Network-aware Demand Response in the Presence of Uncertainties

Gayan Chaminda Lankeshwara

Supervised by:
Dr. Rahul Sharma
Prof. Tapan Saha
Dr. Ruifeng Yan

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Power, Energy and Control Engineering Research Group
School of Information Technology and Electrical Engineering
The University of Queensland, Australia

Outline

- Introduction
- Motivations
- Objectives
- Main Contributions
- Conclusions
- Future Work
- Thesis timeline
- Publications

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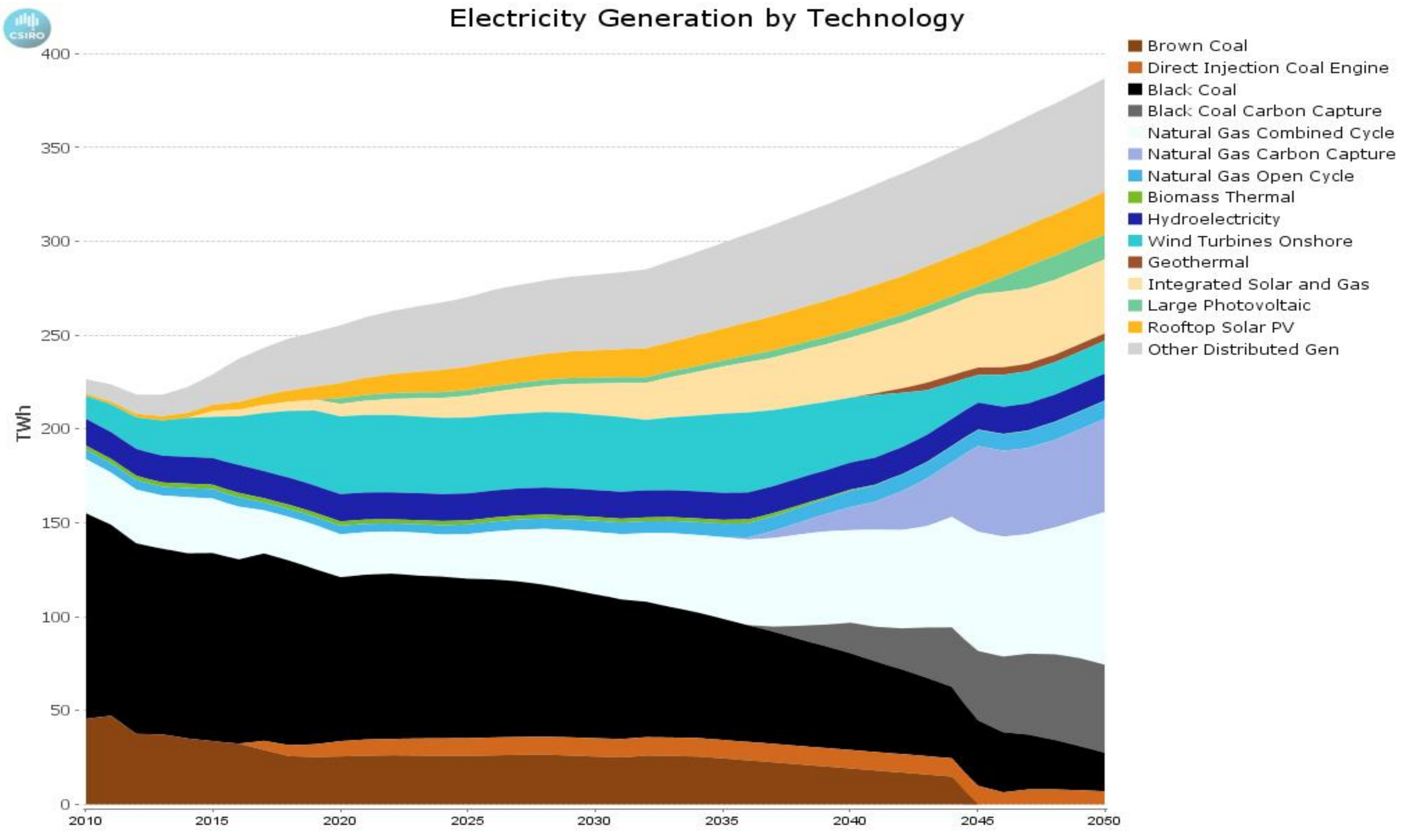
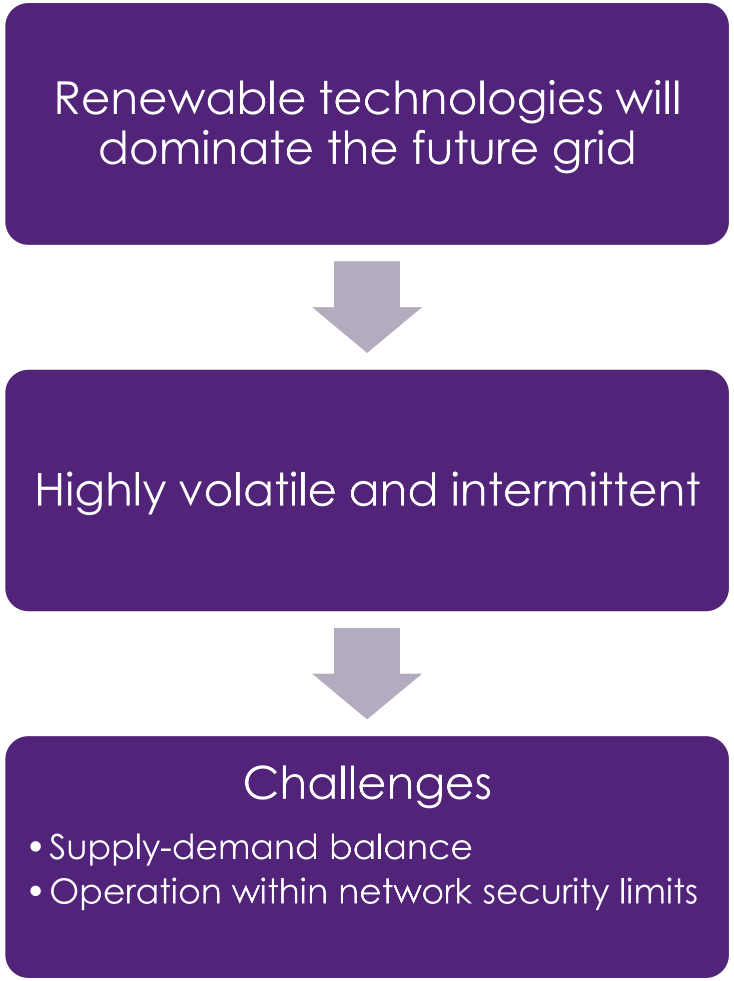
Global Energy Outlook



Source: CSIROs eFuture tool



Renewable technologies will dominate the future grid

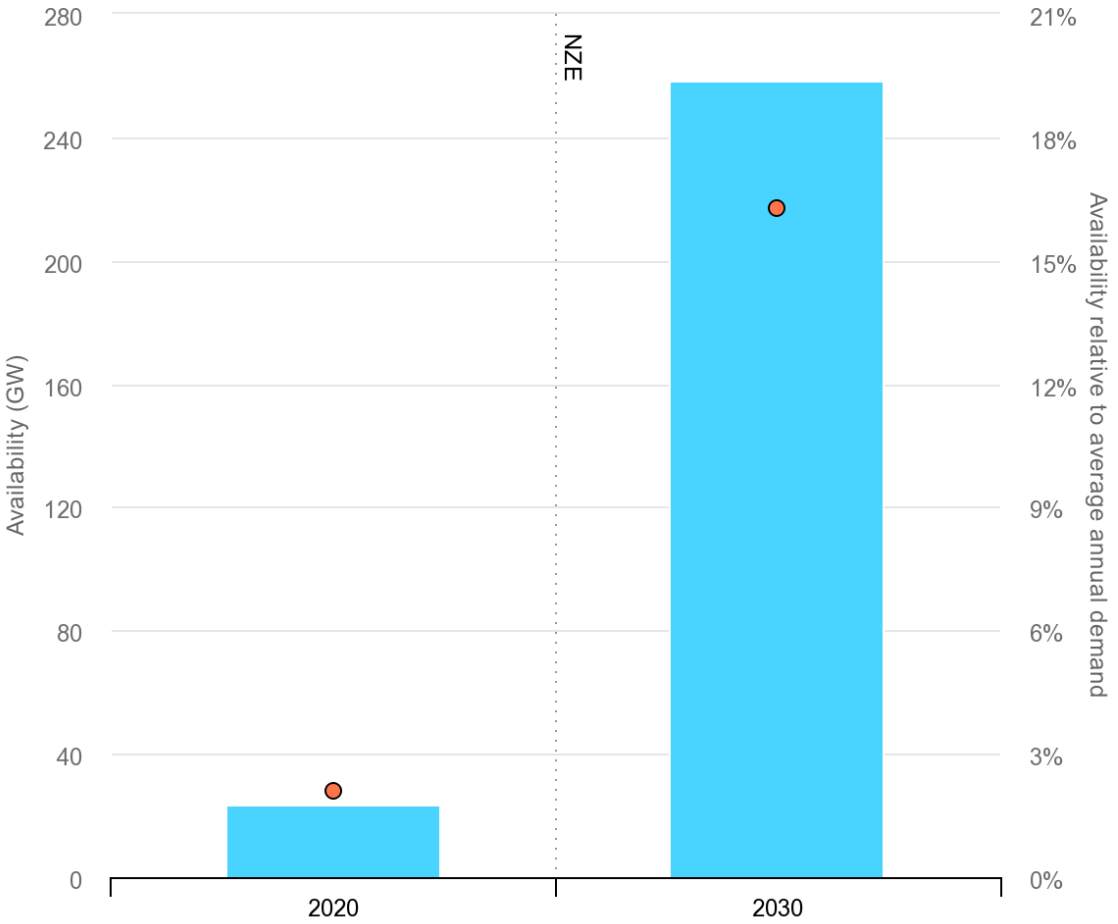
Highly volatile and intermittent

Challenges

- Supply-demand balance
- Operation within network security limits

Non-conventional reserve provisions are essential to maintain network security and reliability.

Demand Response



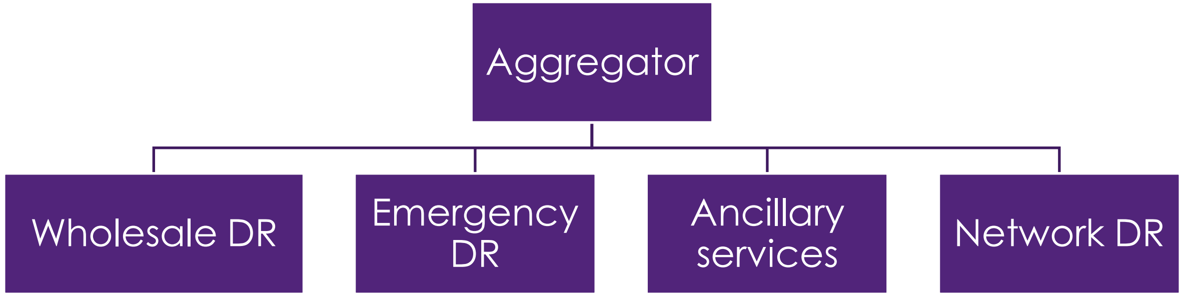
Demand response availability at times of highest flexibility needs and share in total flexibility provision

Consumer-centric approach

Changes in electricity usage from nominal consumption in response to:

- Price signal
- Incentive payment

For power markets,



Aggregator

Wholesale DR

Emergency DR

Ancillary services

Network DR

https://www.iea.org/data-and-statistics/charts/demand-response-availability-at-times-of-highest-flexibility-needs-and-share-in-total-flexibility-provision-in-the-net-zero-scenario-2020-and-2030, IEA.

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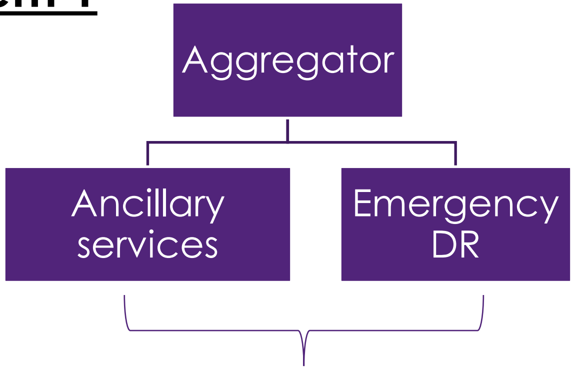
Motivations

Problem 1



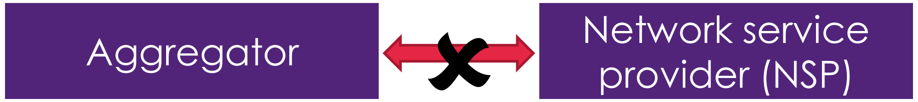
If bids cleared,
commitment is mandatory

Non-compliance → PENALTY

Presence of uncertainties ???

DR aggregator is no longer able to deliver contracted demand in real-time

Problem 2



No knowledge of the network

Only knows network information

No proper coordination between Aggregator and NSP

If households export PV to the grid on top of DR

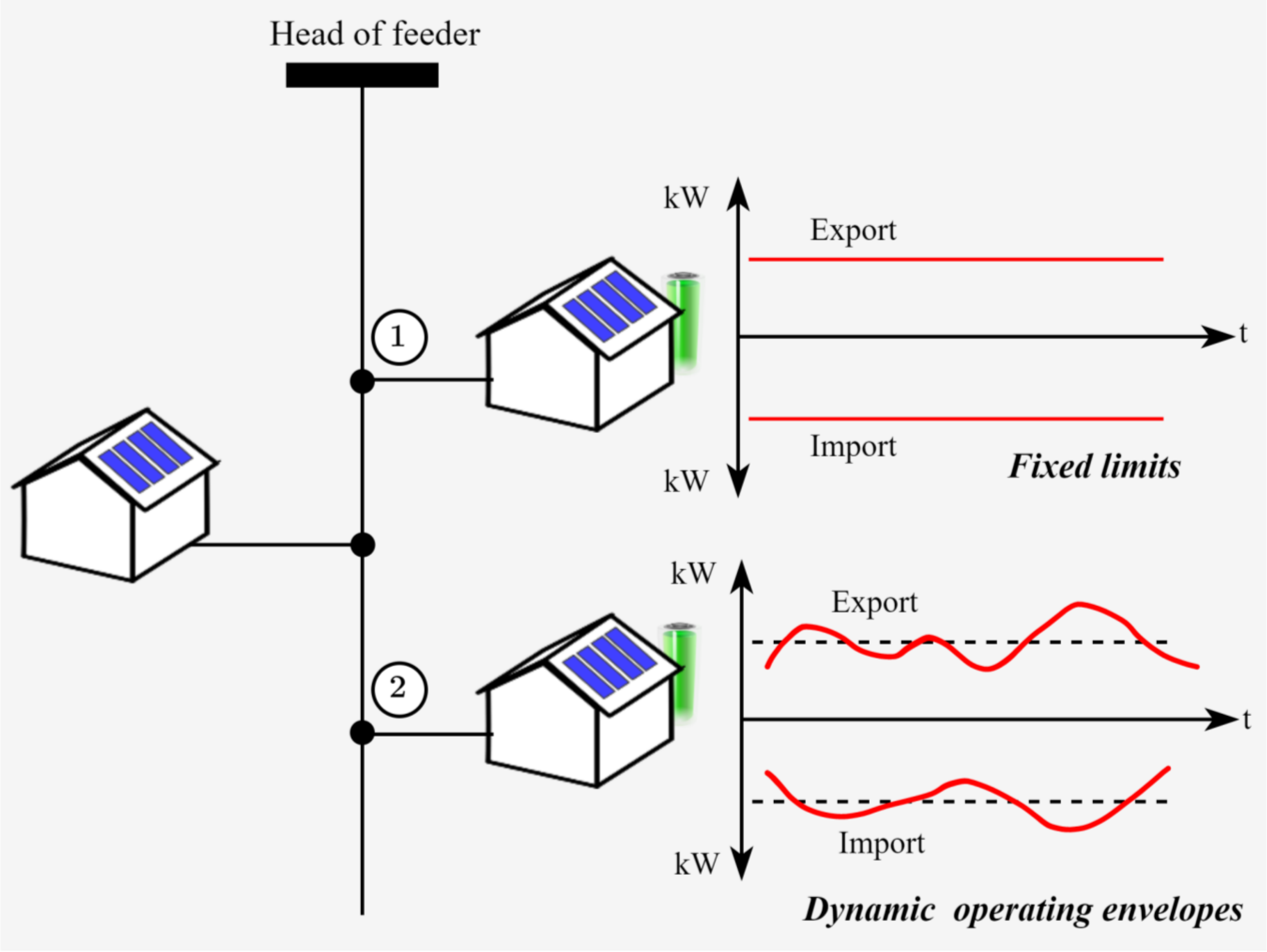
↓

Over-voltage issues and thermal overloading are inevitable

Network-agnostic DR schemes lead to network statutory limit violations!

Network-aware DR schemes that account for uncertainties are vital for real-world implementation

Dynamic operating envelopes (DOE)



"Operating envelopes vary import and export limits over time and location based on the available capacity of the local network or power system as a whole." [1]

More emphasis on DOE for export power management

How feasible is it to adopt the DOE framework for DR applications?

[1] Dynamic Operating Envelopes Working Group, "Outcomes Report." Mar. 2022, [Online]. Available: https://arena.gov.au/assets/2022/03/dynamic-operating-envelope-working-group-outcomes-report.pdf.

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1. **To develop control strategies for residential DR to participate in grid services under uncertainties.**

2. **To propose techniques to establish dynamic operating envelopes in low-voltage distribution networks to ensure network integrity.**

3. **To develop network-aware control schemes for residential DR to participate in grid services under the dynamic operating envelopes framework.**

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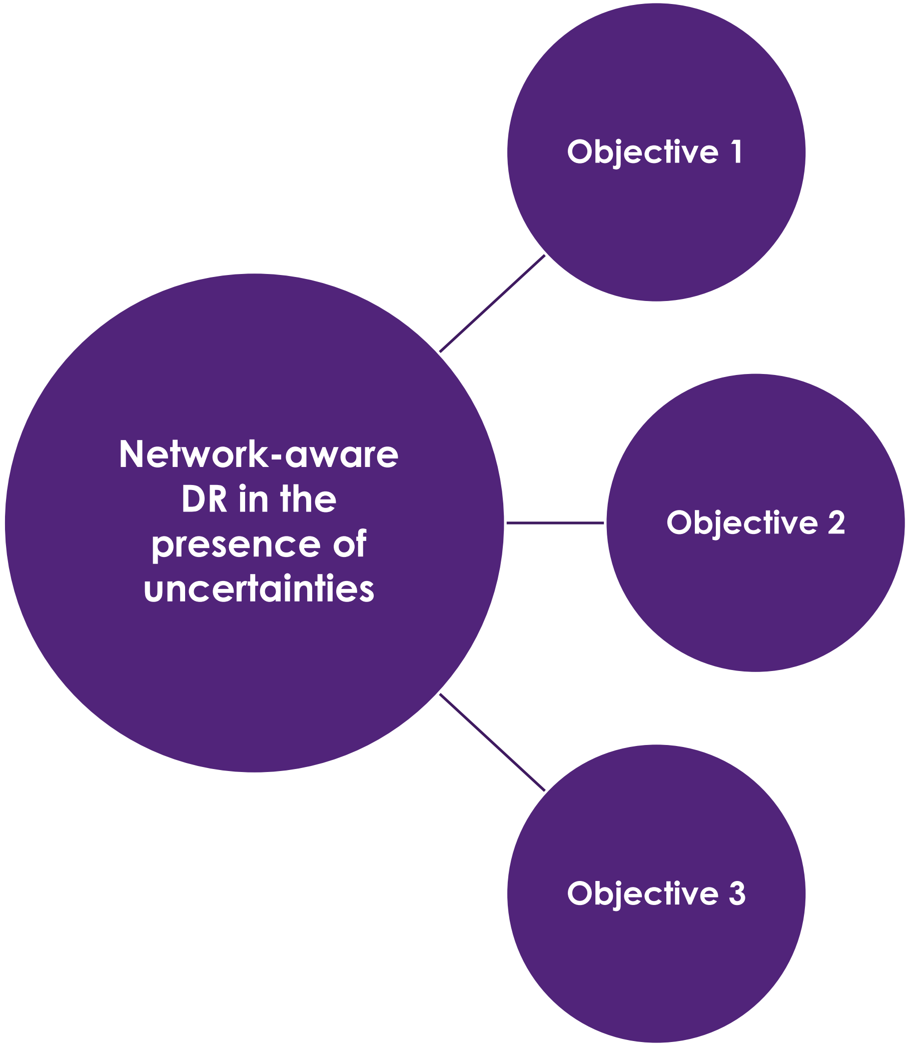
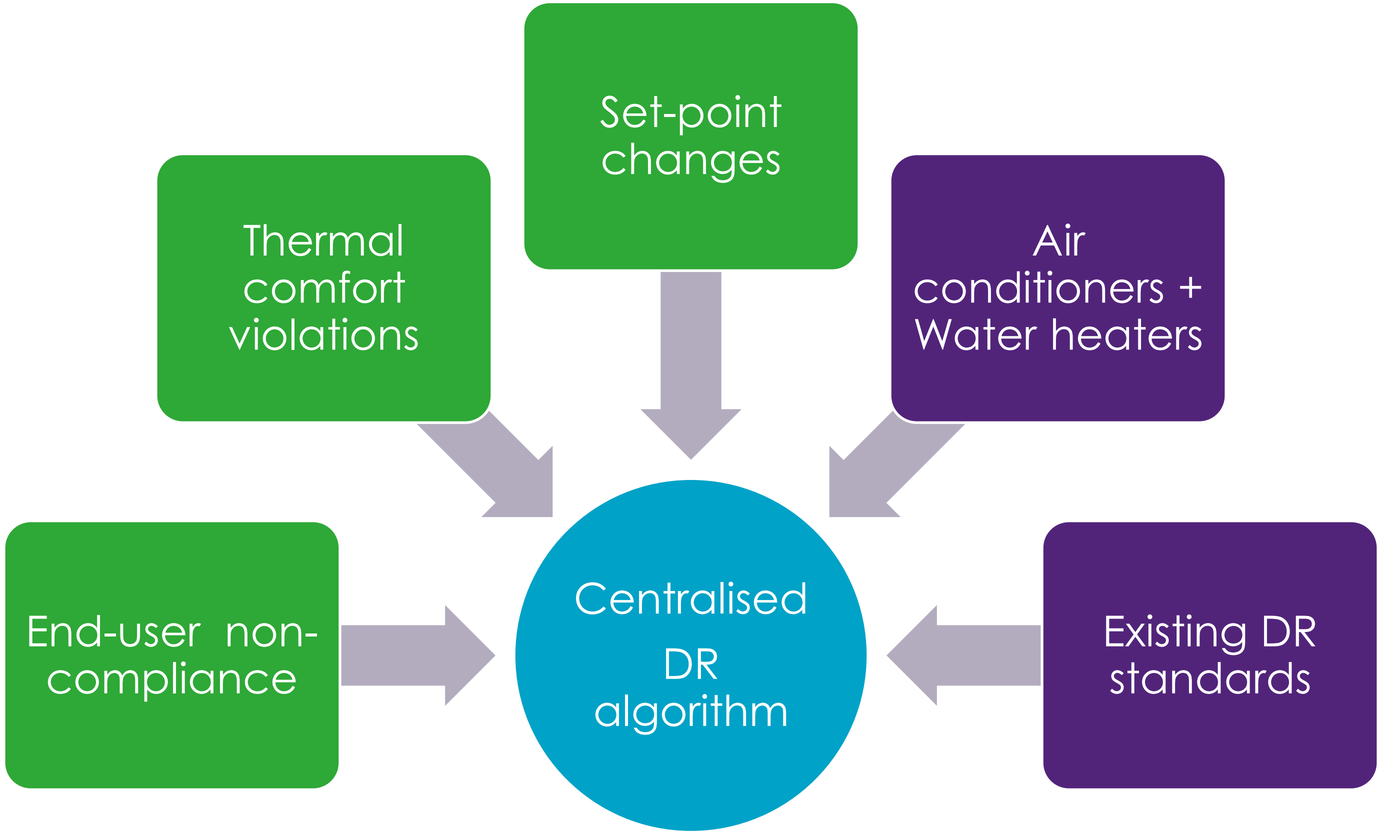


1. Centralised heuristic algorithms for residential DR to participate in grid services under uncertainties
2. Centralised robust MPC scheme for residential DR to participate in grid services under uncertainties
3. Distributed control framework for an aggregator to provide DR in real-time markets under uncertainties

4. A real-time approach for the DNSP to assign dynamic export limits for households with rooftop PV connections
5. A real-time approach for the DNSP to establish household operating envelopes that account for end-user flexibility

6. A real-time coordinated scheme for residential DR in LV networks under the dynamic operating envelopes framework

Contribution 1: Centralised heuristic algorithms for residential DR to participate in grid services under uncertainties


Set-point changes

Thermal comfort violations

Air conditioners + Water heaters

End-user non-compliance

Centralised DR algorithm

Existing DR standards

AS/NZS 4755.3 DR standards

Mode	Action
DRM 1	Do not consumer power
DRM 2	Limit consumption to 75% rated
DRM 3	Limit consumption to 50% rated

G. Lankeshwara, R. Sharma, R. Yan, and T. K. Saha, "Control algorithms to mitigate the effect of uncertainties in residential demand management," *Applied Energy (Elsevier)*, vol. 306, p. 117971, 2022, doi: 10.1016/j.apenergy.2021.117971.

Approach

System operator load set-point

P_{ref}

Marginal cluster and lower priority clusters

One-step ahead optimisation in the marginal cluster

Aggregator dispatches set-points

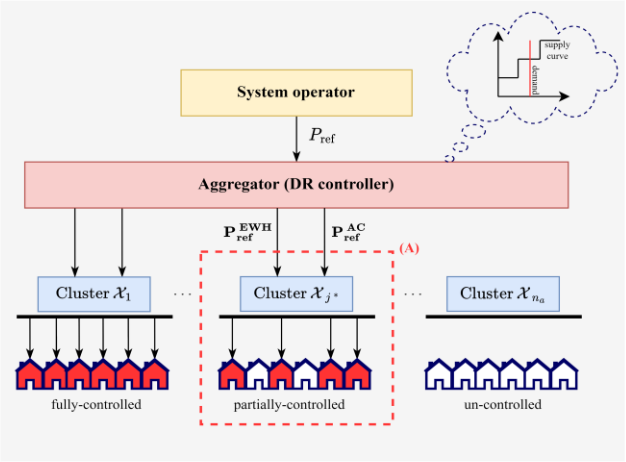
Subsystem power update and temperature calculations

Comparison with desired DR

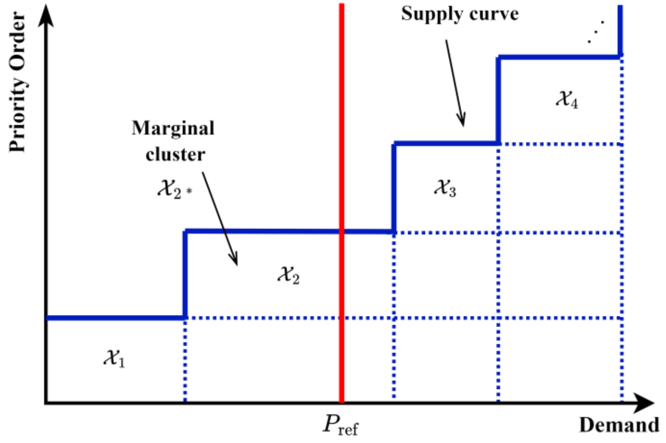
Assessment of uncertainties

Update load set-point for the next step

- **Non-compliance**
- **Thermal comfort violations**
- **Load set-point changes**



Conceptual priority-based ranking mechanism and supply curve emulation



One-step ahead optimisation

Minimising cost +
Minimising thermal discomfort

$$F = w_{\text{cost}} \cdot \sum C_p(t) \cdot \left(P_i(t) - \Delta P_i(t)\right) \cdot \Delta t + w_{\text{dis}} \cdot \sum DI_i(t)^2 \quad \forall i \in \mathcal{X}_{j^*}$$

$$\underset{\Delta P_i^{\text{AC}}, \Delta P_i^{\text{EWH}}}{\text{minimise}} \quad F(\cdot)$$

$$\sum_i \Delta P_i^{\text{AC}}(t) + \sum_i \Delta P_i^{\text{EWH}}(t) \leq \overline{P}_{\text{ref}}(t)$$

$$\underline{P}_i^{\text{AC}} \leq P_i^{\text{AC}}(t) \leq \overline{P}_i^{\text{AC}}$$

$$\underline{P}_i^{\text{EWH}} \leq P_i^{\text{EWH}}(t) \leq \overline{P}_i^{\text{EWH}}$$

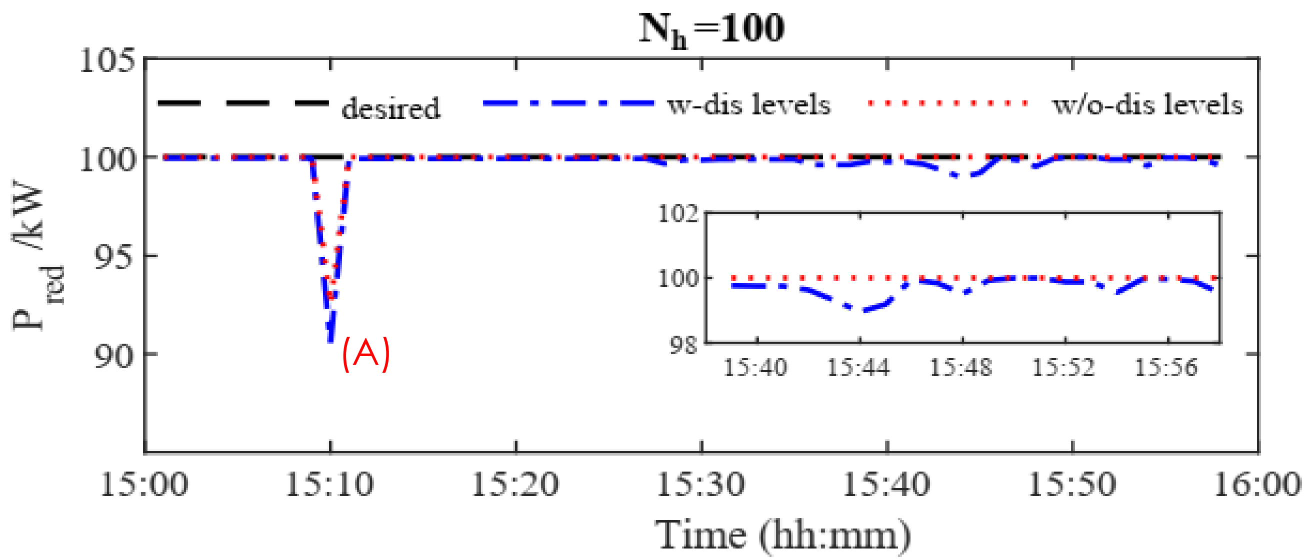
$$P_i^{\text{AC}}(t) = K_i^{\text{AC}}(t) \cdot P_{i,\text{rated}}^{\text{AC}}$$

$$P_i^{\text{EWH}}(t) = K_i^{\text{EWH}}(t) \cdot P_{i,\text{rated}}^{\text{EWH}}$$

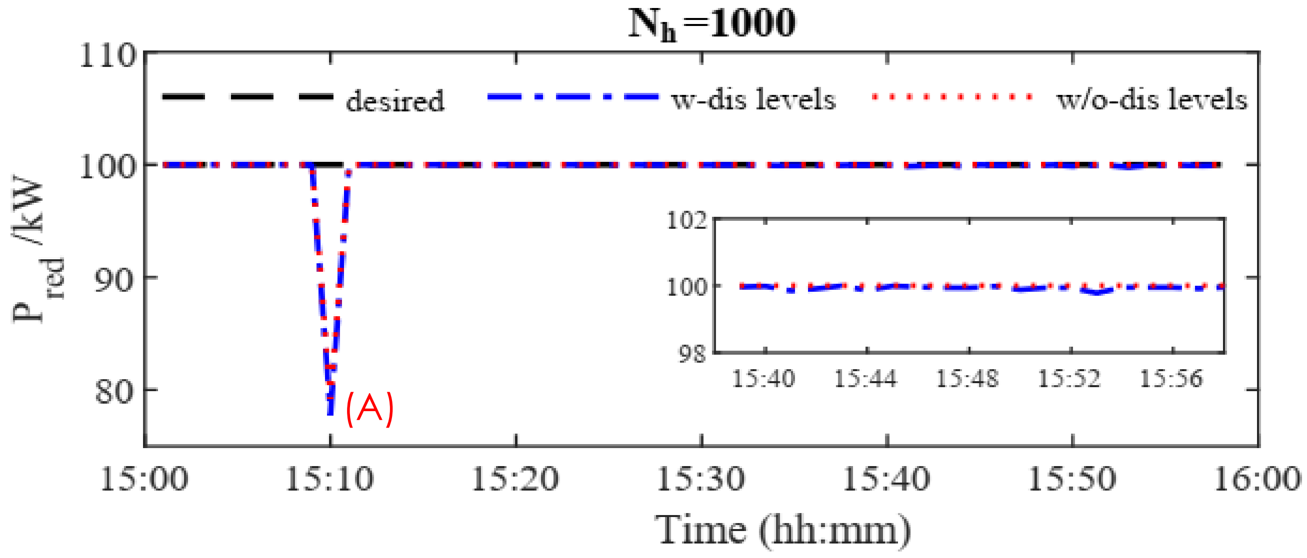
$$K_i^{\text{AC}}(t), K_i^{\text{EWH}}(t) \in \mathcal{S} := \{0.25, 0.50, 0.75, 1.0\}$$

$$w_{\text{cost}} + w_{\text{dis}} = 1$$

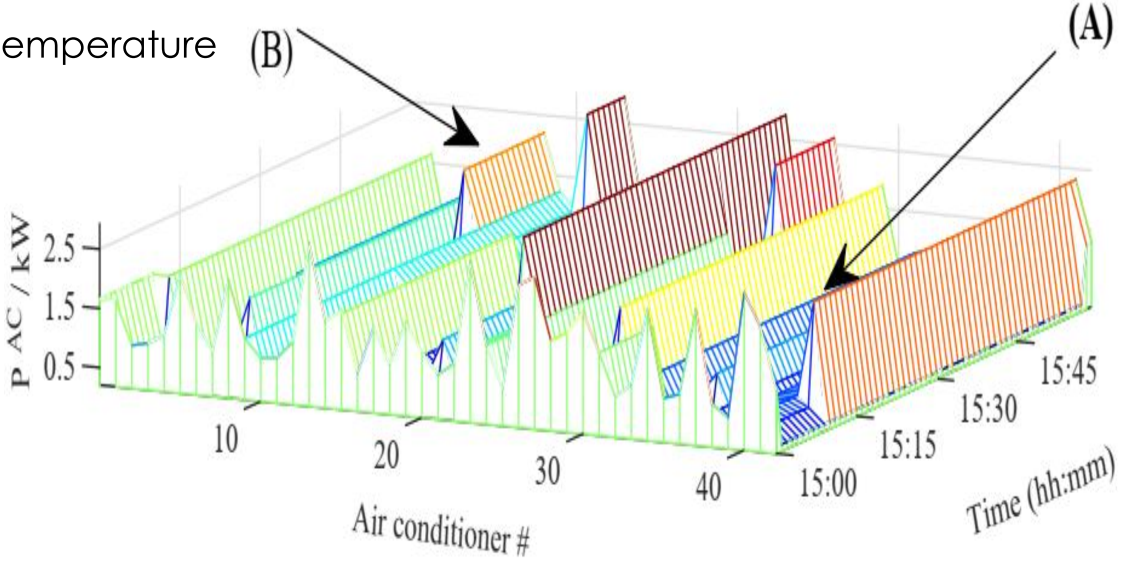
Results



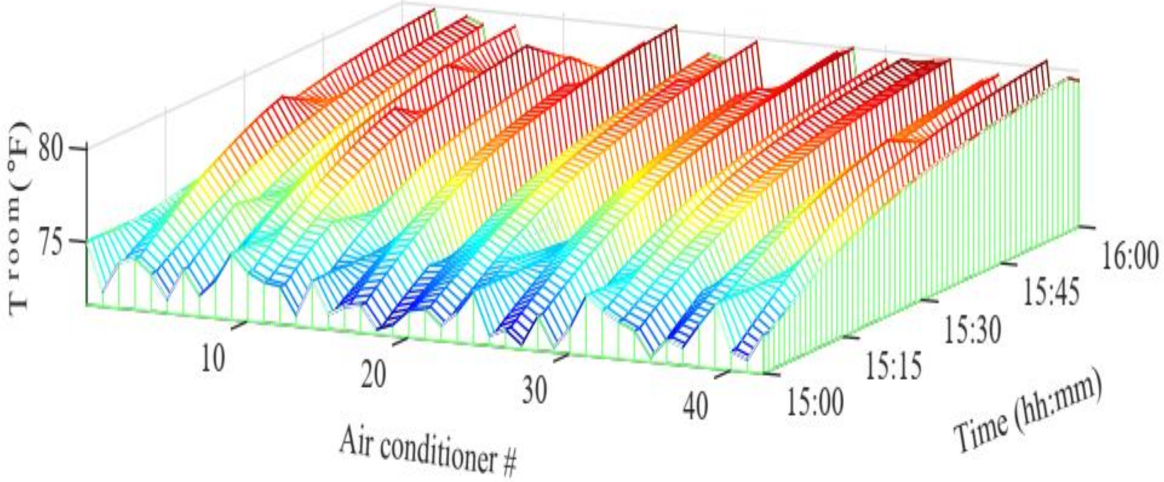
customer
override event
(A)



The tracking performance increases as the population size (N_h) increases.


Resuming operation after temperature violations

override event

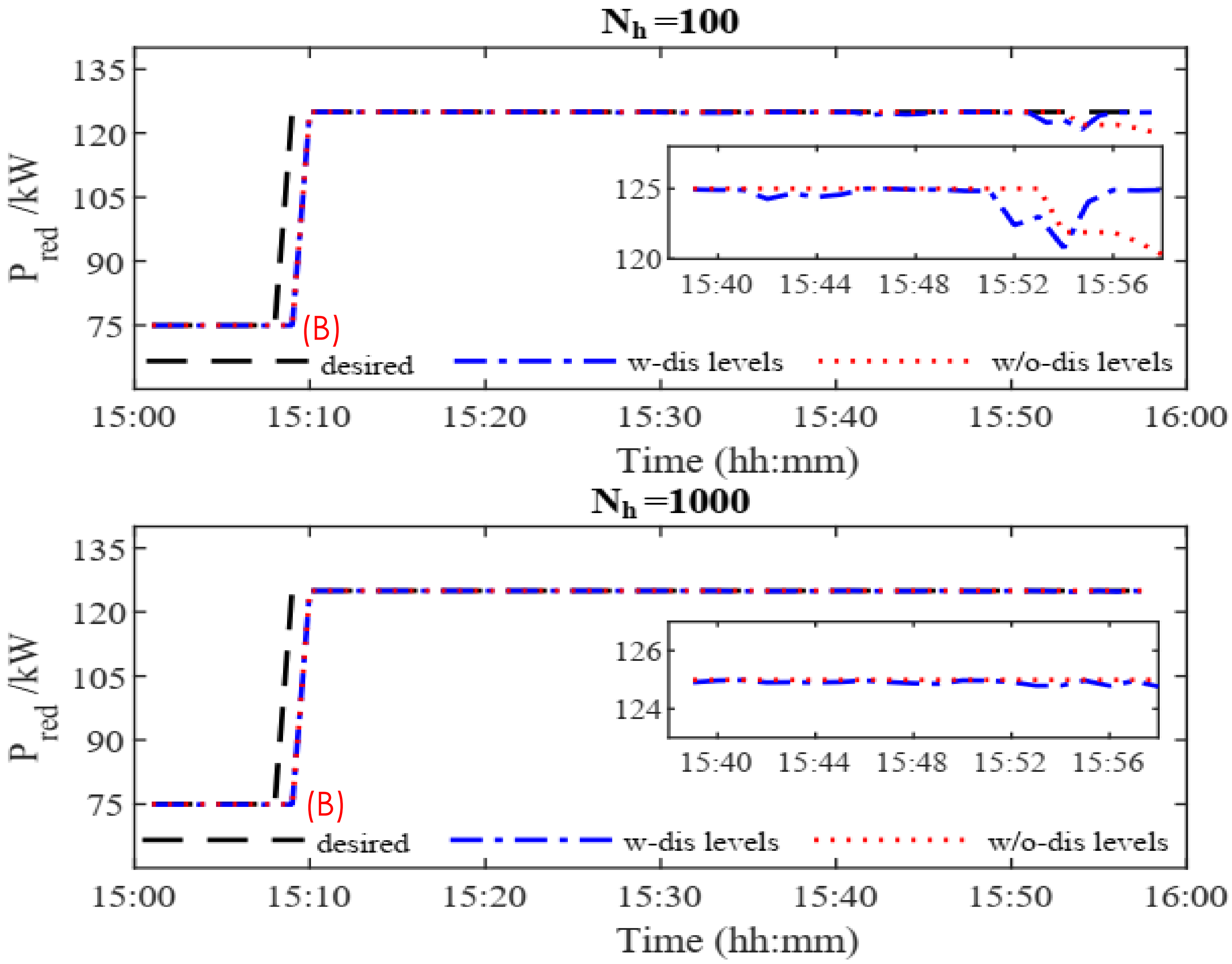


Thermal comfort limits for AC:

$\mathcal{U}(68, 80)°F$

Thermal comfort is maintained in the event of a customer override event.

Set-point change (B)



The tracking performance increases as the population size (N_h) increases.

Computational performance

Number of houses (N_h)	Total execution time (sec)			
	customer override		*set-point change*	
	without-discrete	with-discrete	without-discrete	with-discrete
100	55.22	142.8	14.52	213.5
1000	188.6	2857	176.0	2823

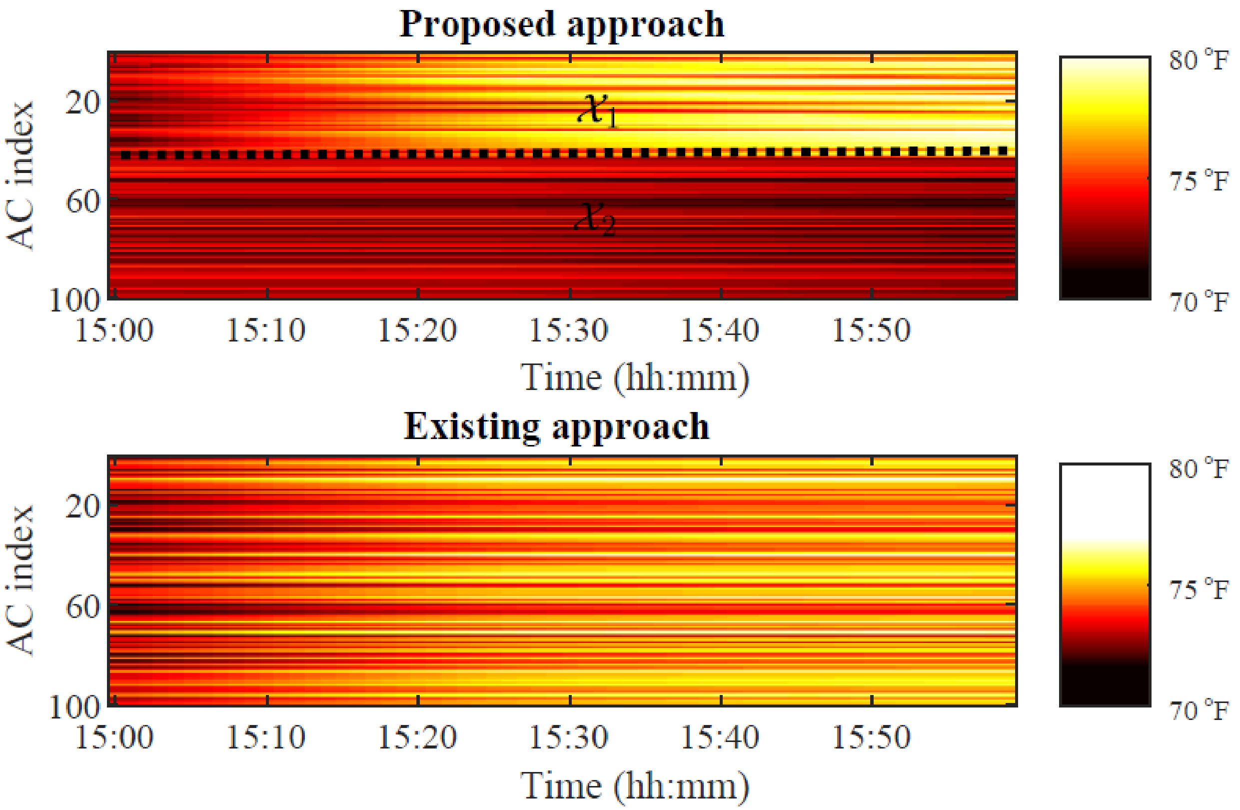
** Simulations are performed on a computing facility equipped with an Intel(R) Xeon(R) CPI E5-2680 v3 @ 2.5 GHz with 32 GB memory

Sampling interval = 1-min

With $N_h = 1000$, total execution time < 3600 sec (1-hour)

Approach is scalable.

Comparison with *PeakSmart* (existing approach)

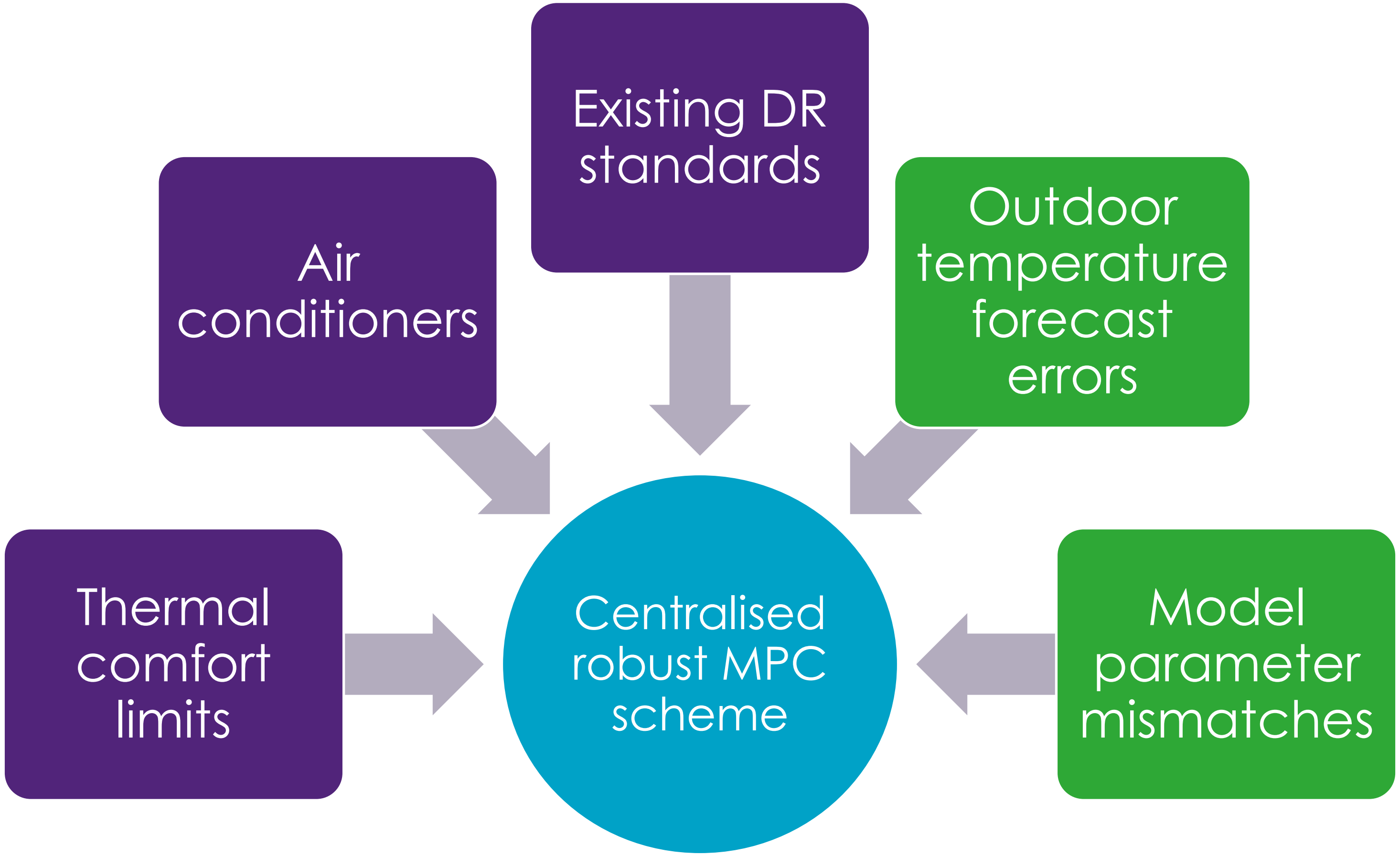


Proposed approach only controls a portion of ACs

Reduced control effort requirement

https://www.energex.com.au/home/control-your-energy/cashback-rewards-program/industry-information/peaksmart-installer-incentive-program

Contribution 2: Centralised robust MPC scheme for residential DR to participate in grid services under uncertainties


Existing DR standards

Air conditioners

Outdoor temperature forecast errors

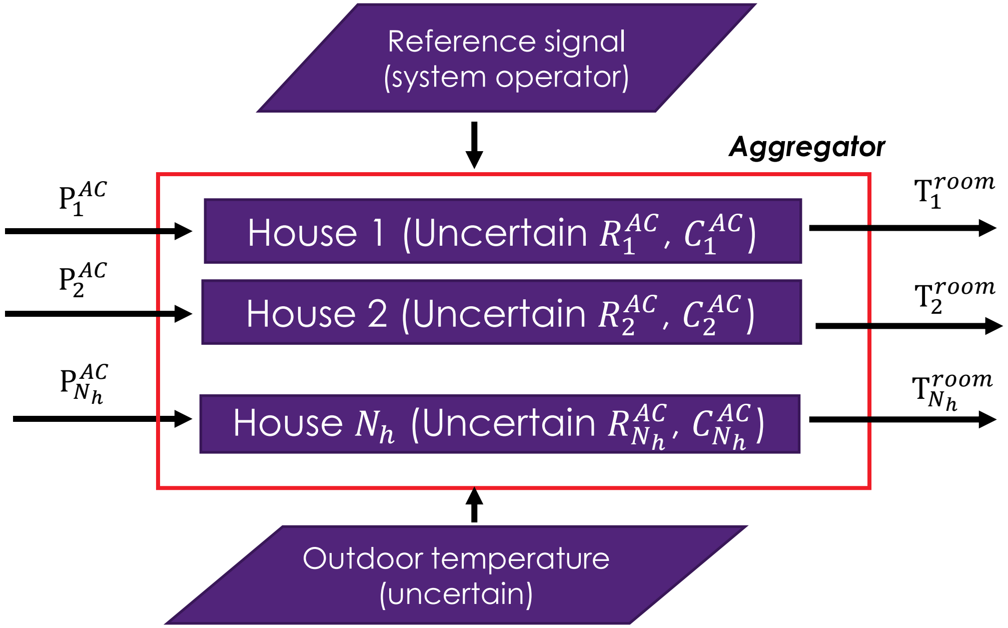
Thermal comfort limits

Centralised robust MPC scheme

Model parameter mismatches

G. Lankeshwara, R. Sharma, R. Yan, and T. K. Saha, "Control of Residential Air-conditioning Loads to Provide Regulation Services under Uncertainties," in *IEEE Power and Energy Society General Meeting*, 2021, vol. 2021-July, pp. 1–5, doi: 10.1109/PESGM46819.2021.9637890.

System model



Aggregate system obtained by stacking individual state space models

$$\mathbf{x}(t+1) = \mathbf{A}\mathbf{x}(t) + \mathbf{B}\mathbf{u}(k) + \mathbf{D}\mathbf{v}(k) + \mathbf{w}(k)$$
$$\mathbf{y}(k) = \mathbf{C}\mathbf{x}(k)$$

$\mathbf{x}(t) = \left[x_1(t), x_2(t) \ldots, x_{N_h}(t)\right]^{\mathrm{T}} \in \mathbb{R}^{N_h}$	Indoor temperature
$\mathbf{u}(t) = \left[u_1(t), u_2(k), \ldots, u_{N_h}(t)\right]^{\mathrm{T}} \in \mathbb{R}^{N_h}$	Power consumption of ACs
$\mathbf{v}(t) = \left[v_1(t), v_2(k), \ldots, v_{N_h}(t)\right]^{\mathrm{T}} \in \mathbb{R}^{N_h}$	Nominal outdoor temperature
$\mathbf{w}(t) = \left[w_1(t), w_2(k), \ldots, w_{N_h}(t)\right]^{\mathrm{T}} \in \mathbb{R}^{N_h}$	Uncertainties

Derivation of the model with uncertainties

$$T_i^{\text{room}}(t+1) = a_i \cdot T_i^{\text{room}}(t) + (1-a_i)\cdot\left(T_i^{\text{outdoor}}(t) - \eta_i^{\text{AC}} \cdot R_i^{\text{AC}} \cdot P_i^{\text{AC}}(t)\right)$$

$$\boxed{\begin{aligned} R_i^{\text{AC}} &= \tilde{R}_i^{\text{AC}} + \Delta R_i^{\text{AC}} \\ C_i^{\text{AC}} &= \tilde{C}_i^{\text{AC}} + \Delta C_i^{\text{AC}} \end{aligned}}$$

Bounds of uncertainty of thermal parameters known

$$a_i = \exp\left(\frac{-\Delta t}{R_i^{\text{AC}} \cdot C_i^{\text{AC}}}\right)$$
$$= \exp\left(\frac{-\Delta t}{(\tilde{R}_i^{\text{AC}} + \Delta R_i^{\text{AC}})\cdot(\tilde{C}_i^{\text{AC}} + \Delta C_i^{\text{AC}})}\right)$$
$$a_i = \exp\left(\frac{-\Delta t}{\tilde{R}_i^{\text{AC}} \cdot \tilde{C}_i^{\text{AC}} + \tilde{R}_i^{\text{AC}} \cdot \Delta C_i^{\text{AC}} + \tilde{C}_i^{\text{AC}} \cdot \Delta R_i^{\text{AC}} + \Delta R_i^{\text{AC}} \cdot \Delta C_i^{\text{AC}}}\right)$$

$$a_i = \tilde{a}_i + \Delta a_i$$

$$T_i^{\text{room}}(t+1) = \tilde{a}_i \cdot T_i^{\text{room}}(t) + (1-\tilde{a}_i)\left(T_i^{\text{outdoor}}(t) - \eta_i^{\text{AC}} \cdot R_i^{\text{AC}} \cdot P_i^{\text{AC}}(t)\right) + w_i(k)$$

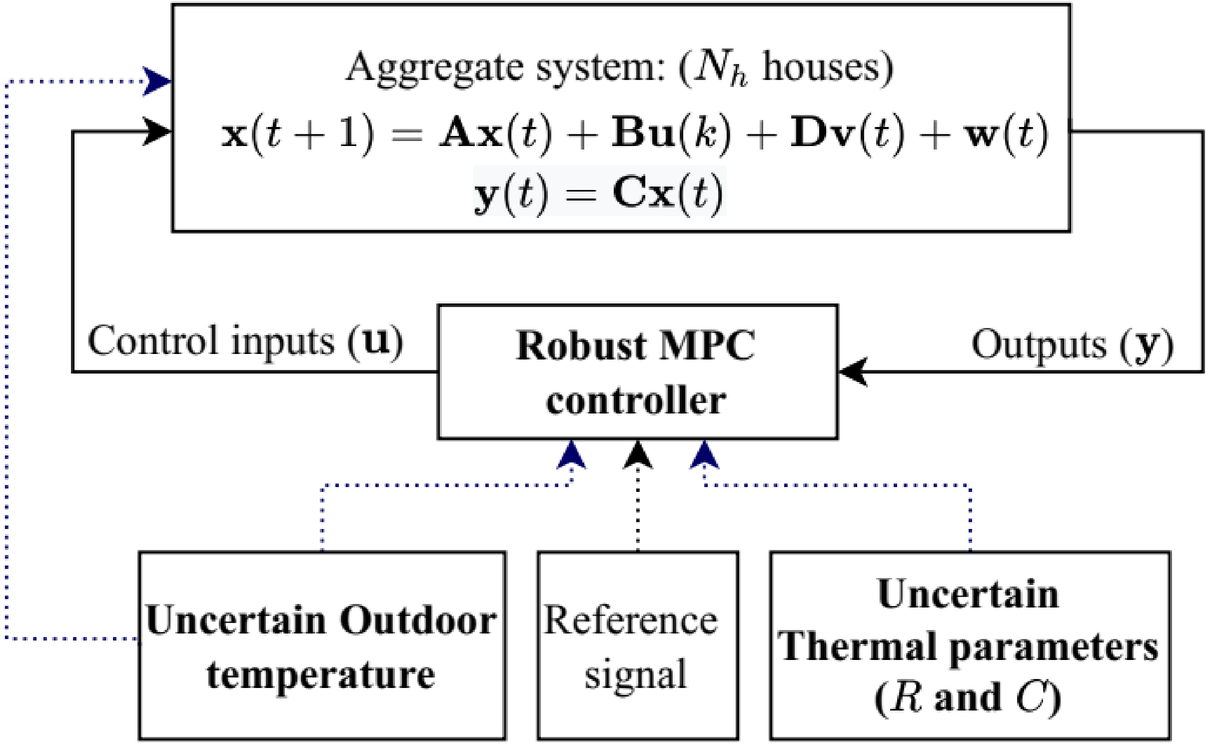
Embedding uncertainties in the model

$$\boxed{\begin{aligned} w_i(t) = {} & (1-\tilde{a}_i)\cdot\left(\Delta T_i^{\text{outdoor}}(t) - \eta_i^{\text{AC}} \cdot \Delta R_i^{\text{AC}} \cdot P_i^{\text{AC}}(t)\right) \\ & - \Delta a_i \cdot \left(T_i^{\text{outdoor}}(t) - \Delta T_i^{\text{outdoor}}(t) - \eta_i^{\text{AC}} \cdot (\tilde{R}_i^{\text{AC}} + \Delta R_i^{\text{AC}}) \cdot P_i^{\text{AC}}(t)\right) \end{aligned}}$$

Individual state-space model with uncertainties

$$x_i(t+1) = A_i x_i(t) + B_i u_i(t) + D_i v_i(t) + w_i(t)$$

Approach



Centralised robust MPC implementation of the aggregate system

Population size $N_h = 1000$

Temperature comfort limits $(22,24)°C$

Robust MPC controller

- Minimising aggregate tracking error
- Minimising the change in temperature from the set-point
- Minimising the control effort

$$\min_{\mathbf{u}} \max_{\mathbf{w}} \sum_{k=0}^{N-1} \left[w_P \cdot \left| P_{\text{agg}}(t+k|t) - P_{\text{ref}}(t+k) \right| + w_x \cdot \left\| \mathbf{x}(t+k|t) - \mathbf{x}^{\text{set}} \right\|_1 + w_{\Delta u} \cdot \left\| \boldsymbol{\Delta u}(t+k|t) \right\|_1 \right]$$

$$\mathbf{x}(t+k+1|t) = A\,\mathbf{x}(t+k|t) + B\,\mathbf{u}(t+k|t) + D\,\mathbf{v}(t+k|t) + \mathbf{w}(t+k|t), \quad \forall k \in \mathbb{Z}_{[0,N-1]}$$

$$P_{\text{agg}}(t+k|t) = \mathbf{P}_{\text{rated}}^{\text{T}} \cdot \mathbf{u}(t+k|t), \quad \forall k \in \mathbb{Z}_{[0,N-1]}$$

$$\boxed{\underline{\mathbf{x}} \leq \mathbf{x}(t+k|t) \leq \overline{\mathbf{x}}, \quad \forall k \in \mathbb{Z}_{[0,N-1]}}$$

Indoor temperature limits

$$\boldsymbol{\Delta u}(t+k|t) = \mathbf{u}(t+k+1|t) - \mathbf{u}(t+k|t), \quad \forall k \in \mathbb{Z}_{[0,N-1]}$$

$$\boxed{u_i(t+k|t) = \begin{cases} 0.5 \cdot P_{i,\text{rated}}^{\text{AC}} \\ 0.75 \cdot P_{i,\text{rated}}^{\text{AC}} & \forall i,\ \forall k \in \mathbb{Z}_{[0,N-1]} \\ P_{i,\text{rated}}^{\text{AC}} \end{cases}}$$

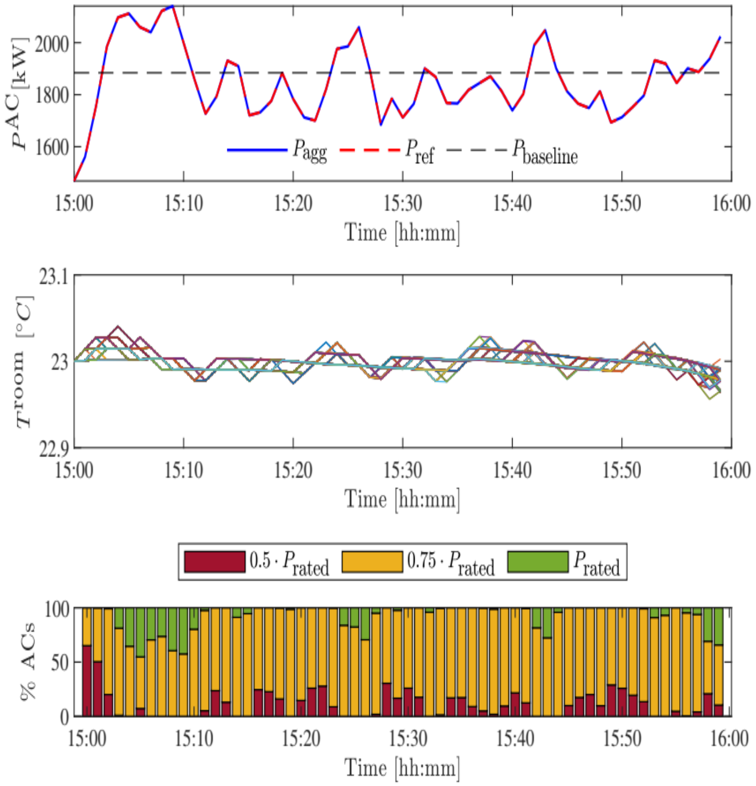
DRM compliance

$$\boxed{\mathbf{w}(t+k|t) \subseteq \mathbb{W}, \quad \forall k \in \mathbb{Z}_{[0,N-1]}}$$

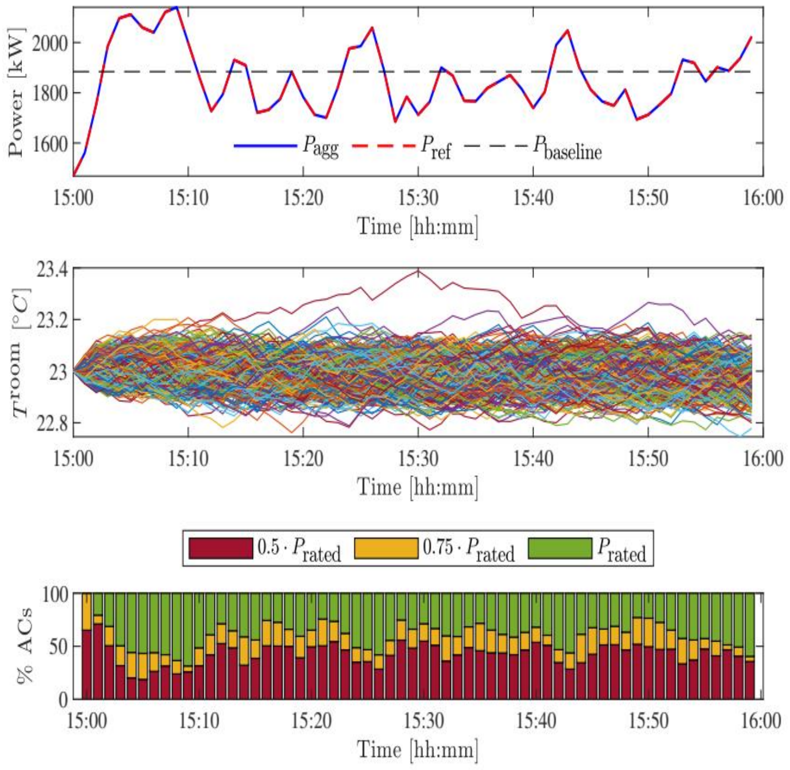
Uncertainties

$$\mathbb{W} = \{\mathbf{w} : \|\mathbf{w}\|_\infty \leq \mathbf{w}_0\}$$

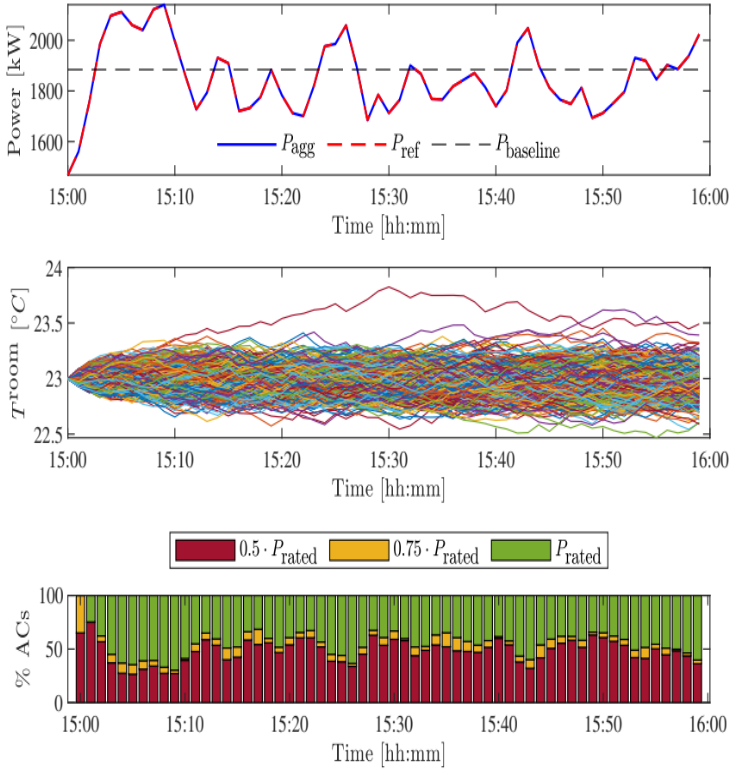
Results



Nominal scenario



with $w_0 = 0.05°C$

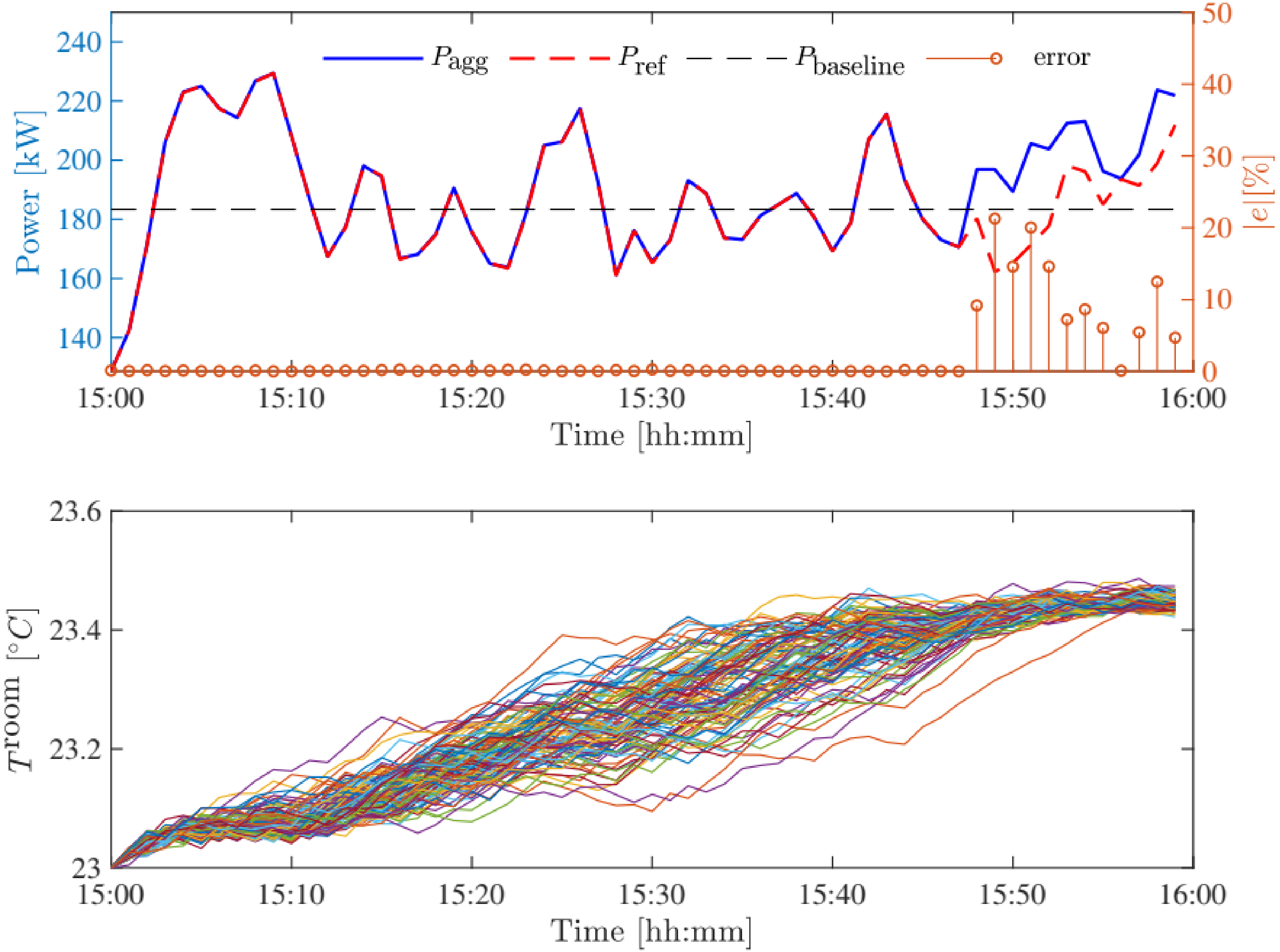


with $w_0 = 0.075°C$

Accurate tracking can be achieved in the presence of uncertainties while regulating the operation within thermal comfort limits.

Minimum control action on air-conditioners operating under AS 4755.3 DR standards.

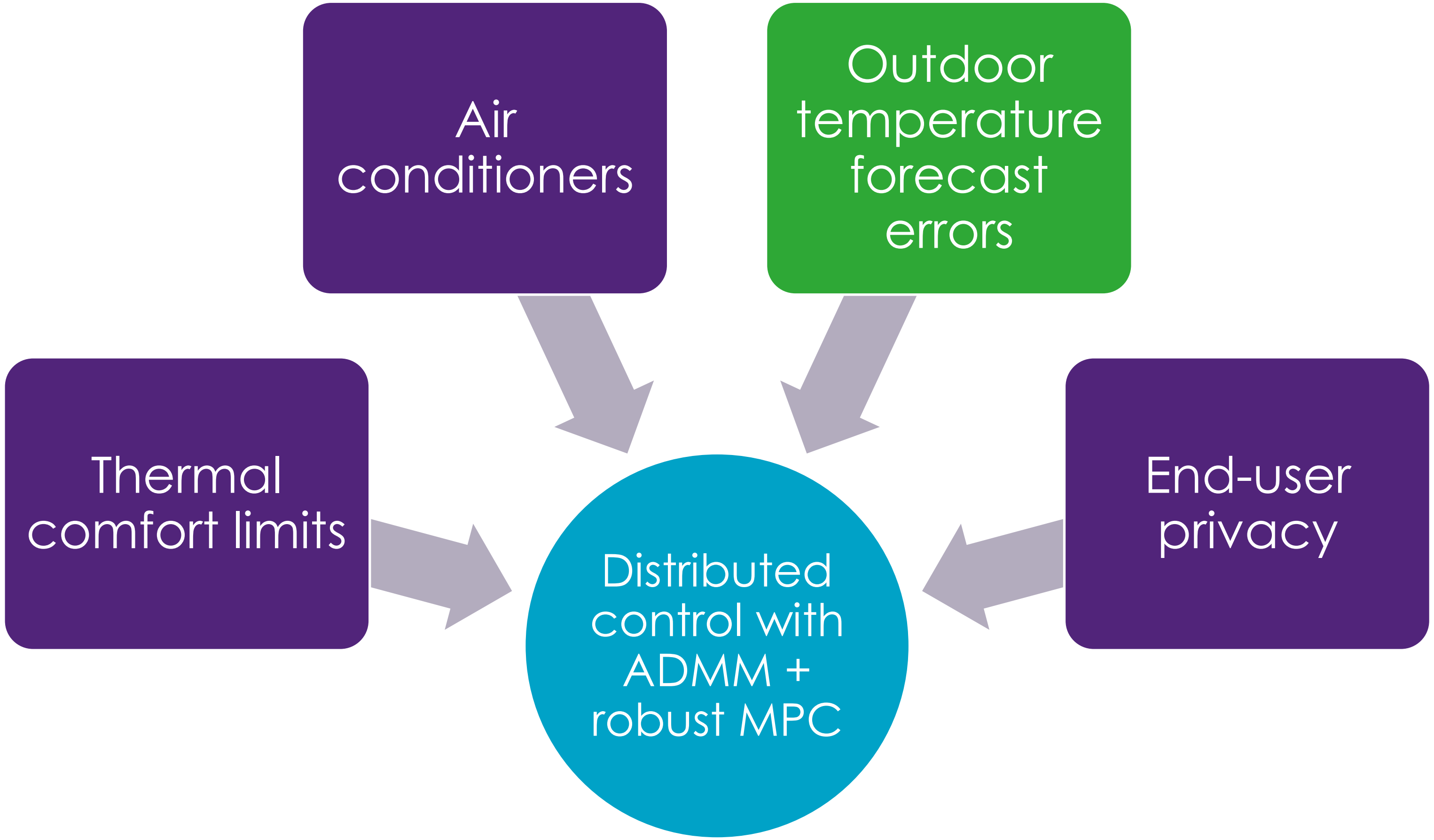
Tracking performance under tightened temperature limits



with $w_0 = 0.02°C$ under $[22.5°C, 23.5°\,C]$ for $N_h = 100$

Tracking performance is compromised under tight temperature comfort limits in the presence of uncertainties.

Contribution 3: Distributed control framework for an aggregator to provide DR in real-time markets under uncertainties



Air conditioners

Outdoor temperature forecast errors

Thermal comfort limits

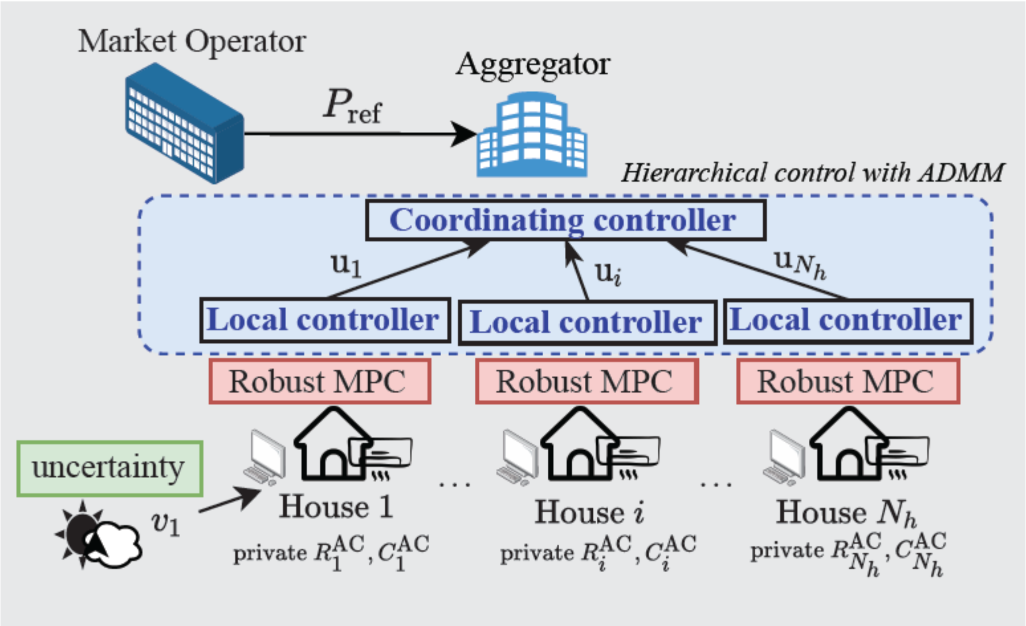
End-user privacy

Distributed control with ADMM + robust MPC

G. Lankeshwara, R. Sharma, R. Yan, and T. K. Saha, "A hierarchical control scheme for residential air-conditioning loads to provide real-time market services under uncertainties," *Energy (Elsevier)*, vol. 250, p. 123796, 2022, doi: 10.1016/j.energy.2022.123796.

G. Lankeshwara and R. Sharma, "A Model-based Approach for the Robust Automation of Residential Loads to Provide Grid Services," *International Journal of Control (Taylor & Francis)*, **(first revision)**

Approach



Overall implementation

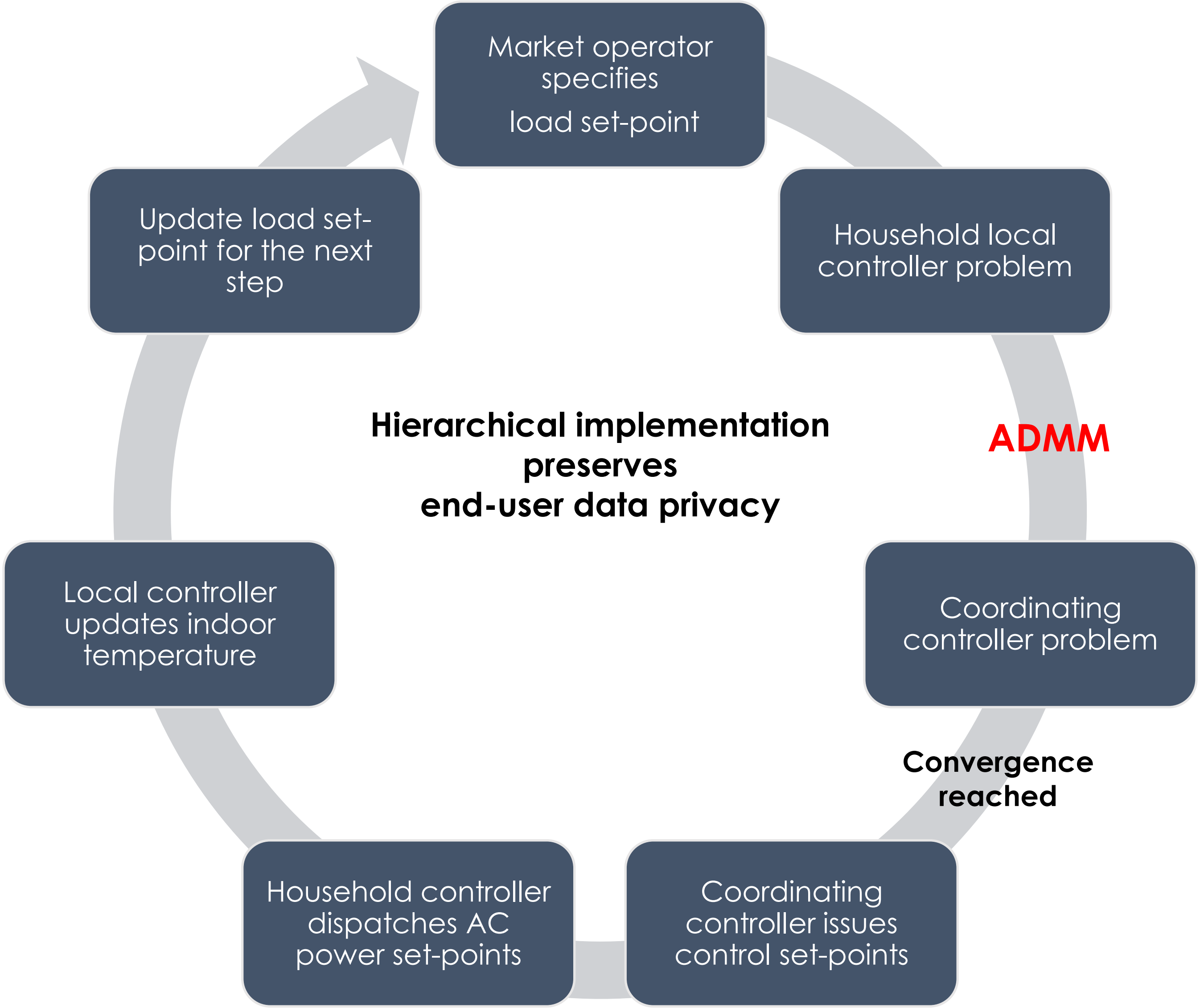
Household local controller (robust MPC)

- Minimise AC energy cost
- Address uncertainties in outdoor temperature forecasts

Coordinating controller at the Aggregator

Tracking the load set-point signal in real-time energy markets

At each time step,



Market operator specifies load set-point

Household local controller problem

Coordinating controller problem

Coordinating controller issues control set-points

Household controller dispatches AC power set-points

Local controller updates indoor temperature

Update load set-point for the next step

ADMM

Convergence reached

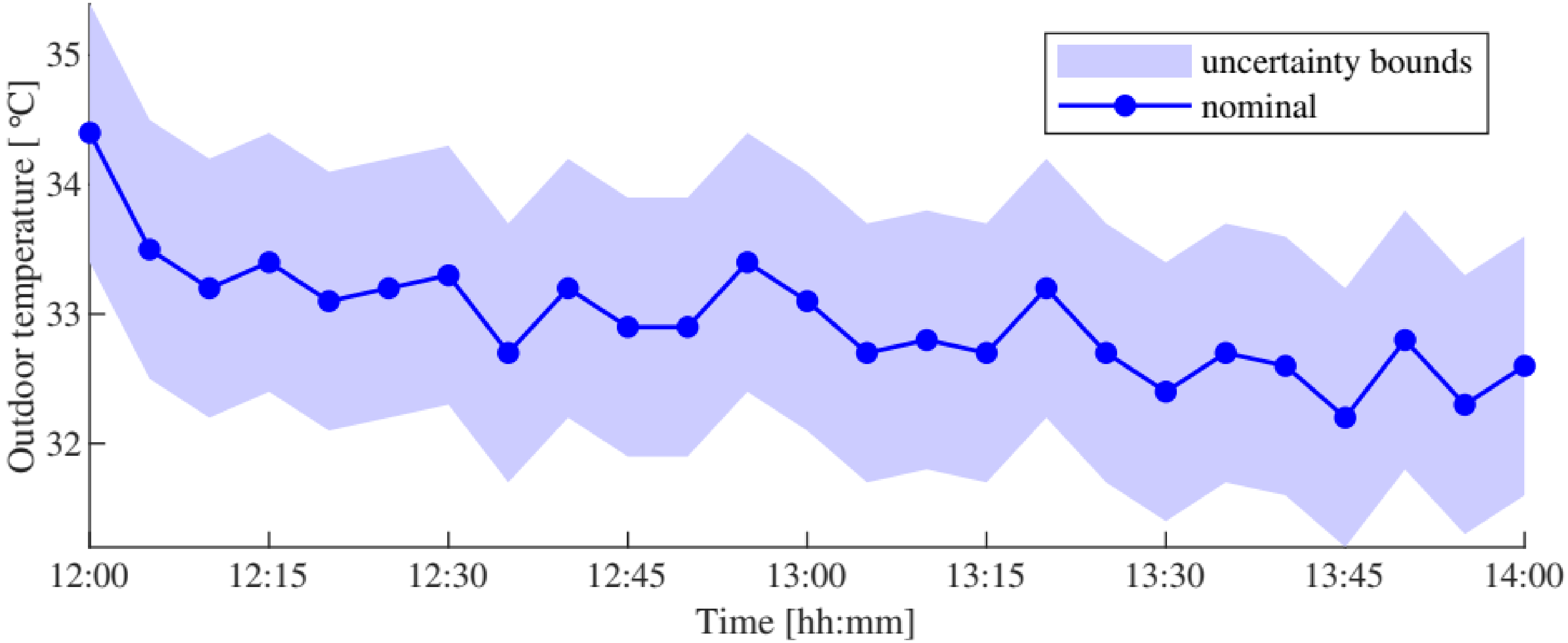
Hierarchical implementation preserves end-user data privacy

Data

- 500 air conditioners
- $P_{rated} \sim \mathcal{N}(2.5, 3.5)$ kW
- Thermal comfort limits: $[22, 24]°C$
- Sampling time = 5-mins

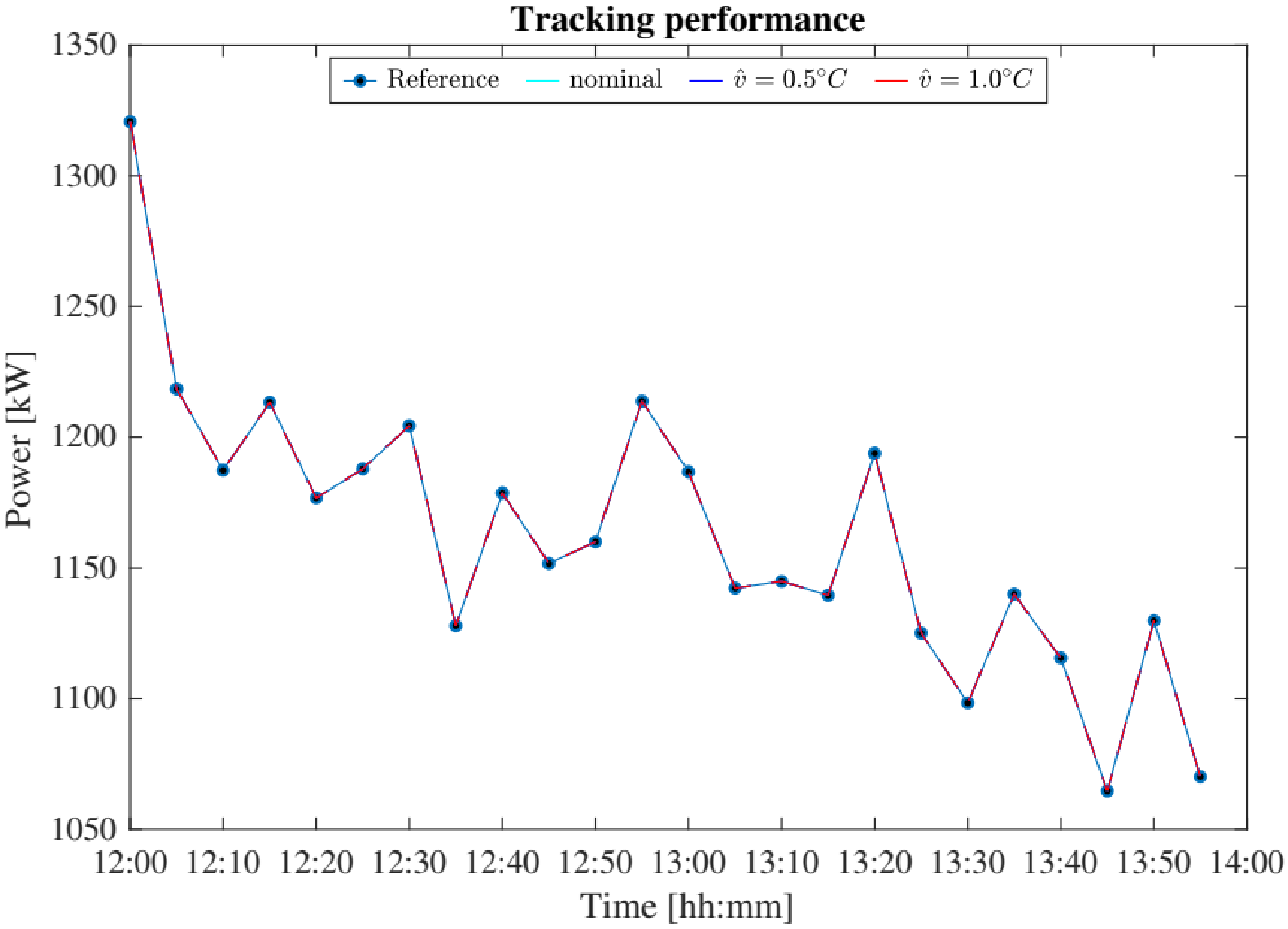
Three scenarios:

1. Nominal case – no uncertainties
2. With outdoor temperature bounds $(\hat{v}) = 0.5°C$
3. With outdoor temperature bounds $(\hat{v}) = 1.0°C$



Uncertainty bounds for outdoor temperature

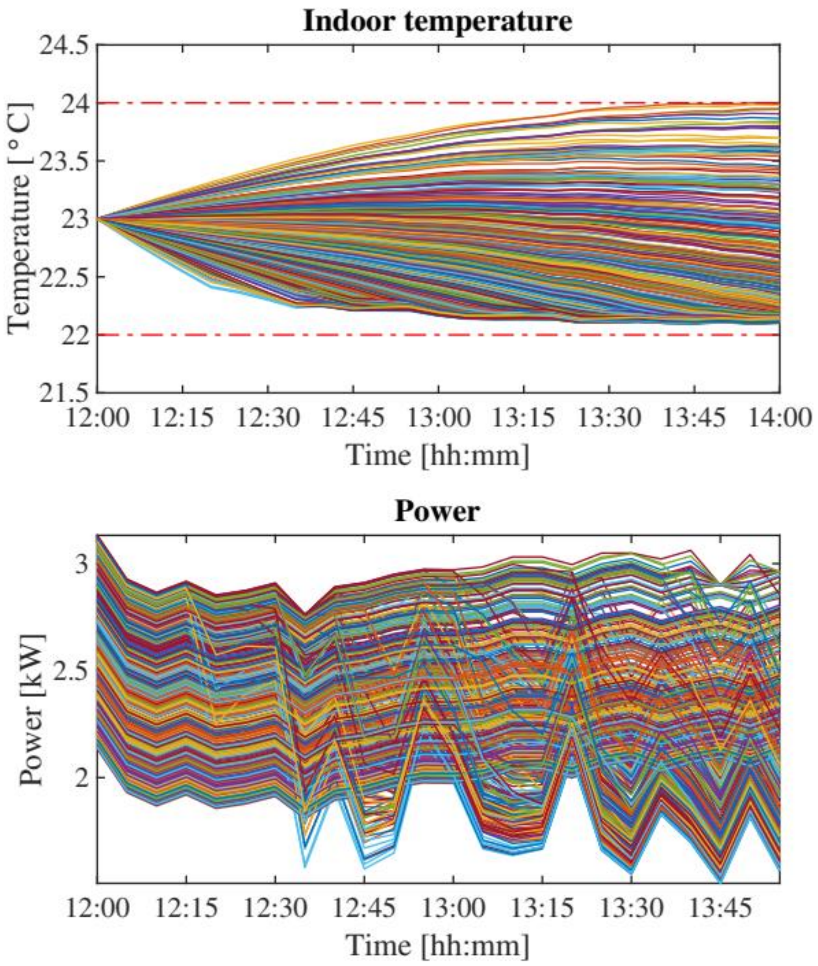
Results



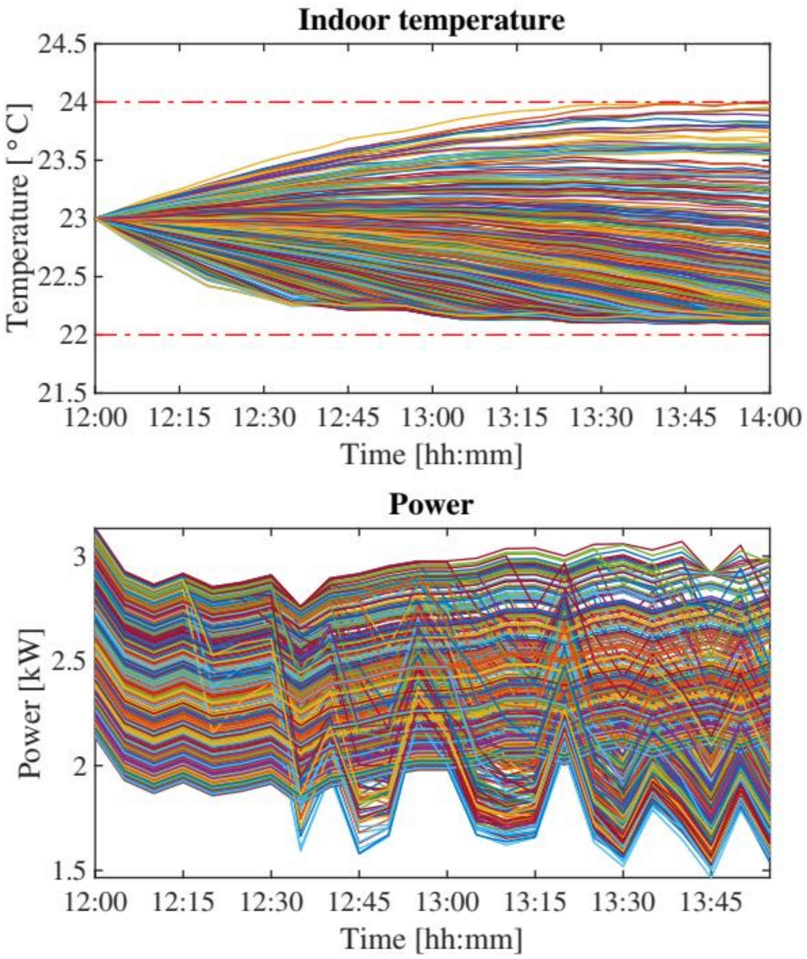
Scenario	MAE (Tracking) [kW]
Nominal	0.0051
$\hat{v} = 0.5°C$	0.0054
$\hat{v} = 1.0°C$	0.0055

Precise tracking of the load set-point signal up to outdoor temperature within $\pm 1.0°C$ from its nominal value.

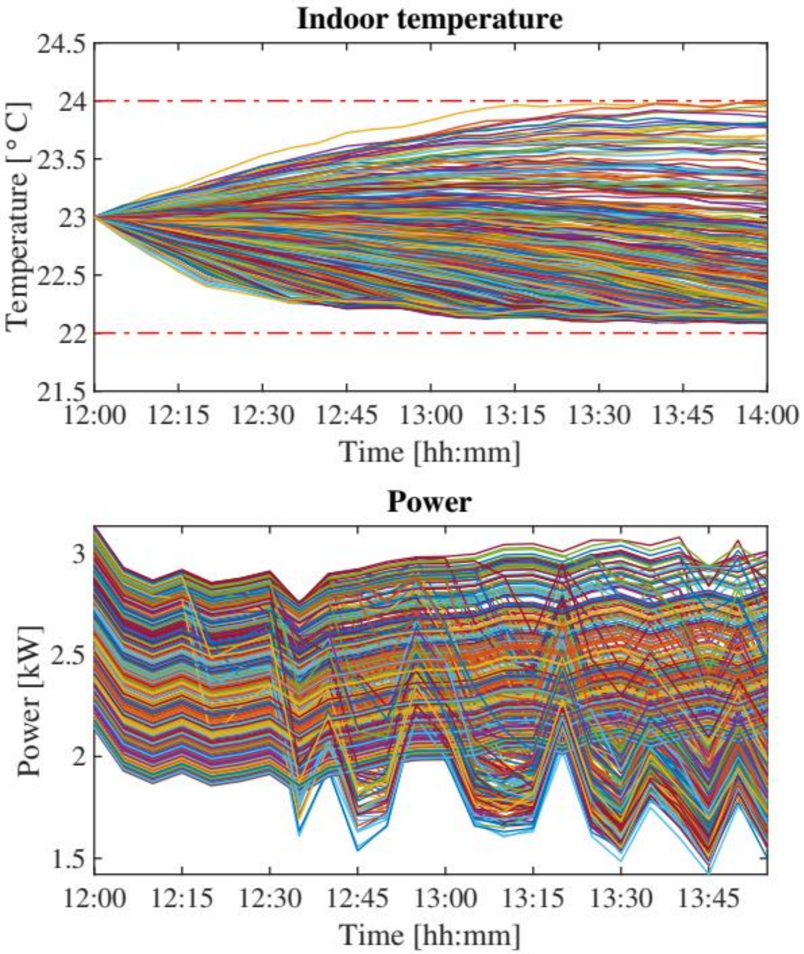
Contribution 3: Distributed control framework for an aggregator to provide DR in real-time markets under uncertainties



Nominal scenario



with $\hat{v} = 0.5°C$



with $\hat{v} = 1.0°C$

Indoor thermal comfort is preserved within $(22, 24)°C$ in the presence of uncertainties up to $\pm 1.0°C$ of outdoor temperature from its nominal value.

Computational performance (for a DR duration of 2-hours)

Population size	Nominal scenario [min]	Under uncertainties [min]	
		$\hat{v} = 0.5°C$	$\hat{v} = 1.0°C$
100	4.748	5.135	5.478
500	19.85	20.31	20.31
1000	**39.51**	**40.38**	**40.23**

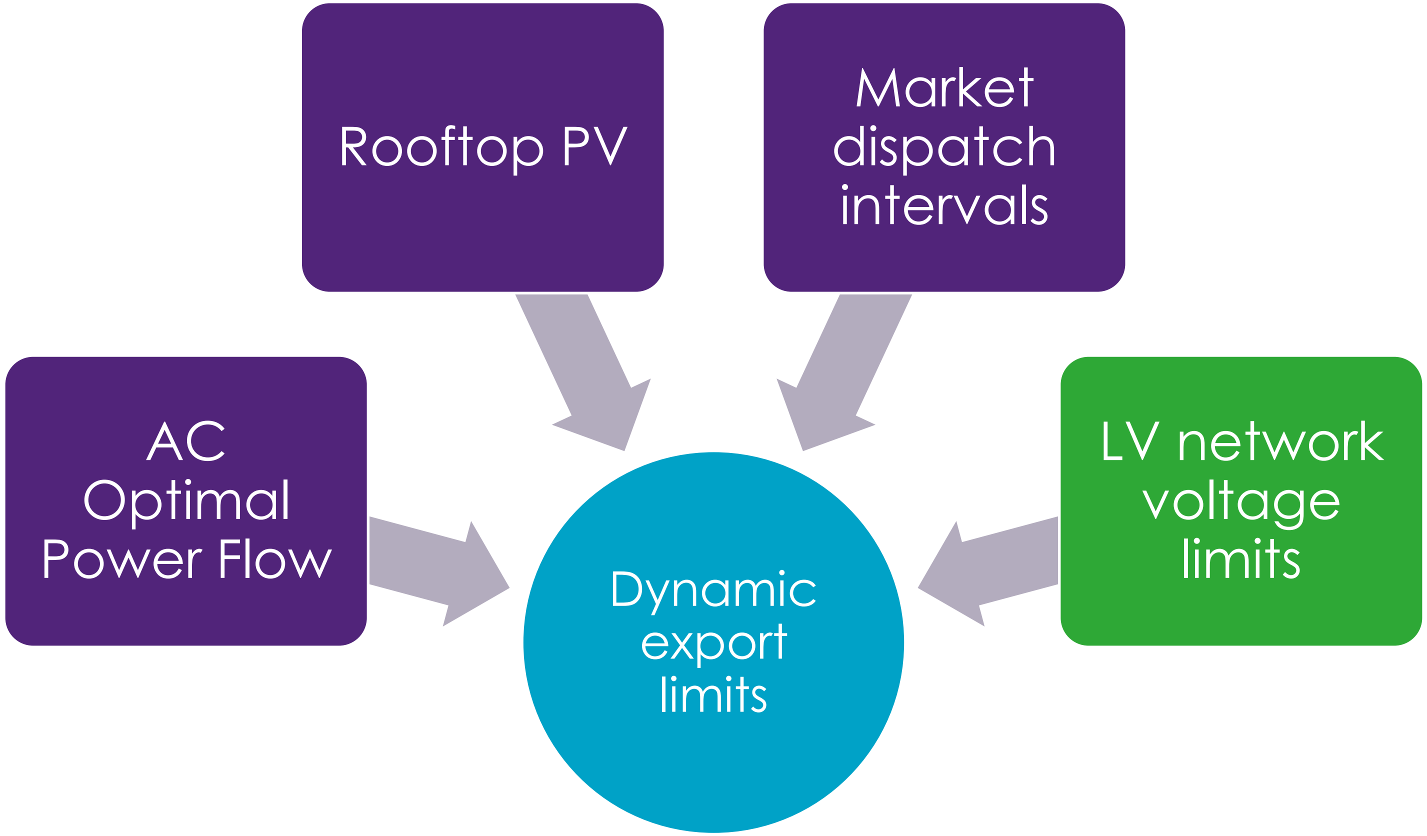
** Simulations are performed on a computing facility equipped with an Intel(R) Xeon(R) CPI E5-2680 v3 @ 2.5 GHz with 64 GB memory (parallel execution of the local controller problem)

Sampling time = 5-mins

Total execution time < 2-hours (120-mins)

The overall hierarchical implementation is scalable in the presence of uncertainties.

Contribution 4: A real-time approach for the DNSP to assign dynamic export limits for households with rooftop PV connections



Rooftop PV

Market dispatch intervals

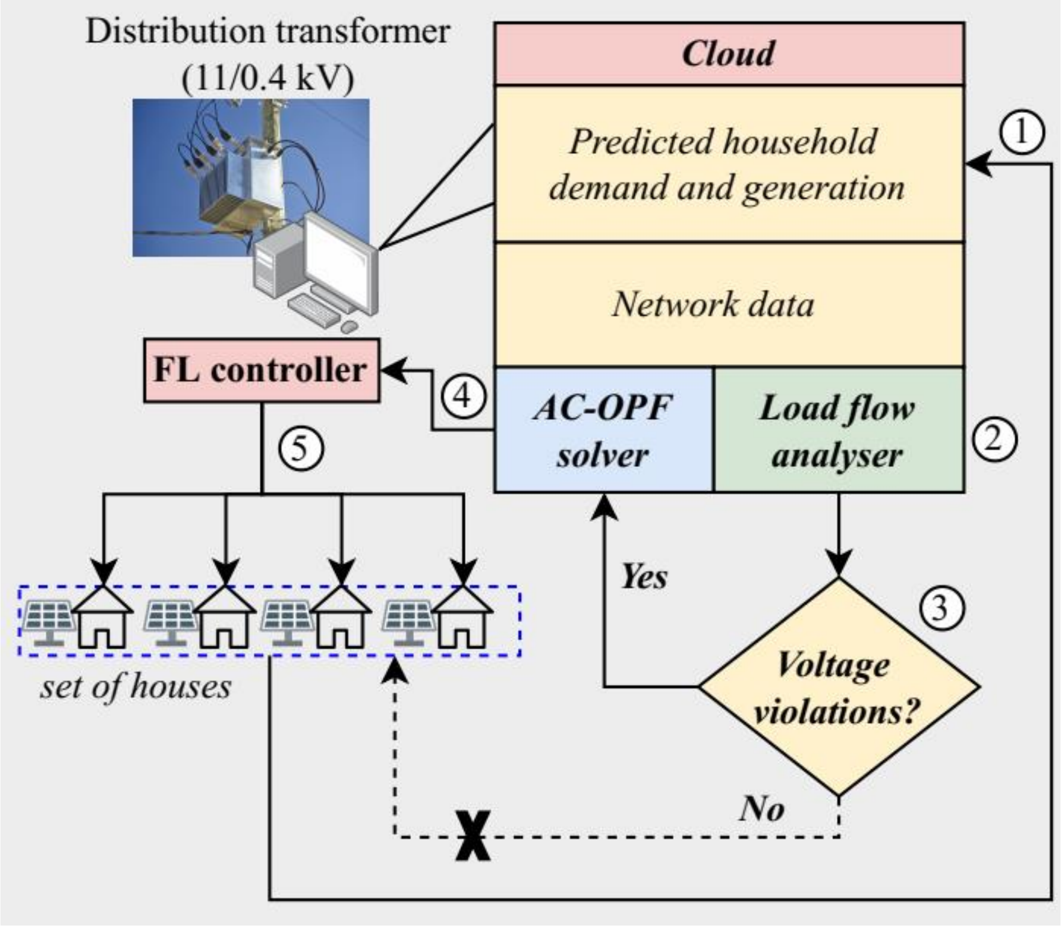
AC Optimal Power Flow

LV network voltage limits

Dynamic export limits

G. Lankeshwara, “A Real-time Control Approach to Maximise the Utilisation of Rooftop PV Using Dynamic Export Limits,” in *2021 IEEE PES Innovative Smart Grid Technologies - Asia (ISGT Asia)*, Dec. 2021, pp. 1–5, doi: 10.1109/ISGTAsia49270.2021.9715714.

Approach



A block diagram of the overall implementation

Dynamic export limits via AC-OPF

Minimising the deviation of PV active power from the intended operation

$$F(t) = \sum_{h \in \mathcal{H}'} \left(P_h^{\mathrm{PV}}(t) - \tilde{P}_h^{\mathrm{PV}}(t) \right)^2$$

$$0 \le P_h^{\mathrm{PV}}(t) \le \tilde{P}_h^{\mathrm{PV}}(t)$$

$$Q_h^{\mathrm{PV}}(t) = 0$$

$$\tilde{Q}_h^{\mathrm{L}}(t) = \tilde{P}_h^{\mathrm{L}}(t) \cdot \tan\left(\cos^{-1}\left(\varphi_h^{\mathrm{L}}\right) \right)$$

Non-convex

$$\left\{ \begin{aligned} P_i^{\mathrm{inj}}(t) = {} & \mathbf{Re}\left(V_i(t)\right) \sum_{j \in \mathcal{N}' \cup \{0\}} \left[G_{ij} \mathbf{Re}\left(V_j(t)\right) - B_{ij} \mathbf{Im}\left(V_j(t)\right) \right] \\ & + \mathbf{Im}\left(V_i(t)\right) \sum_{j \in \mathcal{N}' \cup \{0\}} \left[G_{ij} \mathbf{Im}\left(V_j(t)\right) + B_{ij} \mathbf{Re}\left(V_j(t)\right) \right] \\ Q_i^{\mathrm{inj}}(t) = {} & \mathbf{Im}\left(V_i(t)\right) \sum_{j \in \mathcal{N}' \cup \{0\}} \left[G_{ij} \mathbf{Re}\left(V_j(t)\right) - B_{ij} \mathbf{Im}\left(V_j(t)\right) \right] \\ & - \mathbf{Re}\left(V_i(t)\right) \sum_{j \in \mathcal{N}' \cup \{0\}} \left[G_{ij} \mathbf{Im}\left(V_j(t)\right) + B_{ij} \mathbf{Re}\left(V_j(t)\right) \right] \\ & \forall i \in \mathcal{N}', t \in \mathcal{T} \end{aligned} \right.$$

$$P_i^{\mathrm{inj}}(t) = P_h^{\mathrm{PV}}(t) - \tilde{P}_h^{\mathrm{L}}(t), \quad i \in \mathcal{N}', h \in \mathcal{H}'$$

$$Q_i^{\mathrm{inj}}(t) = Q_h^{\mathrm{PV}}(t) - \tilde{Q}_h^{\mathrm{L}}(t), \quad i \in \mathcal{N}', h \in \mathcal{H}'$$

$$\boxed{\begin{aligned} \underline{v} \le \left|V_i(t)\right| \le \overline{v} \\ \underline{\theta} \le \angle V_i(t) \le \overline{\theta} \end{aligned}}$$

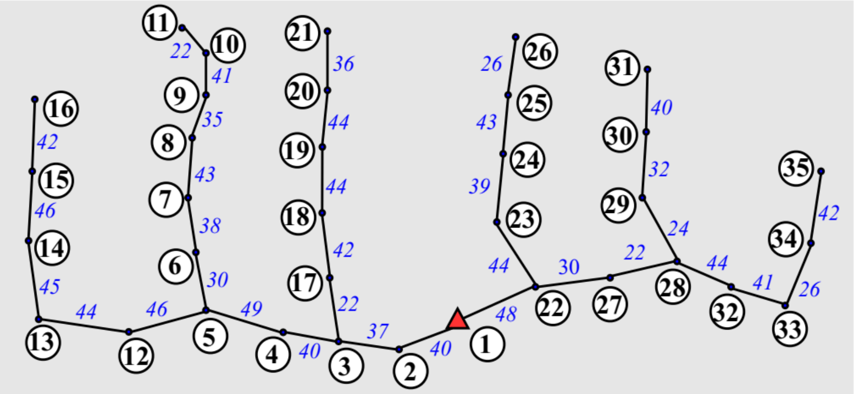
Voltage limits

Results

- Sampling time = 5-mins

Three scenarios:

- No export limits
- With fixed export limits (5-kW)
- With dynamic export limits



Single Line Diagram of the LV network

Computational performance (24-hour period)

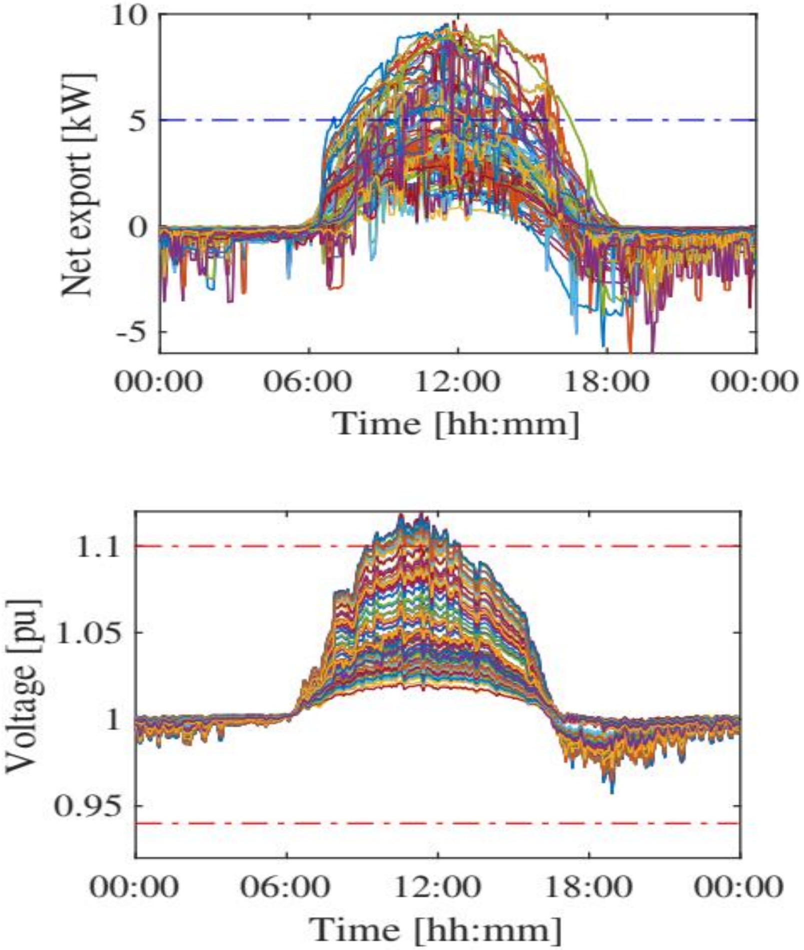
Scenario	Total execution time (sec)
No export limits	8.82
Fixed export limits	8.89
Dynamic export limits	110.56

** Simulations are performed on desktop computer equipped with an Intel(R) Core i7 3.20 GHz CPU and 16 GB RAM memory.

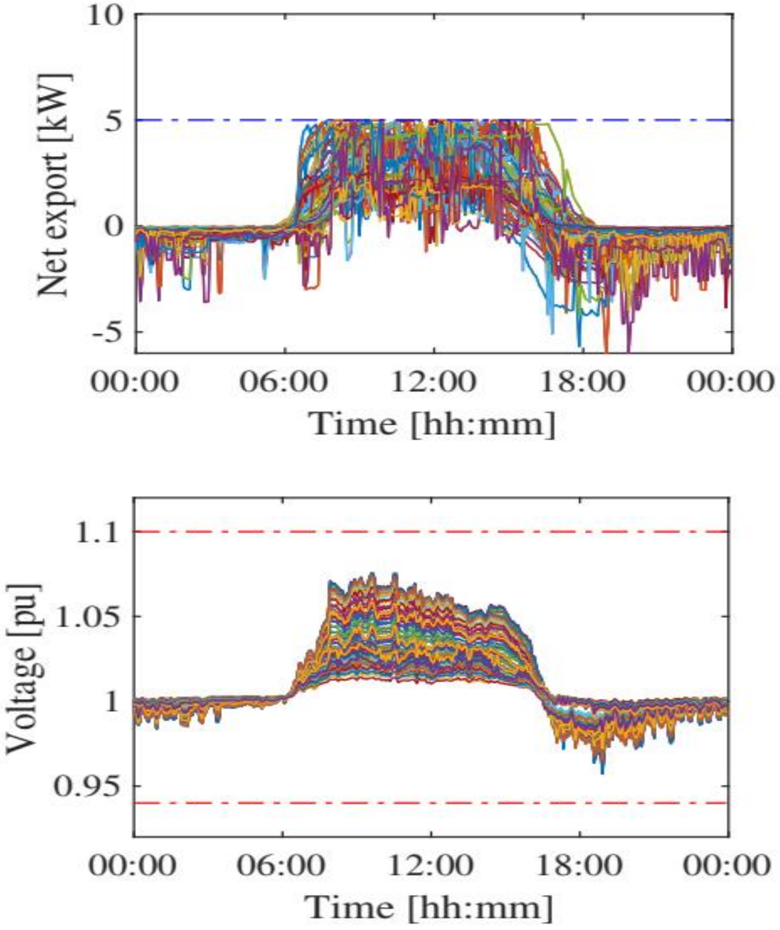
The proposed approach is scalable under 5-min dispatch intervals.

Contribution 4: A real-time approach for the DNSP to assign dynamic export limits for households with rooftop PV connections

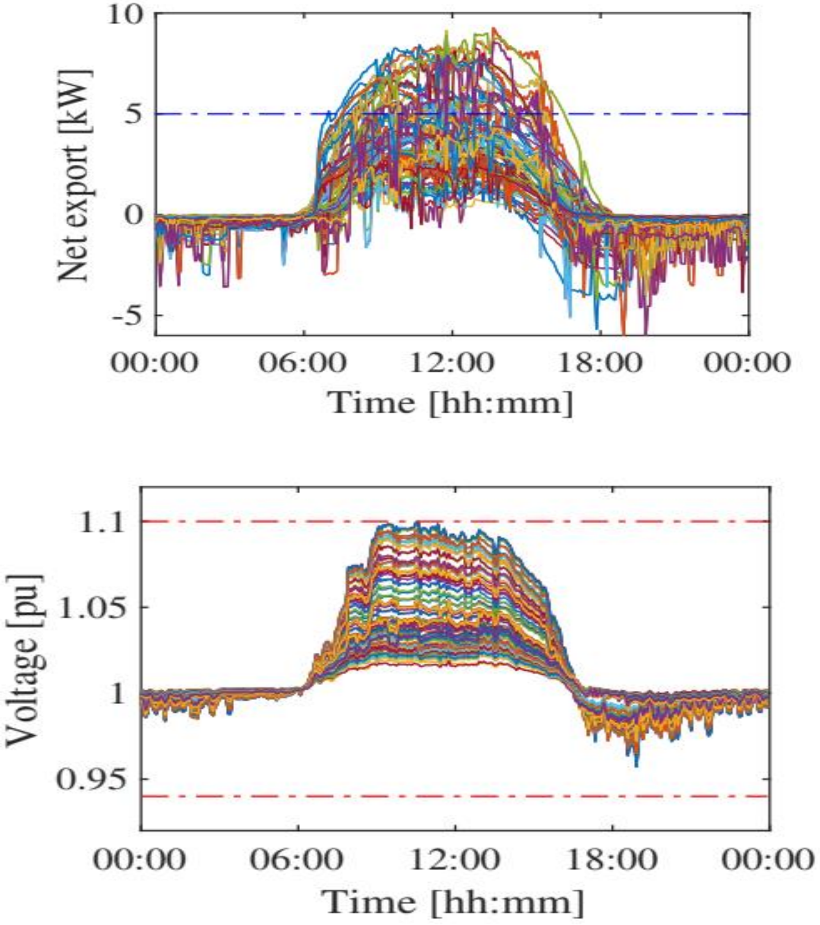
No export limits



Fixed export limits

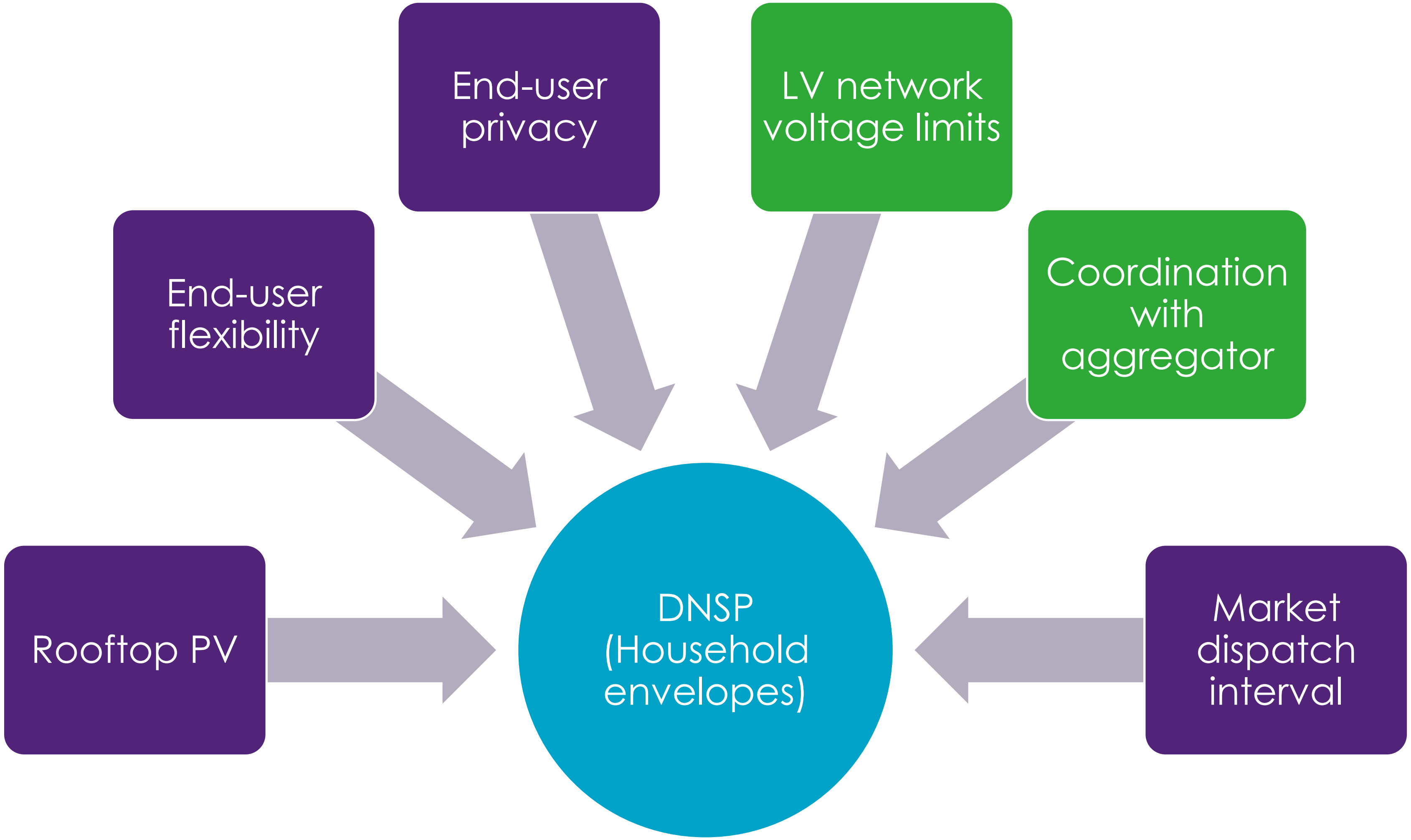


Dynamic export limits



Under the proposed dynamic envelopes framework, end-users can export more power to the grid without violating voltage limits.

Contribution 5: A real-time approach for the DNSP to establish household operating envelopes that account for end-user flexibility



End-user privacy

LV network voltage limits

End-user flexibility

Coordination with aggregator

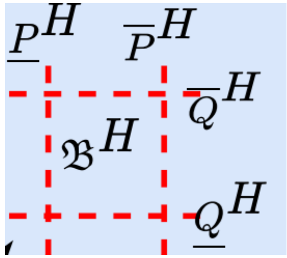
Rooftop PV

DNSP (Household envelopes)

Market dispatch interval

G. Lankeshwara, R. Sharma, R. Yan, and T. K. Saha, “Operating Envelopes to Manage Low-voltage Distribution Networks,” **to be submitted to *IEEE Transactions on Power Systems***

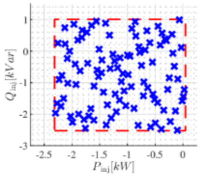
Approach



Households determine limits of operation

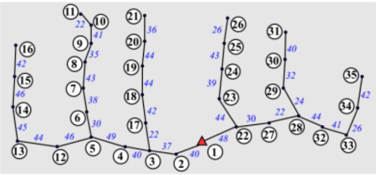
(P-Q space)

Privacy preserved



DNSP samples household operating region

- Latin Hypercube sampling (LHS)



DNPS performs probabilistic load flows

Check for voltage violations

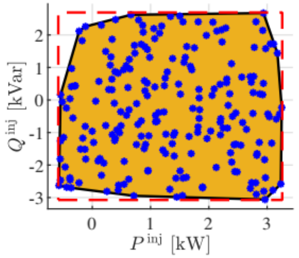
- If Yes, neglect the scenario
- If No, move to the next step

$$0.95\,pu < v < 1.10\,pu$$

Obtain the set of feasible P-Q pairs for households

- All cases without voltage violations

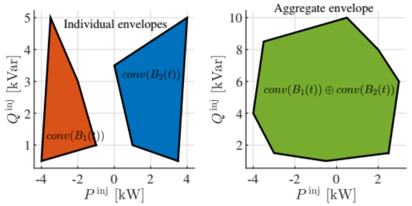
Accounts for network voltage limits



$$\mathbf{conv}(\mathcal{B}_t^h) := \left\{ (P^h_{\text{inj},t}, Q^h_{\text{inj},t}) \,\middle|\, \mathbf{A} \cdot [P^h_{\text{inj},t}, Q^h_{\text{inj},t}]^T \leq \mathbf{b} \right\}$$

Convex hull estimation

- Operating envelopes for households



Aggregate envelope

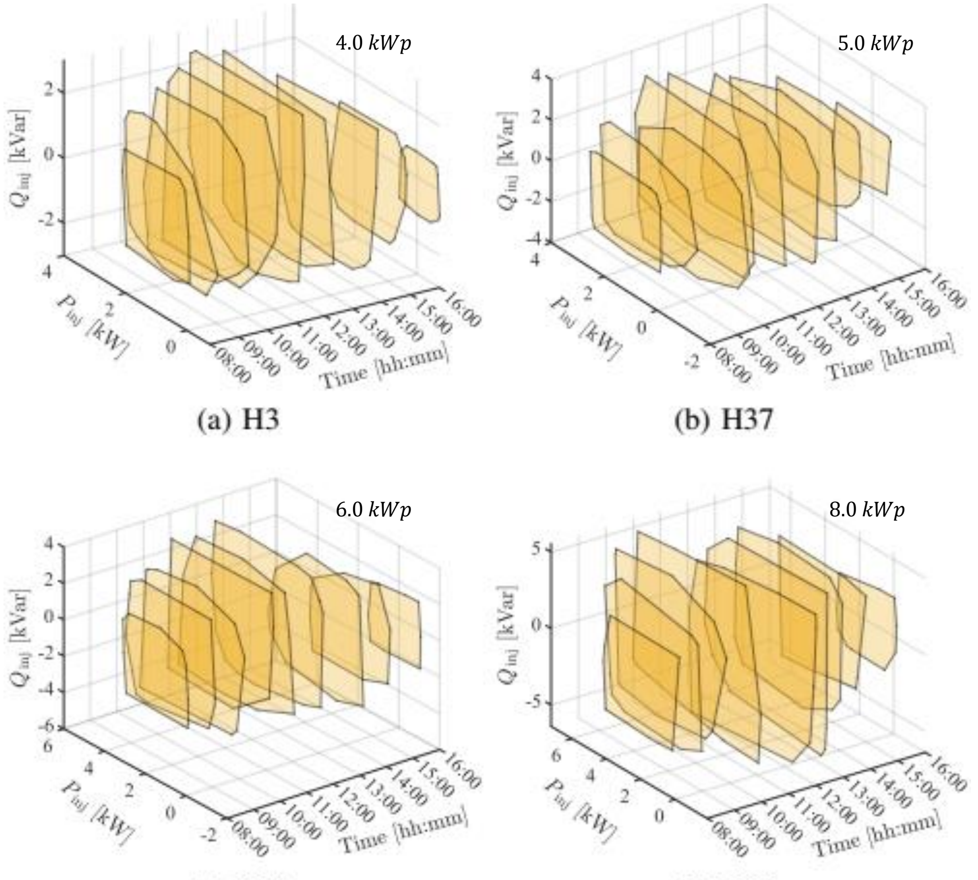
- Head of feeder
- Using Minkowski sum ⊕

Send to aggregator

Privacy and separation between DNSP and aggregator

Results

Dynamic behaviour of envelopes



(a) H3

(b) H37

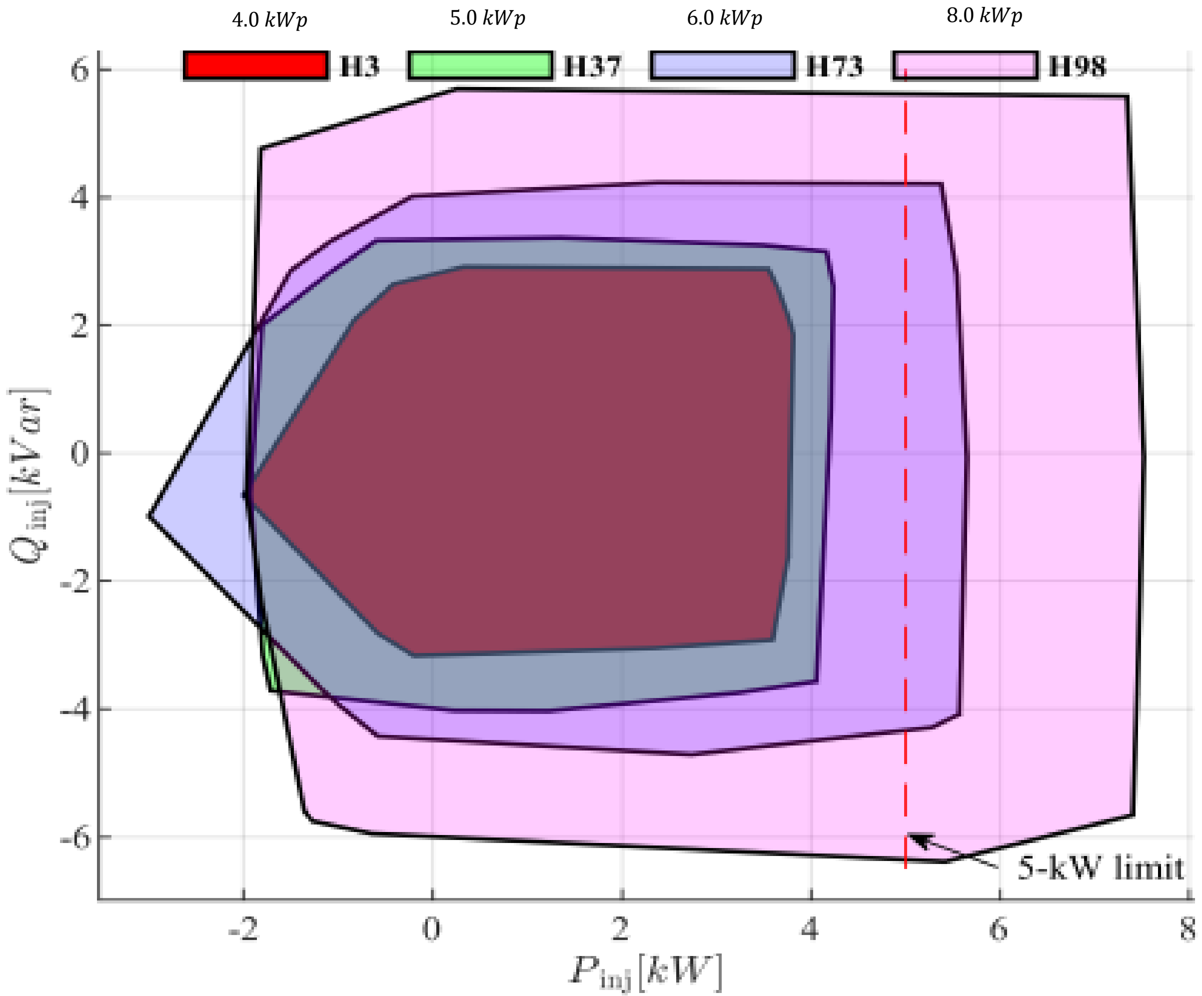
(c) H73

(d) H98

As PV generation ↑, the operating envelope widens.

Feasible operating region expands → Household flexibility ↑

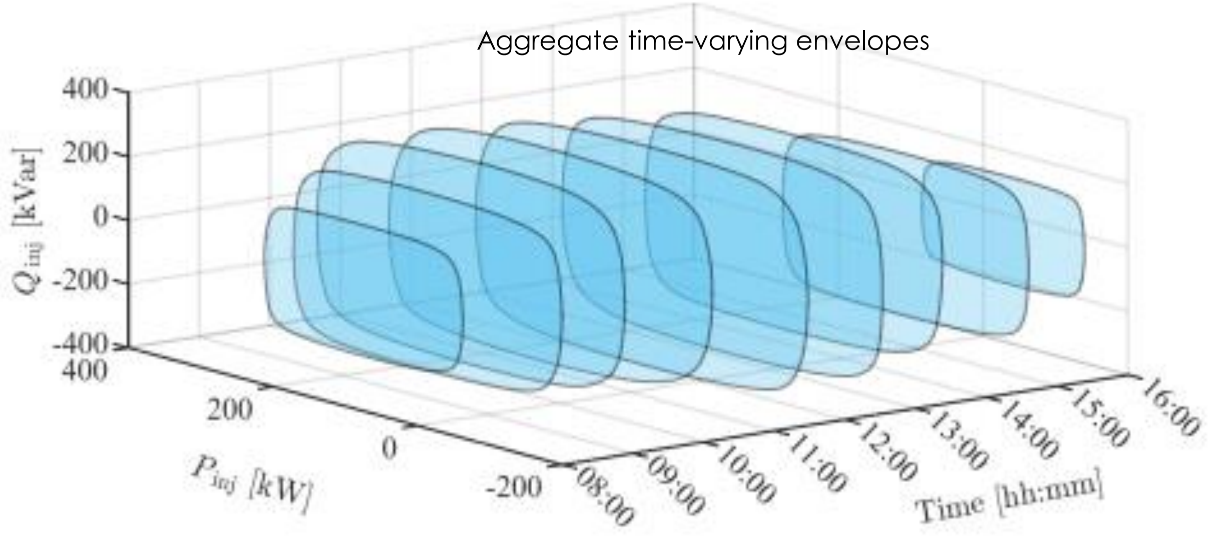
Overall feasible operating region for 24-hours

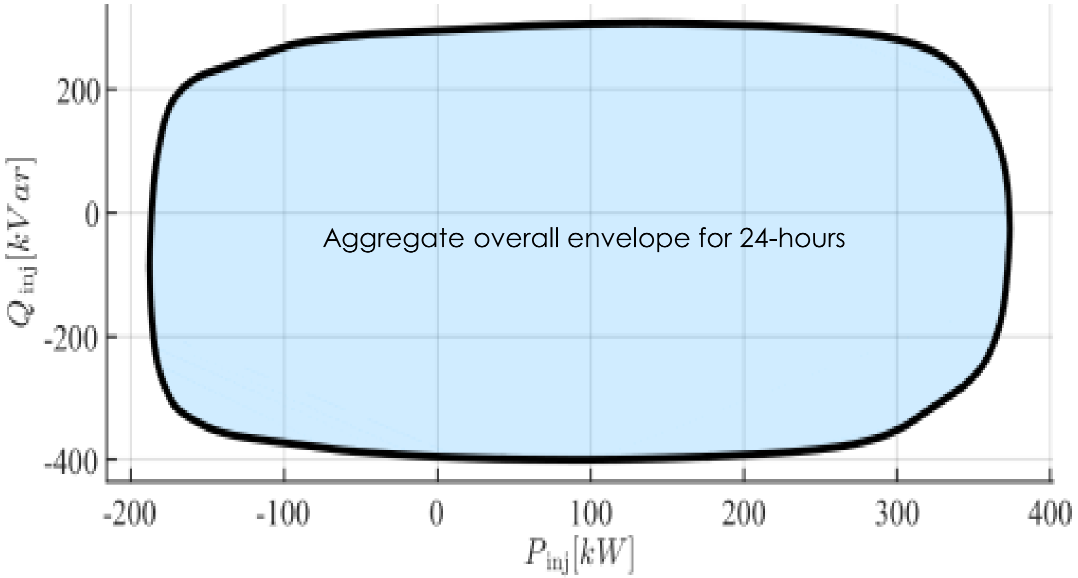


PV inverter rating ↑ envelopes shift towards $P_{inj} > 0$ $(export)$ region

Able to go beyond the fixed 5-kW export limit!

Behaviour of aggregate envelope





As PV generation ↑, aggregate envelope also expands

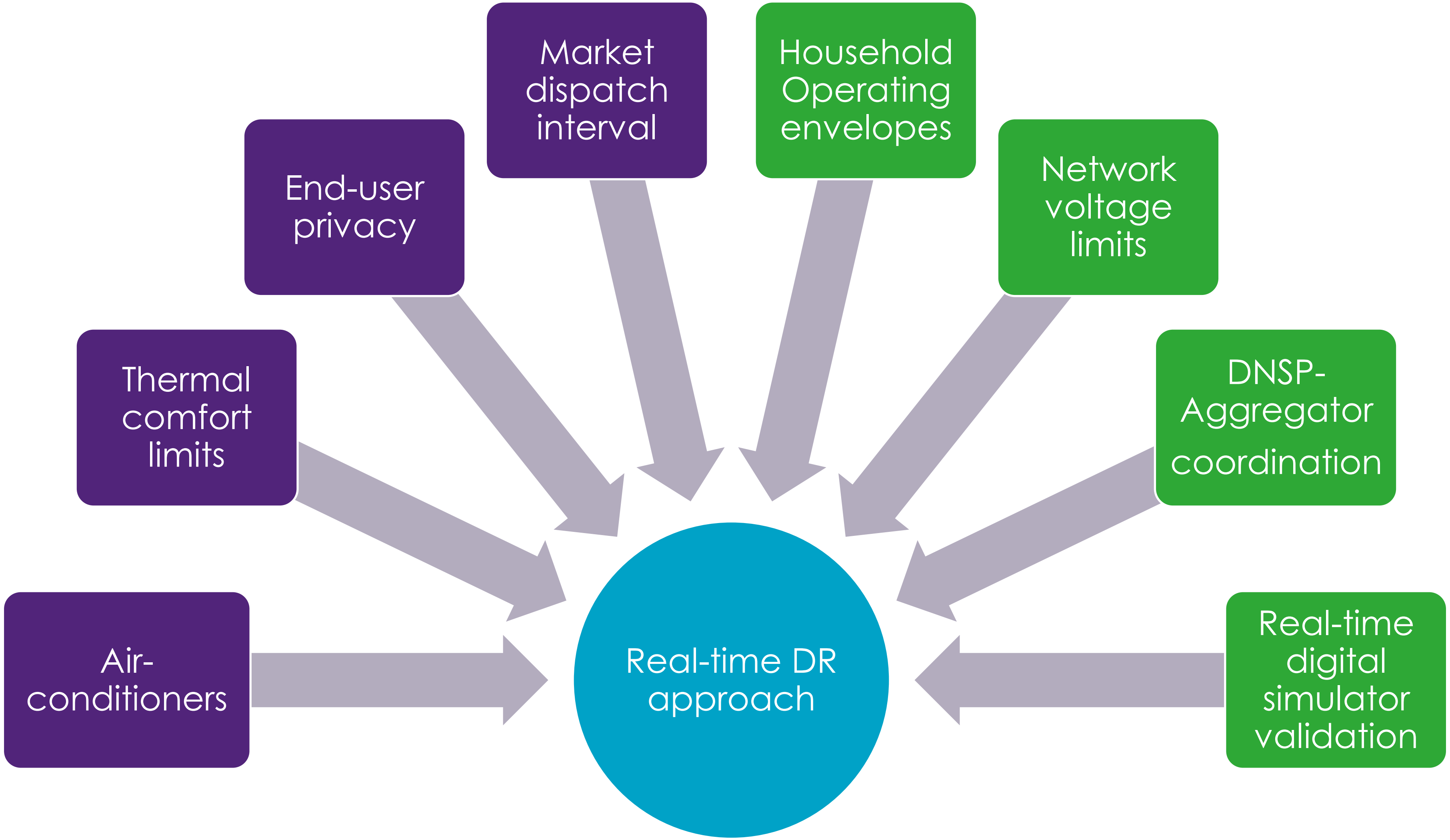
Smooth compared to household operating envelopes

Overall flexibility at the head of the feeder (approx.)

$$-200 < P_{inj} < 350\ kW$$
$$-400 < Q_{inj} < 250\ kVar$$

Aggregate envelopes are helpful for the aggregator in the network-aware market bidding process.

Contribution 6: A real-time coordinated scheme for residential DR in LV networks under the dynamic operating envelopes framework



Air-conditioners

Thermal comfort limits

End-user privacy

Market dispatch interval

Household Operating envelopes

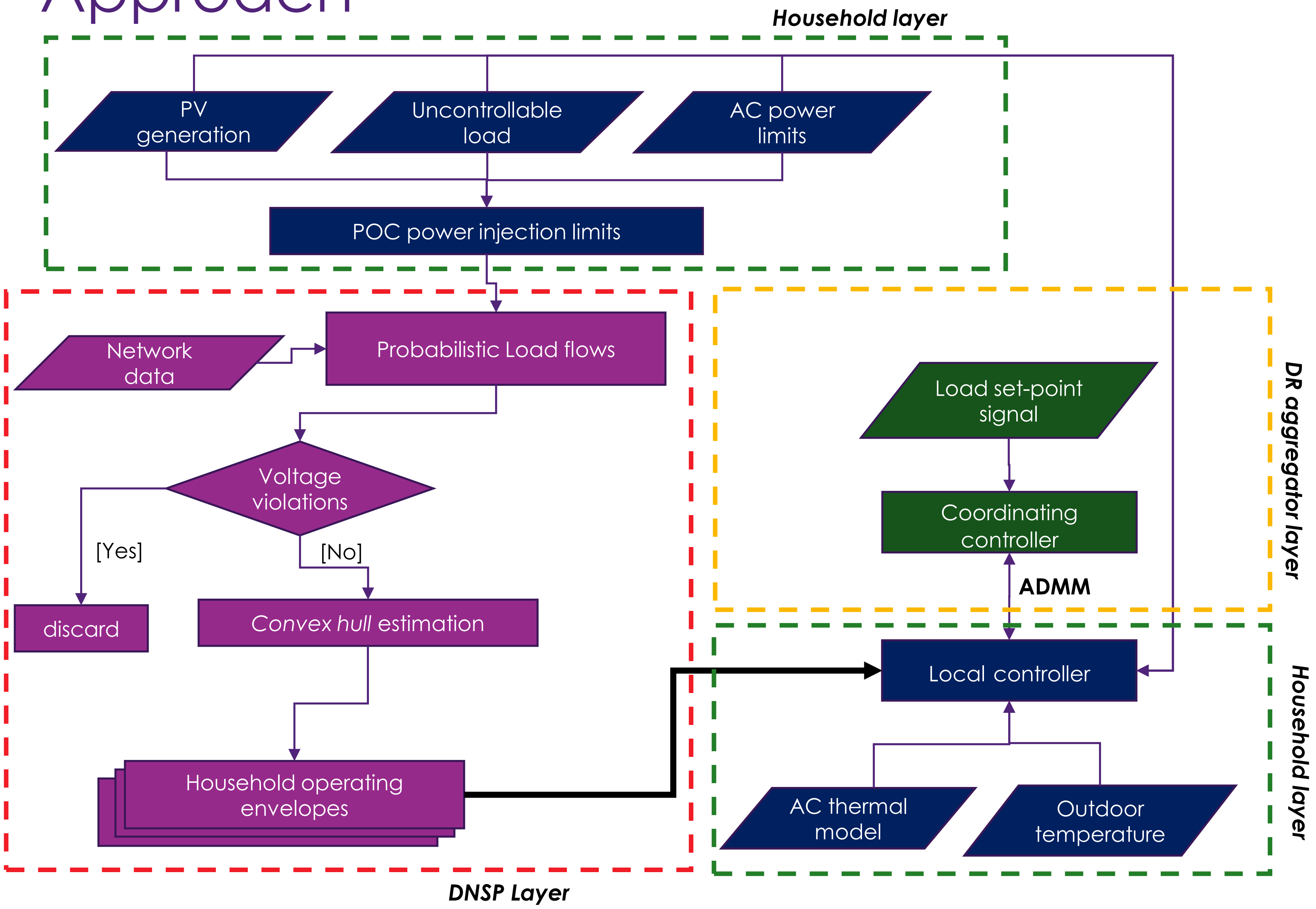
Network voltage limits

DNSP-Aggregator coordination

Real-time digital simulator validation

Real-time DR approach

Approach



DNSP estimates envelopes and passes to the DR aggregator

<u>Household local controller</u>

Minimising household energy cost

subject to:

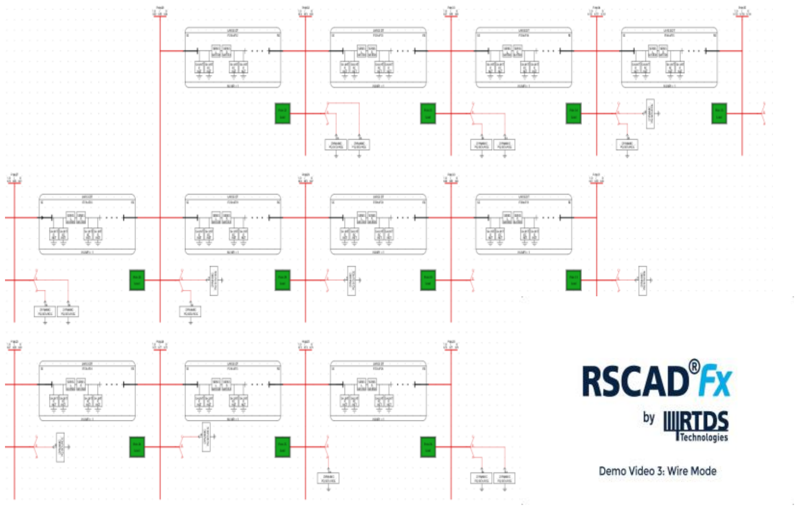
- AC thermal comfort limits
- **Voltage constraints (form of operating envelopes)**

Hierarchical implementation

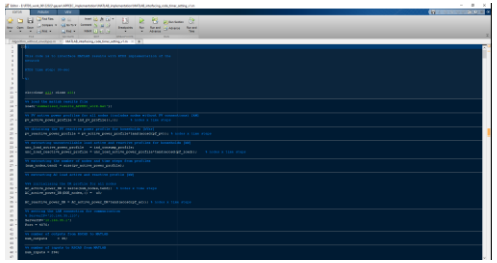
<u>Coordinating controller (DR aggregator)</u>

Minimising tracking error of the load set-point signal

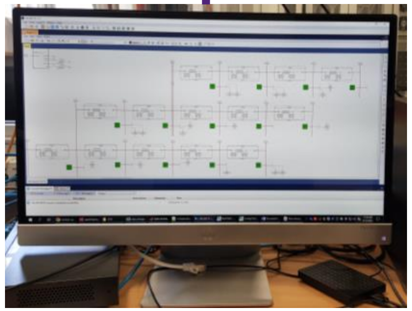
Software-in-the-loop (SIL) setup



Network model in RSCAD FX 1.3.1



MATLAB script for communicating with RTDS



Workstation

LAN switch

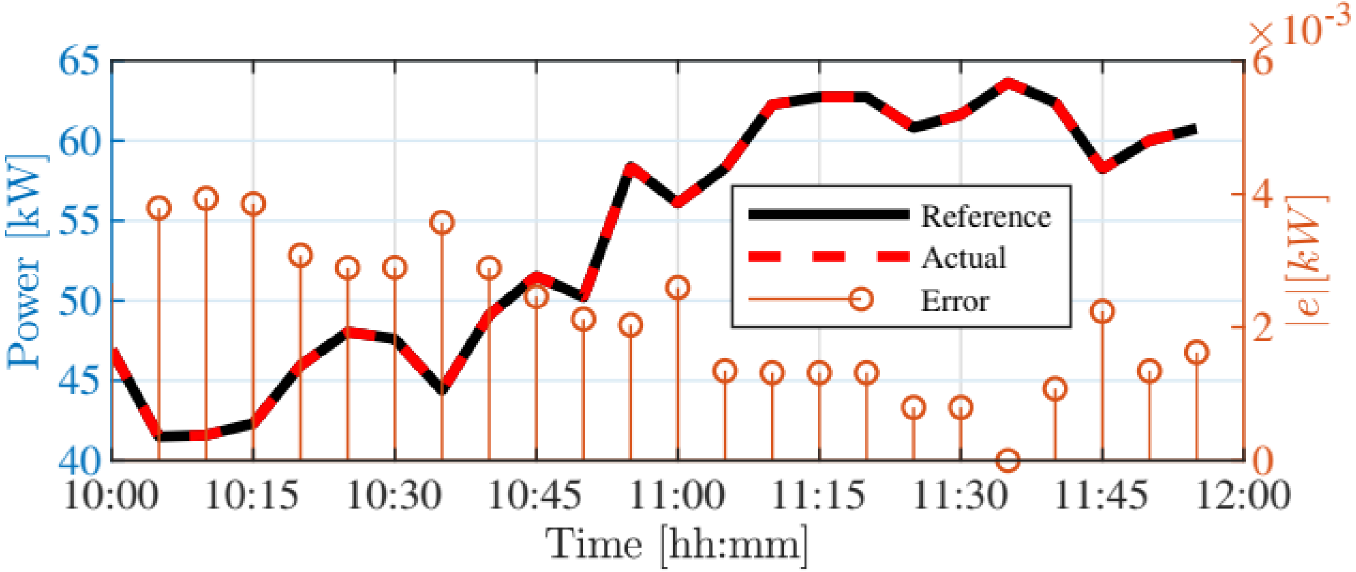
RTDS chassis (NovaCor processor card + GTNETx2 card)

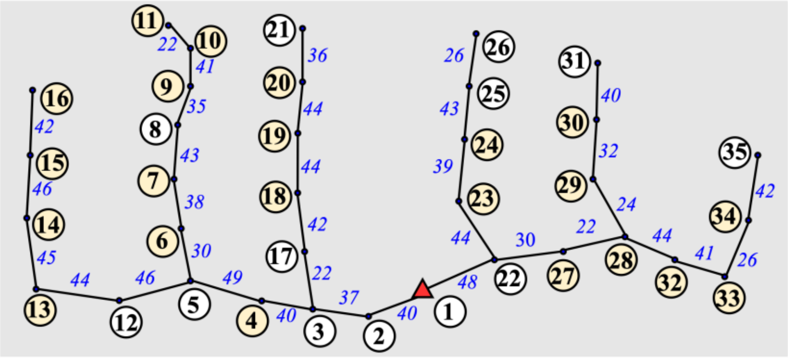
Results

- A realistic residential LV network (102 households)
- Types of customers
  - *Passive* - **56**
  - *DOE* (only participate in DR) – **30**
  - *Non-DOE* (5-kW export limits) – **16**

Sampling time = **5-mins** (aligned with AEMO's operation)

Tracking performance (DR period = 2-hours)

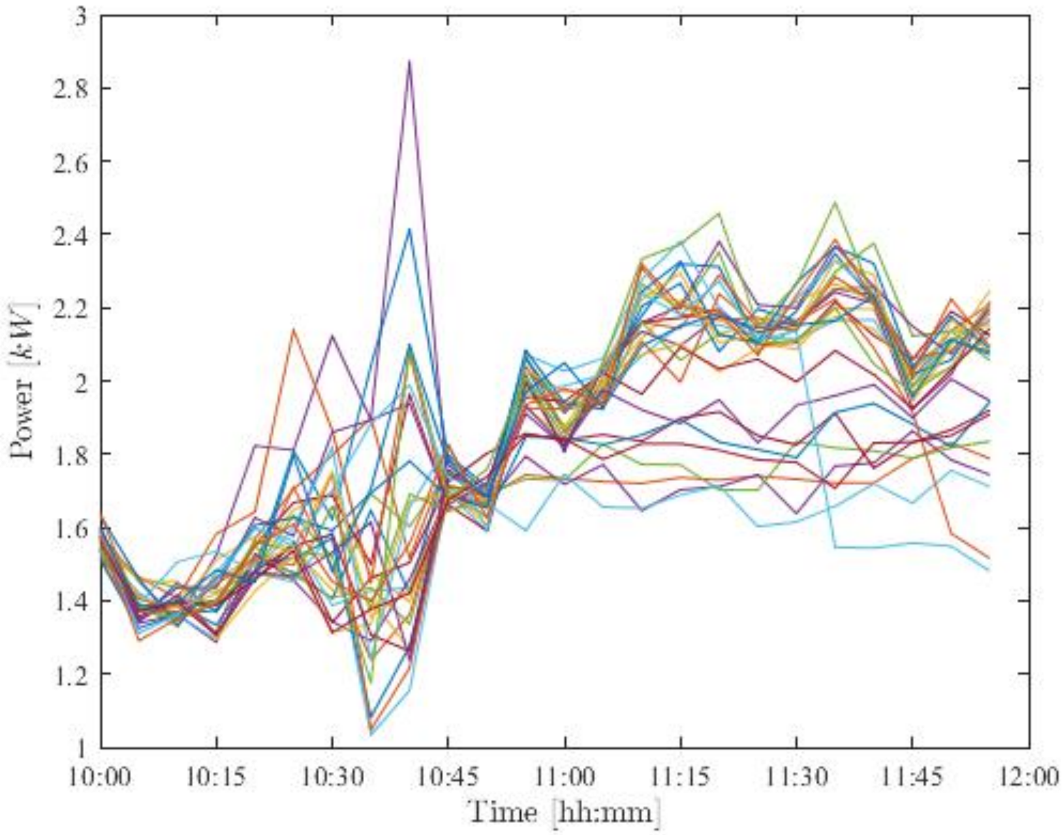




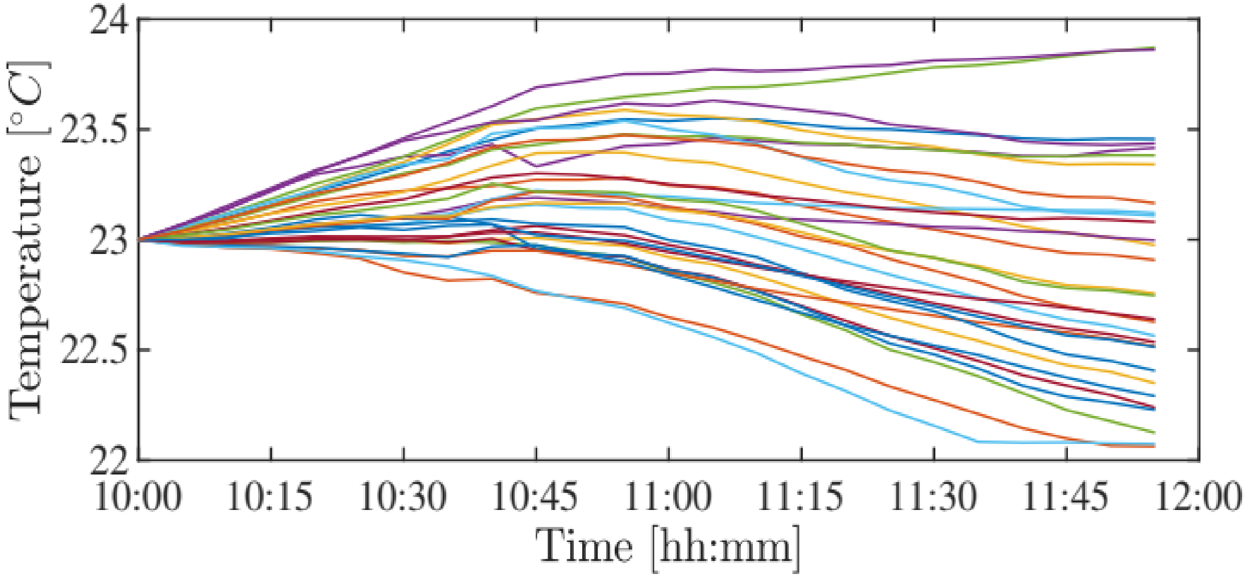
Single Line Diagram of the LV network

Precise tracking of the load set-point is achieved.

Air-conditioner power profile



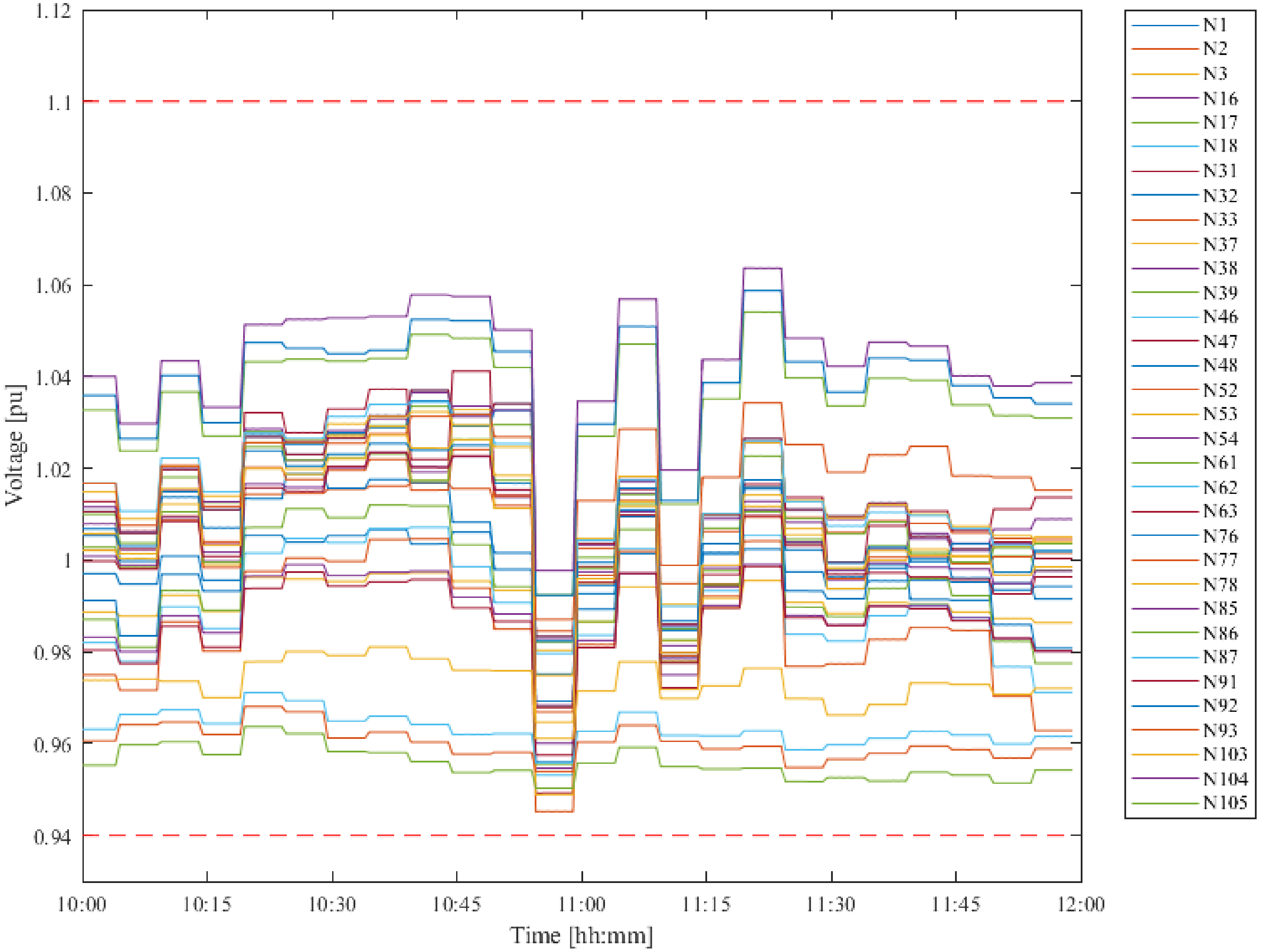
Indoor temperature profile



Thermal comfort limits: $[22,24]°C$

The overall approach preserves thermal comfort for DR customers

Voltage profile of selected nodes (software-in-the-loop simulation)



statutory limits

$$0.94\,pu < v < 1.10\,pu$$

The voltage profile is maintained with statutory limits for the DR period.

Outline

- Introduction
- Motivations
- Objectives
- Main Contributions
- Conclusions
- Future Work
- Thesis timeline
- Publications

- Through effective **uncertainty mitigation techniques**, DR could provide accurate load set-point tracking in electricity markets.
- Factors such as **scalability**, **end-user data privacy** should also be paid attention in developing control schemes for aggregation of residential loads in DR services under uncertainties.
- Dynamic operating envelopes that specify **end-user feasible operating region** without compromising voltage limits are useful for the aggregator in determining **flexibility** in electricity markets.
- With **adequate coordination between the aggregator and the DNSP**, dynamic operating envelopes could be utilised for providing DR services without breaching network technical limits.

Outline

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- DR control schemes robust against **communication failures**
- Contribution of **battery storage** and **electric vehicles** to the dynamic operating envelopes framework
- Establishing operating envelopes for household connections under **demand and generation uncertainties**
- Effect of **controllability** and **geographical distribution of loads** on the performance of DR under the DOE framework
- Effect of **demand composition** of household loads in the provision of DR in low-voltage residential networks

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Thesis timeline

Chapter	Content	Dec 2022	Jan 2023	Feb 2023	Current status
Chapter 1	Introduction	■			Writing–90%
Chapter 2	Literature Review	■			Writing–95%
Chapter 3	Centralised control of DR for grid services under uncertainties	■			Writing–95%
Chapter 4	Distributed control of DR for grid services under uncertainties	■			Writing–95%
Chapter 5	Establishing Dynamic operating envelopes in LV distribution networks	■			Writing–85%
Chapter 6	Dynamic-operating envelopes enabled DR in LV distribution networks		■		Simulations–90% Writing–70%
Chapter 7	Conclusions and Future Work		■		Writing–0%
Thesis Review (M3)		🟥			
Thesis submission				🟥	

Outline

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Peer-reviewed Journals:

- G. Lankeshwara, R. Sharma, R. Yan, and T. K. Saha, "Control algorithms to mitigate the effect of uncertainties in residential demand management," *Applied Energy (Elsevier)*, vol. 306, p. 117971, 2022, doi: 10.1016/j.apenergy.2021.117971.
- G. Lankeshwara, R. Sharma, R. Yan, and T. K. Saha, "A hierarchical control scheme for residential air-conditioning loads to provide real-time market services under uncertainties," *Energy (Elsevier)*, vol. 250, p. 123796, 2022, doi: 10.1016/j.energy.2022.123796.
- G. Lankeshwara and R. Sharma, "A Model-based Approach for the Robust Automation of Residential Loads to Provide Grid Services," *International Journal of Control (Taylor & Francis),* **(first revision)**
- G. Lankeshwara, R. Sharma, R. Yan, and T. K. Saha, "Operating Envelopes to Manage Low-voltage Distribution Networks," (**to be submitted to *IEEE Transactions on Power Systems*)**

Peer-reviewed Conference Papers:

- G. Lankeshwara, R. Sharma, R. Yan, and T. K. Saha, "Control of Residential Air-conditioning Loads to Provide Regulation Services under Uncertainties," in *IEEE Power and Energy Society General Meeting*, 2021, vol. 2021-July, pp. 1–5, doi: 10.1109/PESGM46819.2021.9637890.
- G. Lankeshwara, "A Real-time Control Approach to Maximise the Utilisation of Rooftop PV Using Dynamic Export Limits," in *2021 IEEE PES Innovative Smart Grid Technologies - Asia (ISGT Asia)*, Dec. 2021, pp. 1–5, doi: 10.1109/ISGTAsia49270.2021.9715714.

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Thank you

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