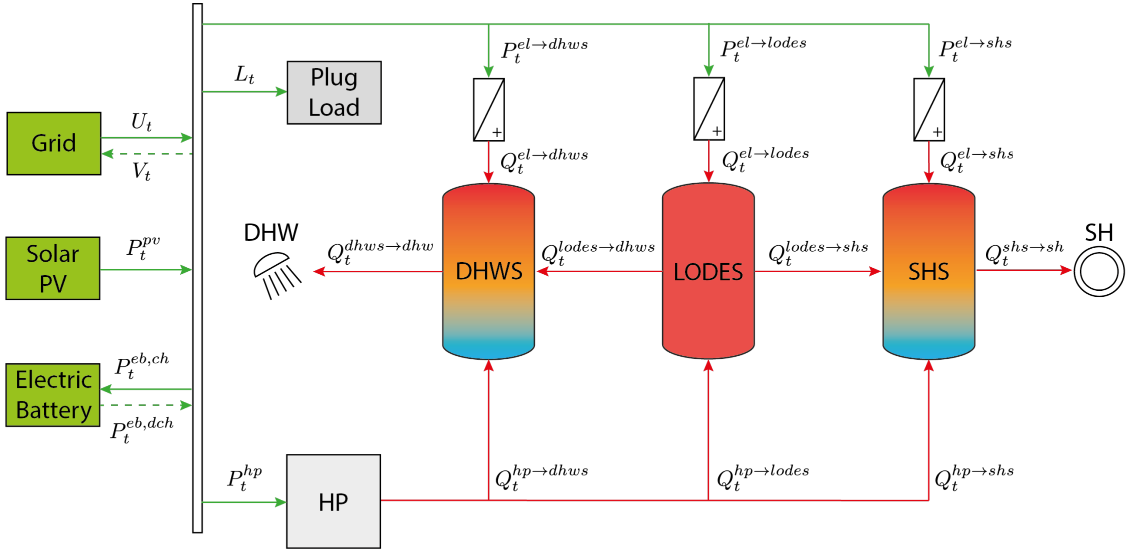
$$Q_t^{hp} = Q_t^{hp \rightarrow shs} + Q_t^{hp \rightarrow dhws} + Q_t^{hp \rightarrow lodes}$$

5. **HP output modes.** Only one mode may be operational at any given time.

$$0 \leq x_t^{hp \rightarrow lodes} + x_t^{hp \rightarrow shs} + x_t^{hp \rightarrow dhws} \leq 1$$

6. **HP conversion energy balance.** The total thermal output from the system must equal the sum of input energies required for all modes, multiplied by the relevant COP.

$$P_t^{hp} = \frac{x_t^{hp \rightarrow lodes} \overline{Q_t^{hp \rightarrow lodes}}}{COP^{lodes}} + \frac{x_t^{hp \rightarrow shs} \overline{Q_t^{hp \rightarrow shs}}}{COP^{shs}} + \frac{x_t^{hp \rightarrow dhws} \overline{Q_t^{hp \rightarrow dhws}}}{COP^{dhws}}$$



Methodology: Short duration control

Constraints

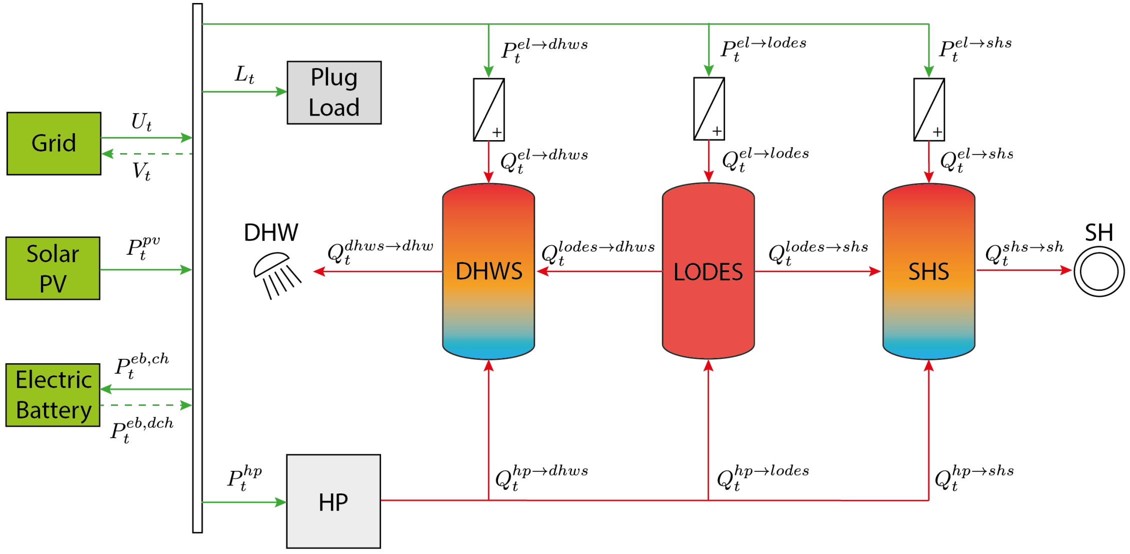
7. **TCS modes.** Only one discharge mode may be operational at any given time.

$$0 \leq x_t^{lodes \rightarrow shs} + x_t^{lodes \rightarrow dhws} + \leq 1$$

8. **SH and DHW Heat demands.** Total system heat output must meet forecast demand for all timepoints.

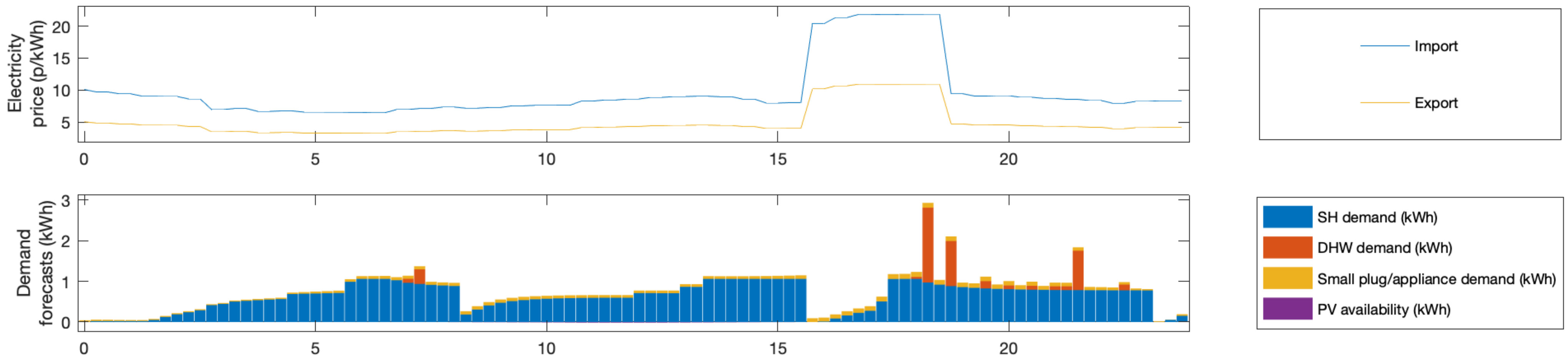
$$\widehat{Q^{dhw}} \leq Q^{dhw}$$
$$\widehat{Q^{sh}} \leq Q^{sh}$$

9. **Upper and lower bounds on decision variables.** Set based on system values, with input/output powers appropriately constrained.



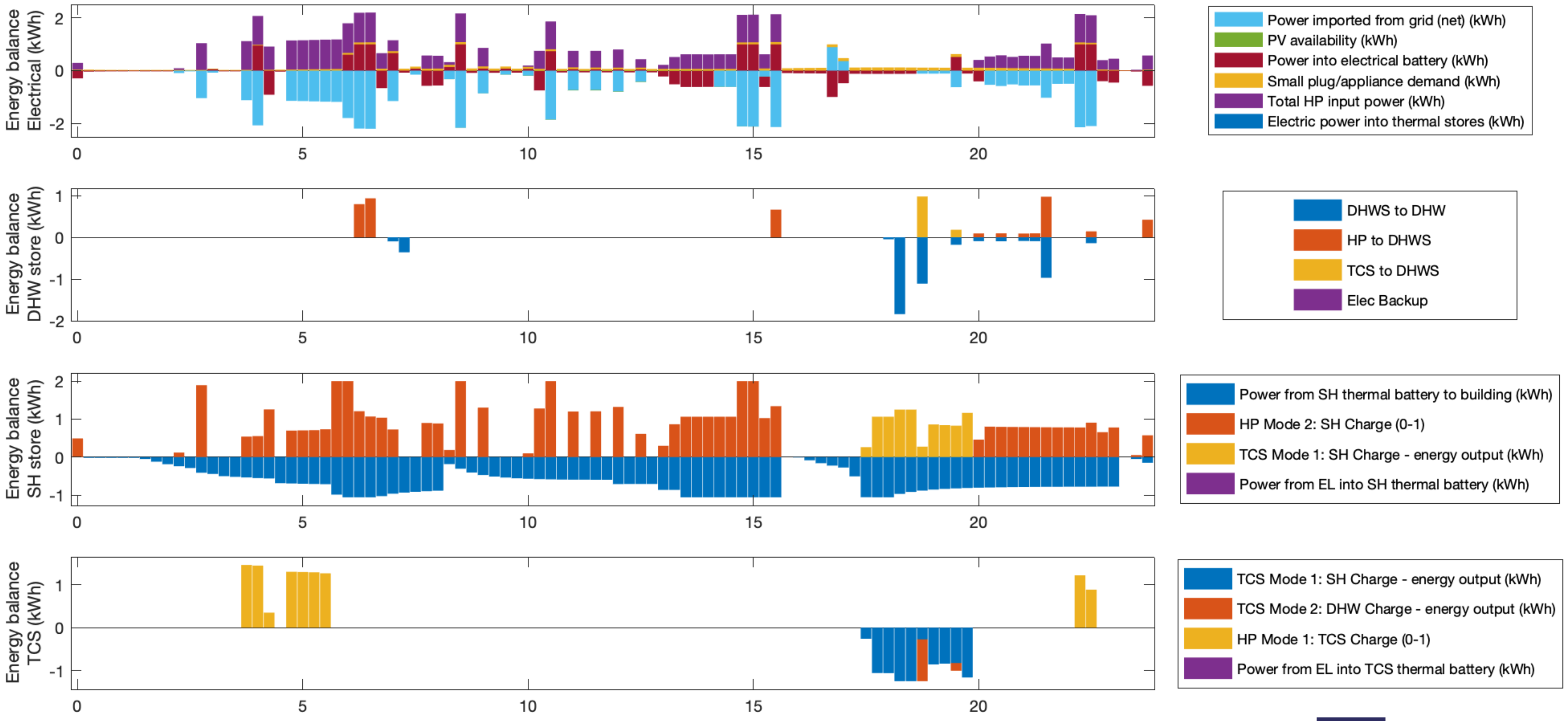
Example Outputs

Forecast variables: Energy prices and demands



Example Outputs

Decision variables: Energy flows



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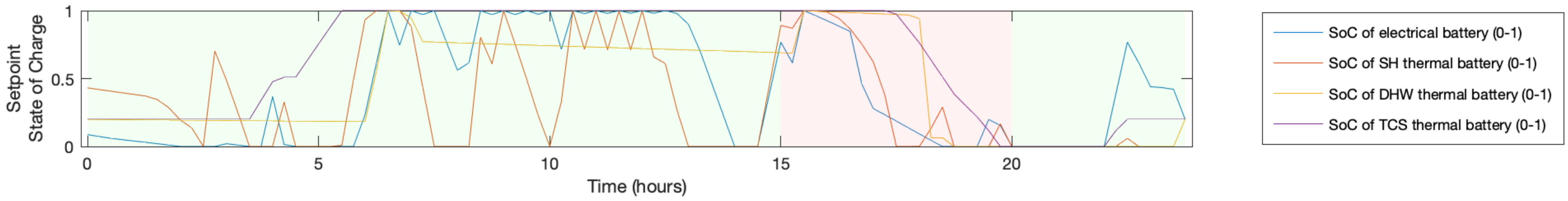
Example Outputs

Decision variables: SOCs



Example Outputs

Forecast and decision variables

Conclusions and Next steps

Conclusions

- A hierarchical scheme has been developed (but not demonstrated in full here!) to enable optimised control of long-duration storage
- A short duration control scheme based on MPC and linear programming (LP/MILP) has been developed and shows promise
  - A comparison to (P)RBC would be of value
  - Work remains on sensitivity to assumptions/simplifications
- There are limits to which MPC can be made “objective”
  - In RBC, biases arise through choice and parameterisation of rules
  - In MPC, parameterisation remains important, with bias also arising through simplifications e.g. of constraints

Conclusions and Next steps

Next steps

- Short term strategies
  - Investigate sensitivity to assumptions/simplifications
- Long term strategies
  - Develop and evaluate a set of long term strategies, both rule-based and MPC-based
  - Benchmark performance against Short Duration model with extended horizon
  - Initial work on efficient arbitrage-based decision making underway
- Forecasts
  - Compare demand forecast methods (model-based, data-based) for different time resolutions/window lengths
- Additional system elements
  - Incorporate EVs: V2G and V2B strategies
- Practical demonstration of control approach within (a) controlled and (b) real-world environments

- Energies Special Issue: https://www.mdpi.com/journal/energies/special_issues/Buildings_Energy_Environment

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Project ADSorB

Advanced Distributed Storage for grid Benefits

Funder: BEIS Net Zero Innovation Portfolio: Longer Duration Energy Storage

Contact: Dr Robert Barthorpe
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The challenge

Decarbonisation of domestic heat offers both huge opportunities and challenges.

Increased penetration of renewable energy generation allied to the electrification of domestic heating systems is expected to create substantial grid balancing issues.

Imbalances in inter-seasonal supply and demand present a particular challenge, promoting interest in long-duration electrical and thermal energy storage.

Our approach

Modular units

for domestic energy systems, for use in new build or retrofit

Thermal storage

utilising innovative, extended-duration thermal storage technologies

Decoupling generation

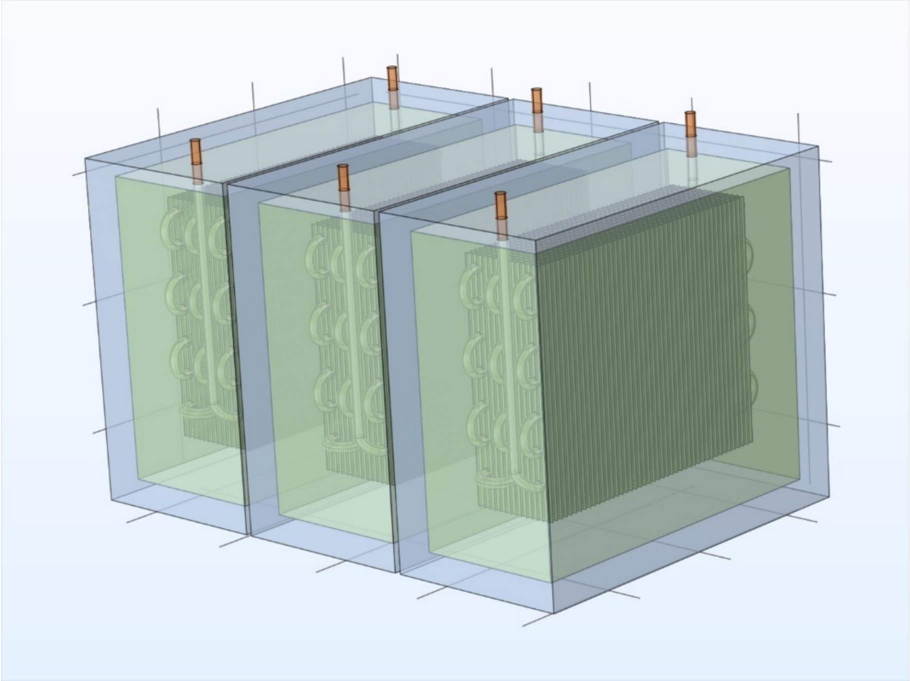
from heat demand over time periods ranging from a few hours to weeks

Occupant benefits

through reduced consumption and grid benefits through deferral

Phase Change Material (PCM) storage

0.18m^3 system comprising 3 modules containing bio-based material.



Flexible system enables variable power outputs, modulated based on demand.

10 kWh Thermal storage capacity

12 kW Peak output per module.

24+ hours Storage duration.

Thermochemical Storage (TCS)

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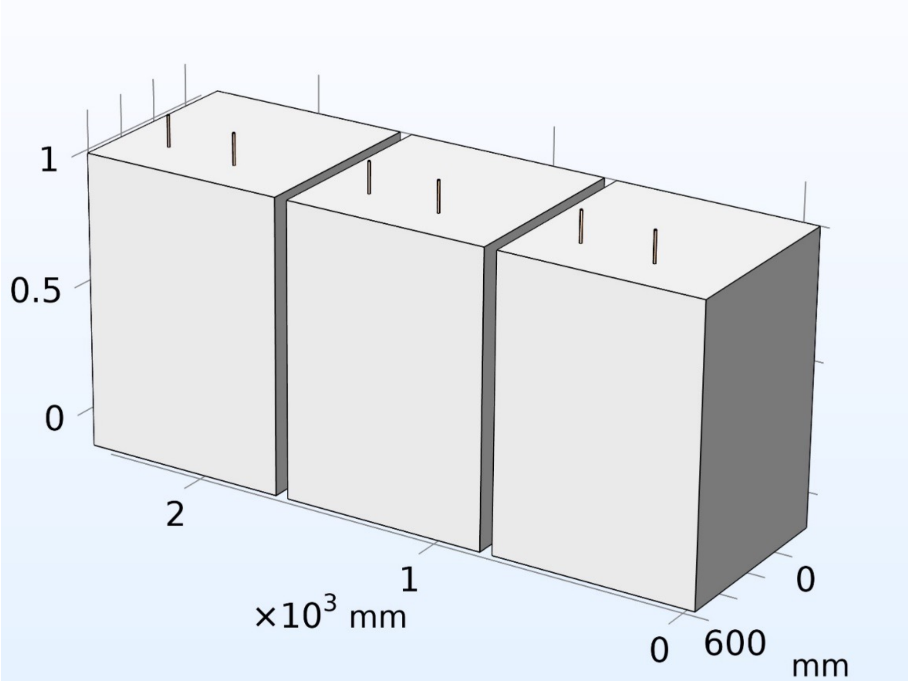
1m^3 system comprises 3 modules containing salt hydrate active material.



Flexible system enables variable power outputs, modulated based on demand.

144 kWh — Thermal storage capacity

17 kW — Peak output per module.

∞ hours — Standing losses over days, weeks, or months.

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Impact: Modelling approach

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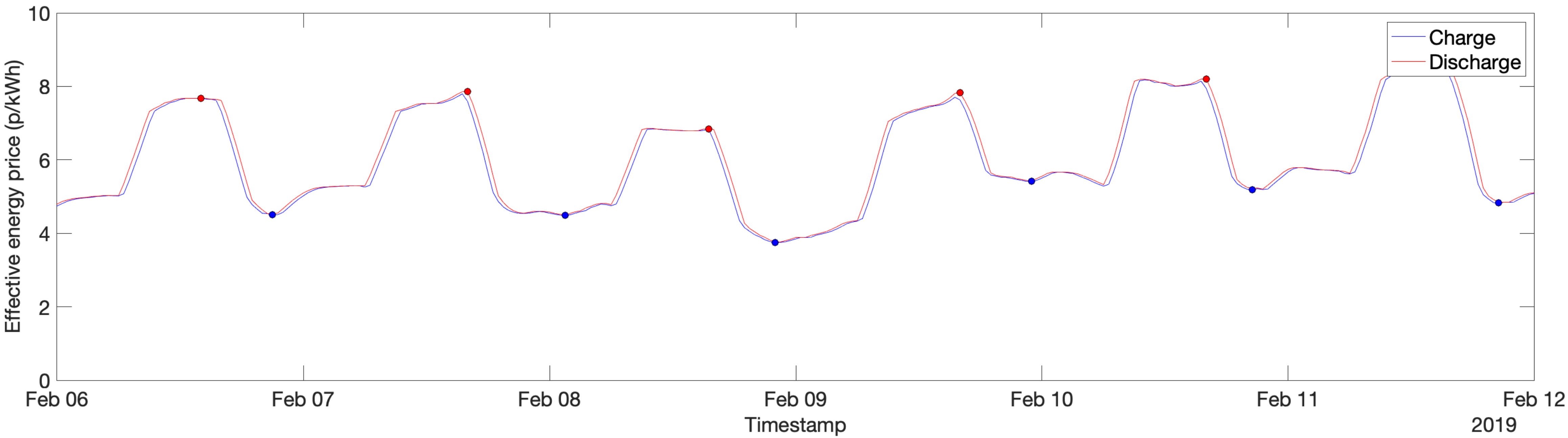
Levelised Cost of Storage (LCOS)

$$LCOS\left[\frac{£}{kWh_{out}}\right] = \frac{CAPEX + \sum_{n=1}^{N}\frac{OPEX_n}{(1+r)^n} + \sum_{n=1}^{N}\frac{Charge\ cost_n}{(1+r)^n} + \frac{EOL}{(1+r)^{N+1}}}{\sum_{n=1}^{N}\frac{Energy\ out_n}{(1+r)^n}}$$

Net Present Value (NPV)

$$NPV[£] = \sum_{n=1}^{N}\frac{Revenue_n}{(1+r)^n} - CAPEX - \sum_{n=1}^{N}\frac{OPEX_n}{(1+r)^n} - \frac{EOL}{(1+r)^{N+1}}$$

Impact: Modelling cost optimisation



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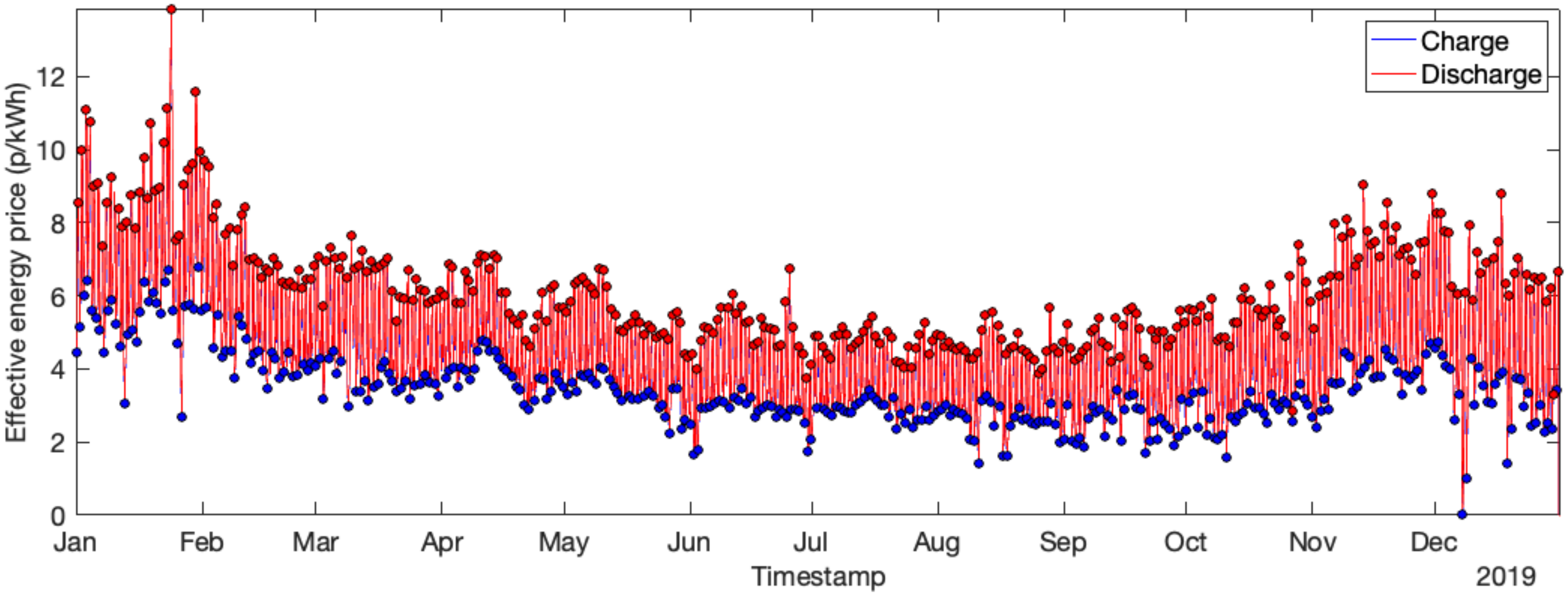
Impact: Modelling cost optimisation



Impact: Modelling cost optimisation

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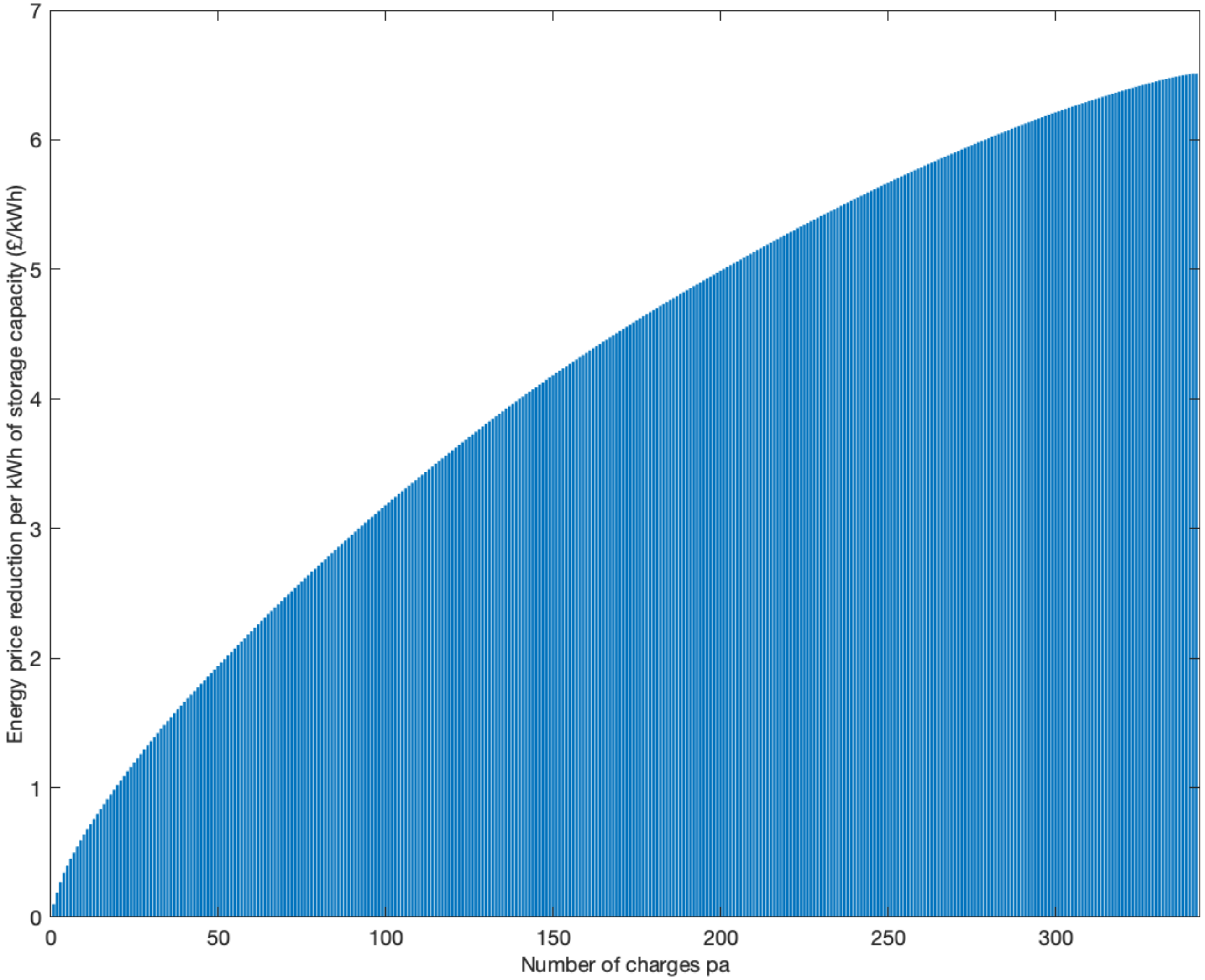

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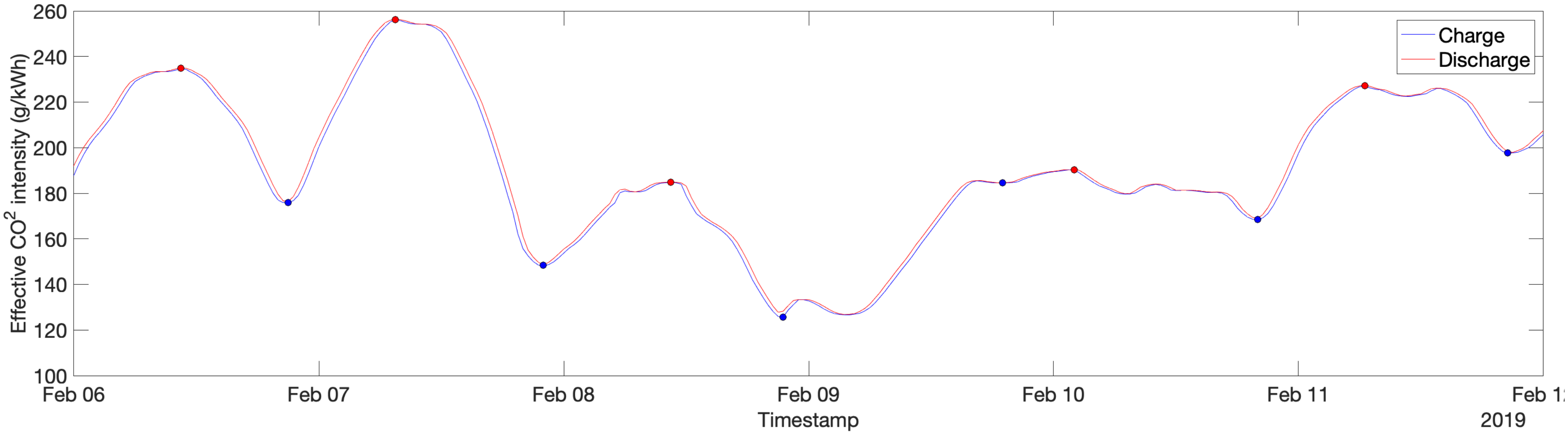
Impact: Modelling CO^2 optimisation



Impact: Modelling CO2 optimisation

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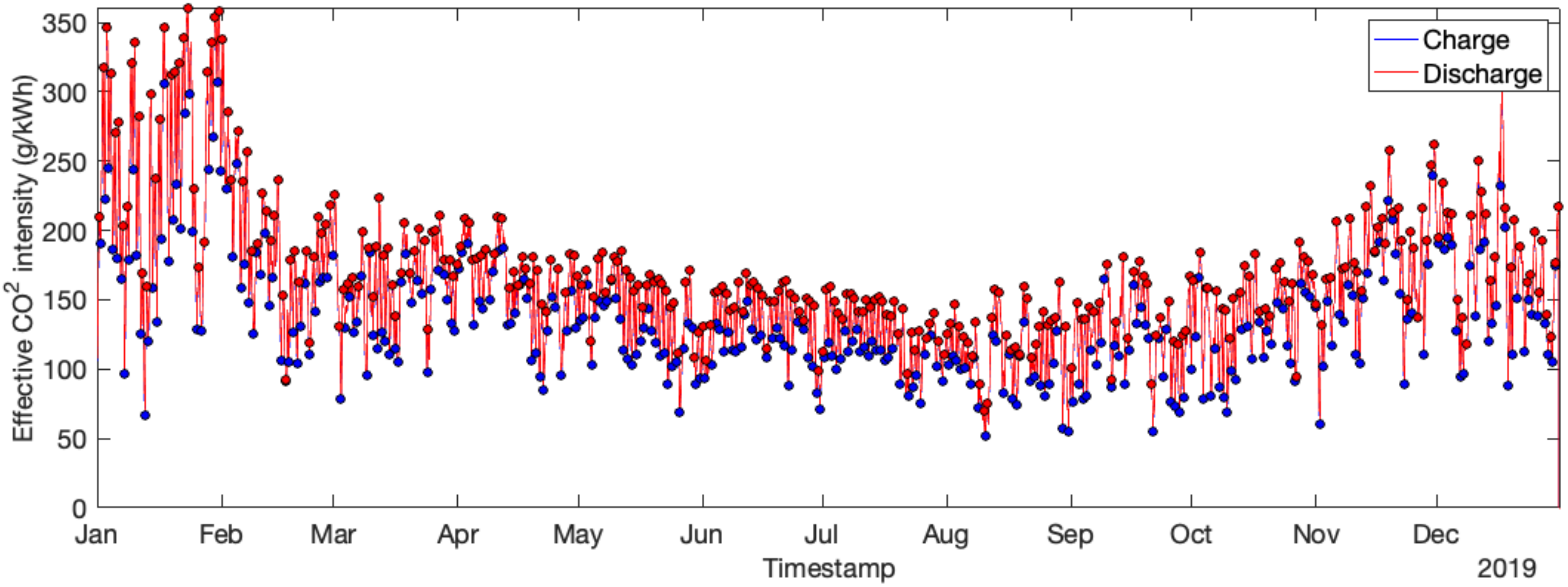

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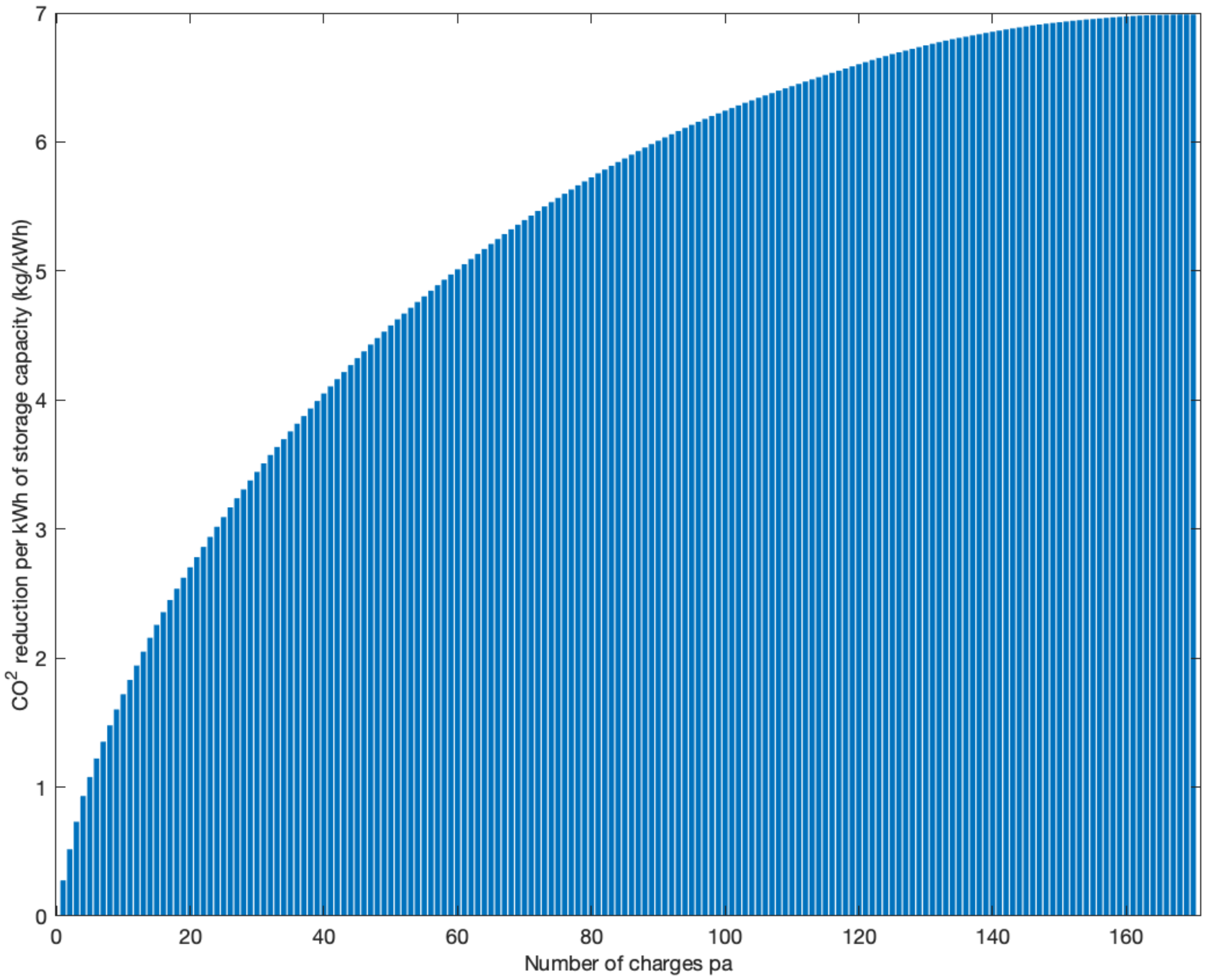

Levelised cost of storage

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Store	CAPEX [£]	OPEX/pa [£]	EoL [£]	Cycles pa	Capacity [kWh]	Charge efficiency [%]	Discharge efficiency [%]	Life [years]	LCOS [p/kWh_{sto}]
Li-Ion	10000	50	100	365	10.4	95	285	10	16.9
HWT	1000	50	100	365	7	300	100	25	9.3
PCM	1250	50	100	365	10	300	100	25	8.4
TCS	1000	50	100	365	10	270	100	25	9.3
TCS	1500	50	100	52	144	240	100	25	8.1

Net present value

Store	Functional capacity [kWh]	Cycles pa	Life [years]	Arbitrage value		NPV [£]
				$/kWh_{cap}$ [£]	Total [£]	
Li-Ion	10.4	338	10	64.83	674	-4521
HWT	7	341	25	24.45	171	2362
PCM	10	340	25	27.77	278	4776
TCS	10	340	25	28.24	282	5143
TCS	144	52	25	1.99	286	4747

Carbon arbitrage

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Store	Functional capacity [kWh]	Cycles pa	Carbon reduction [$kgCO^2$]	Price reduction [£]
Li-Ion	10.4	296	370	166
HWT	7	341	105	21
PCM	10	340	218	51
TCS	10	303	210	47
TCS	144	52	672	3

Phase 2: Development and Live demonstration

Phase 2: Productisation

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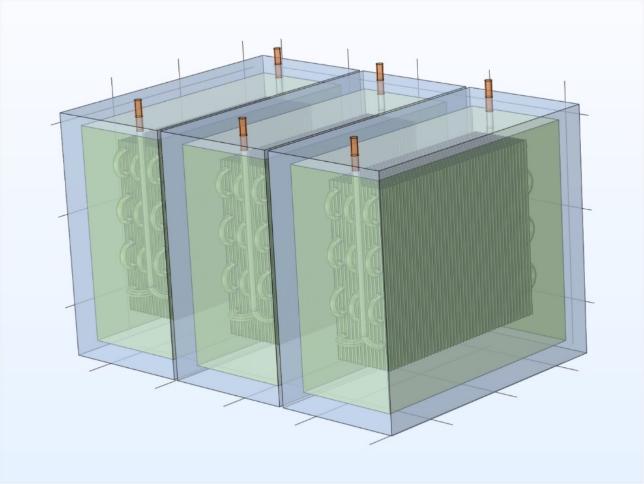

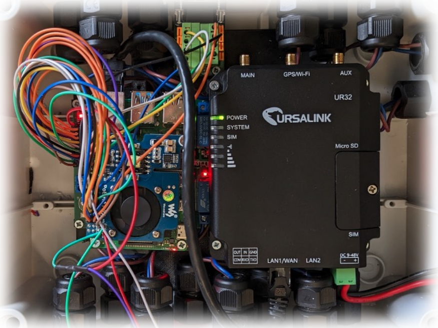

Phase 2: Productisation

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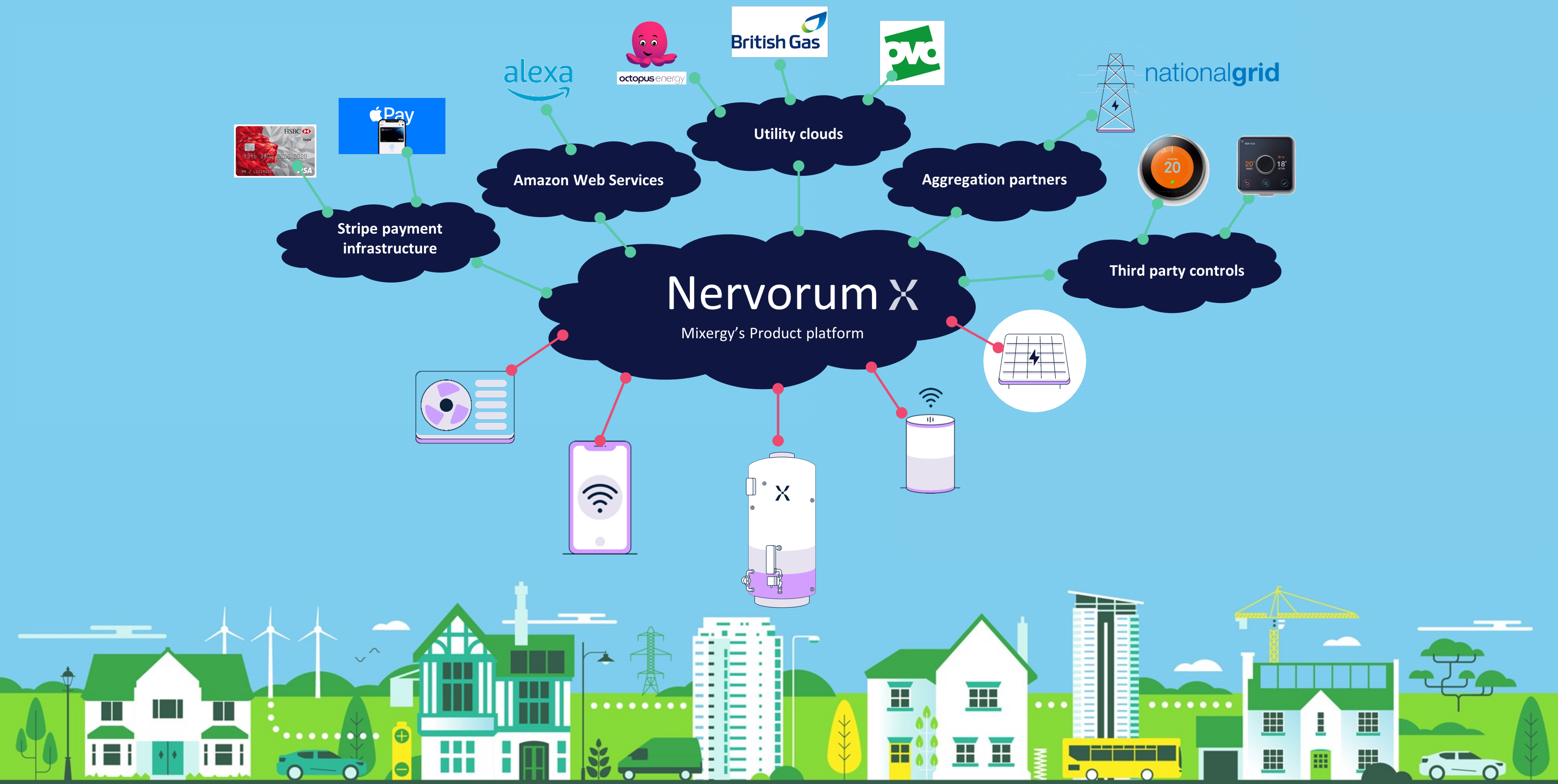

Questions