Control of Residential Inverter-type Air conditioners to Provide Regulation Services under Uncertainties

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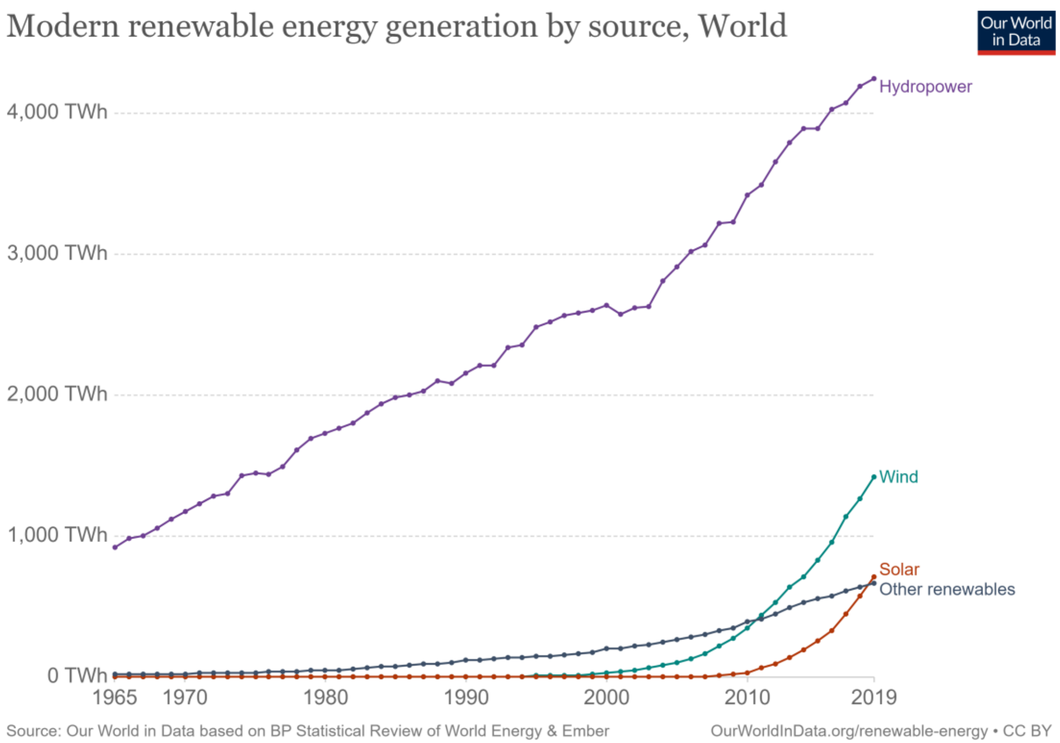
Outline

- Introduction
- Motivation behind the work
- Proposed Methodology
- Results
- Future Work

Why we need Regulation services ?



The rapid growth of intermittent renewable energy generation urges the need of additional reserve capacity to manage the grid.

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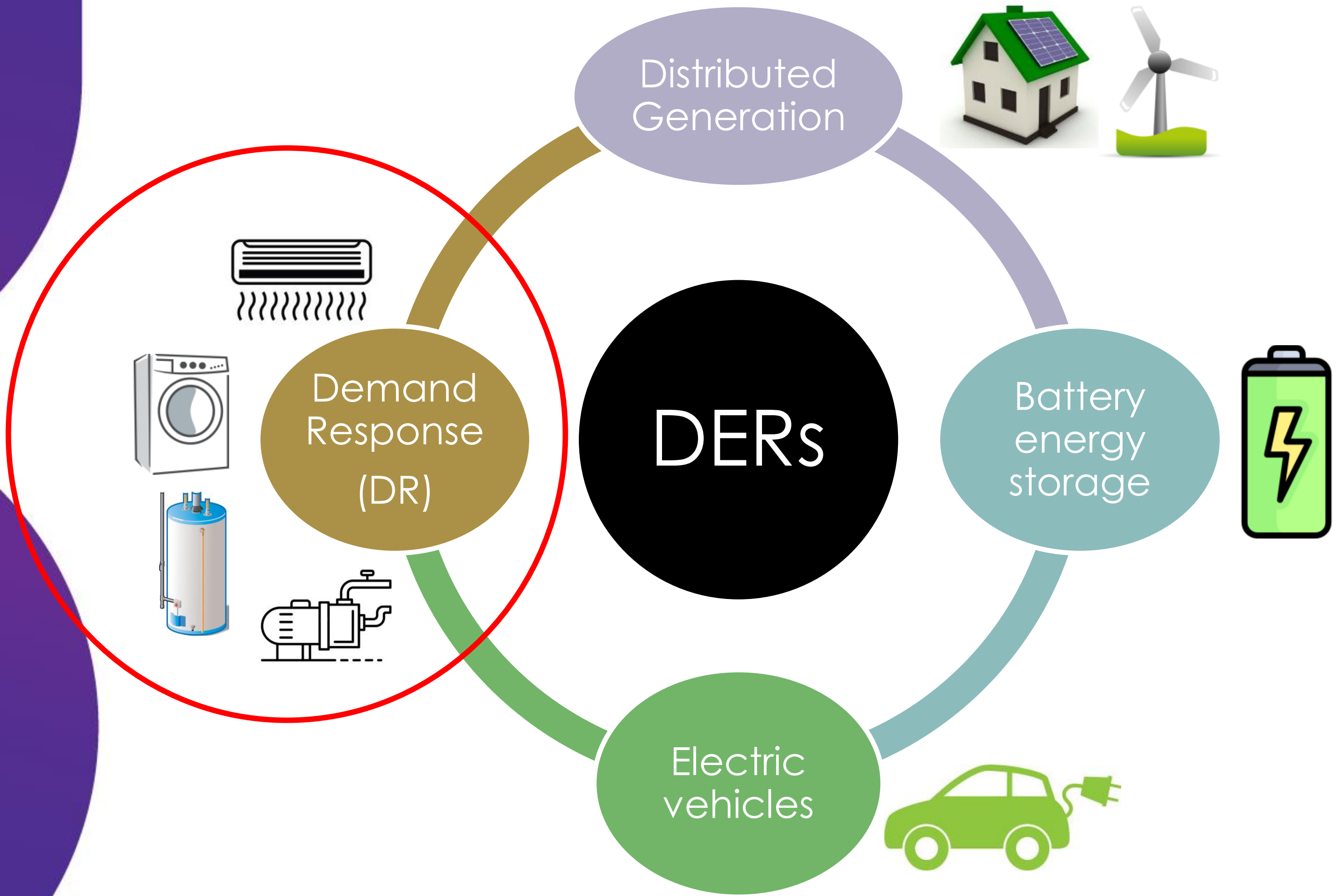
What are Distributed Energy Resources (DERs) and why they are useful ?



DERs are consumer owned devices that can generate, store or smartly manage energy demand.

https://aemo.com.au/en/initiatives/major-programs/nem-distributed-energy-resources-der-program
https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Feb/IRENA_Market_integration_distributed_system_2019.pdf?la=en&hash=2A67D3A224F1443D529935DF471D5EA1E23C774A

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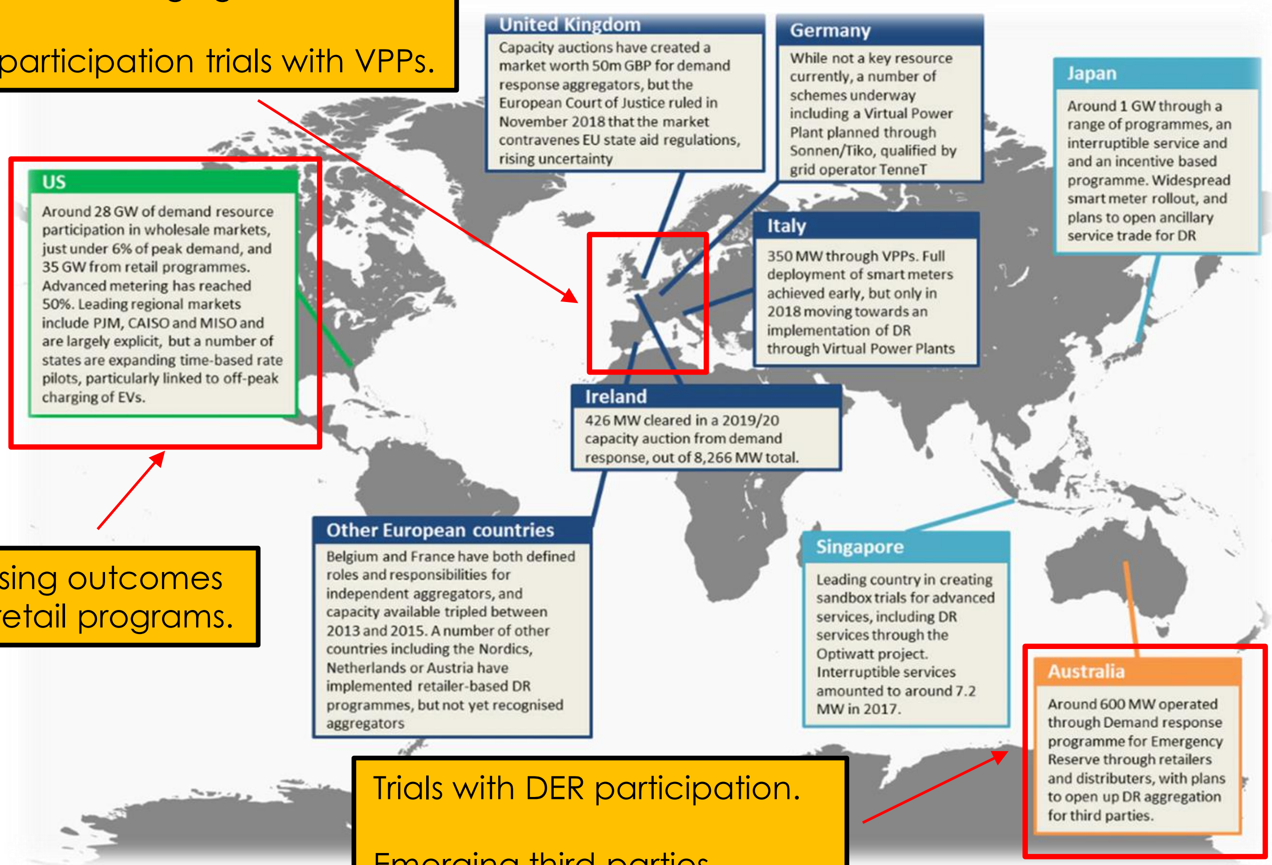
A glimpse of DR initiatives around the world

Aggregators emerging.

Market participation trials with VPPs.



Promising outcomes from retail programs.

Trials with DER participation.

Emerging third parties.

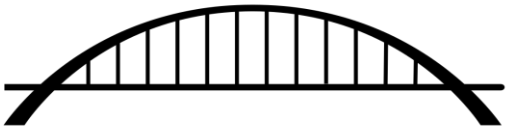
Trials have not been able to capture the residential DER aggregation.

IEA (2020), Tracking Energy Integration 2020, IEA, Paris https://www.iea.org/reports/tracking-energy-integration-2019

Existing vs. Future prospects

Current applications of DR

Level	Applications	R	C	I
Retail	Peak shaving	✓	✓	✓
	Time –based programs	✓	✓	✓
Market	Wholesale & ancillary markets	✗	✓	✓



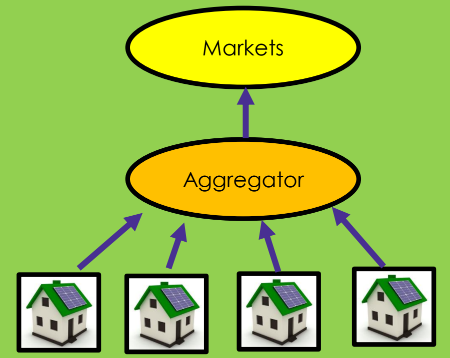
Issues

- Uncertainties in DER aggregation
- Lack of control algorithms
- Compliance with existing standards

Future potential applications of DR

DER aggregation in

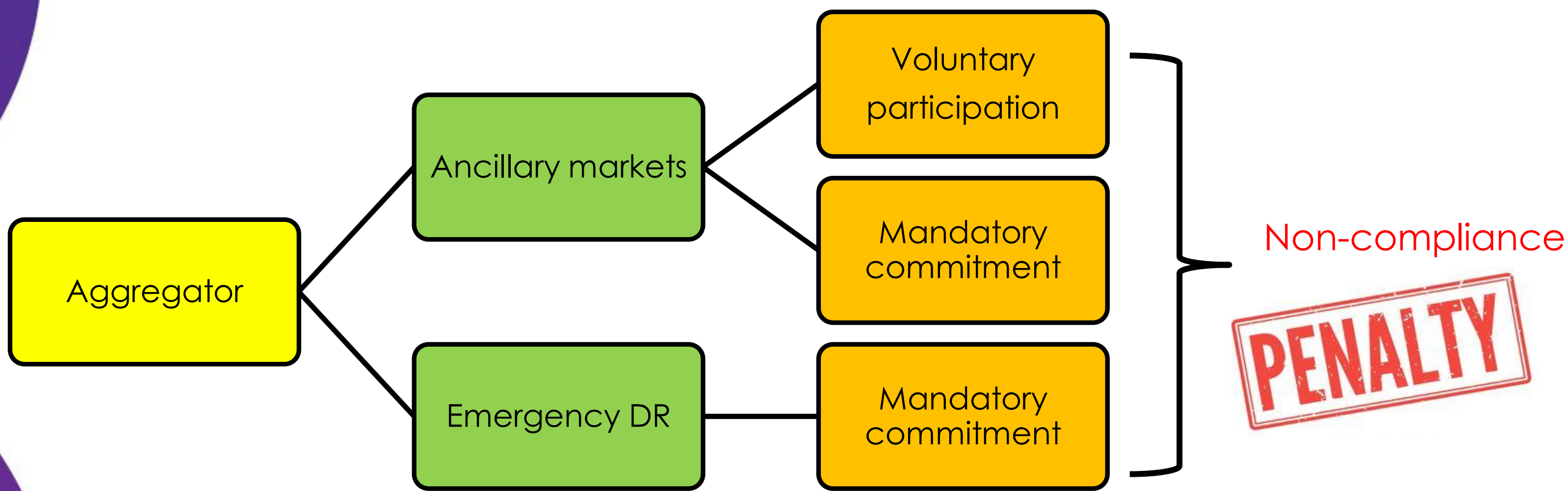
- Energy markets
- Ancillary service markets
- Emergency DR



Under-utilising the capacity of DER possessed by residential customers is a missed opportunity in electricity markets.

Why uncertainties need to be addressed?

According to market policies [1],



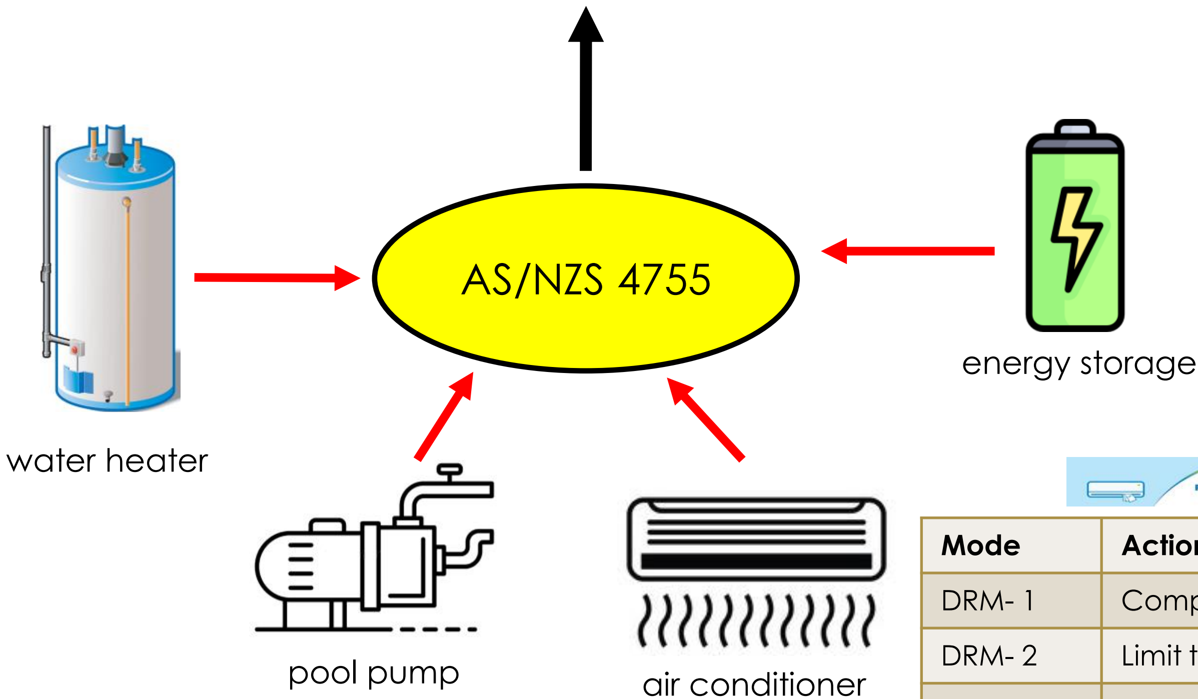
Presence of uncertainties ?

Aggregator at risk of receiving financial penalties for not delivering contracted demand in real-time.

[1] https://pjm.com/markets-and-operations.aspx

Demand Response Standards

Operation under discrete consumption levels.



Mode	Action
DRM- 1	Compressor off
DRM- 2	Limit to 50% rated
DRM- 3	Limit to 75% rated

Load control algorithms in existing literature hardly take account of existing DR standards.

https://www.energex.com.au/home/control-your-energy/positive-payback-program/positive-payback-for-business/air-conditioning-rewards

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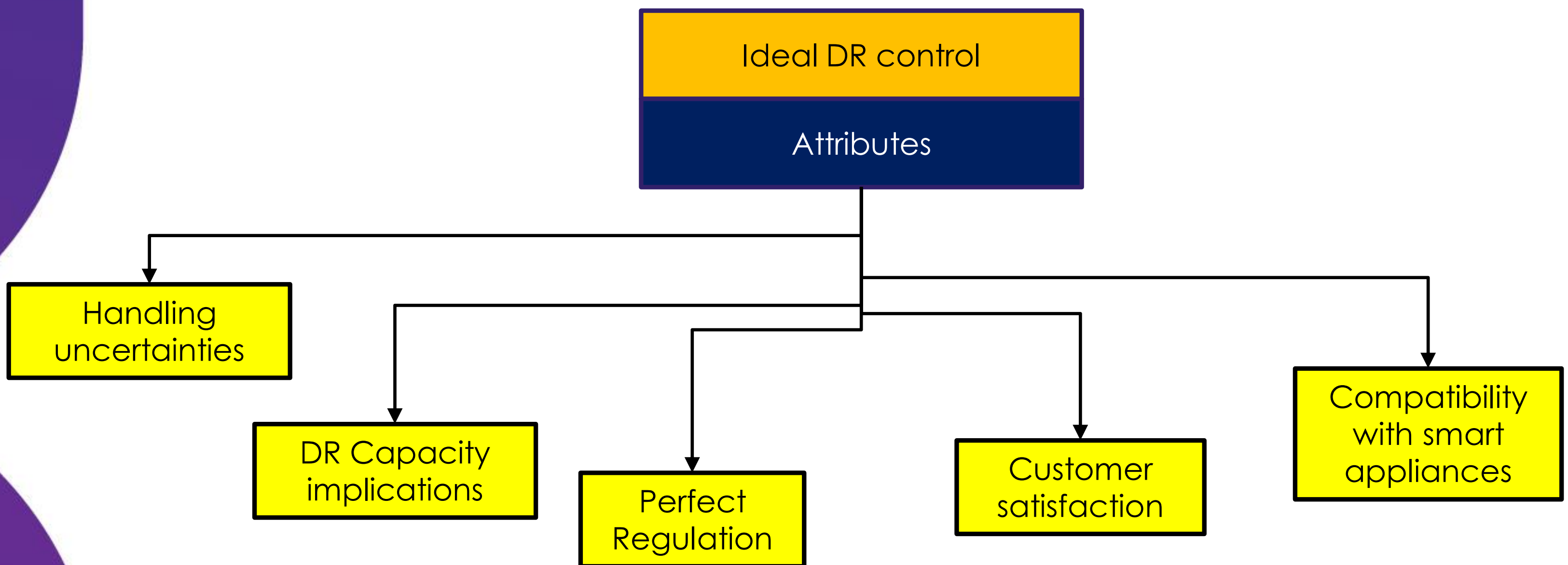
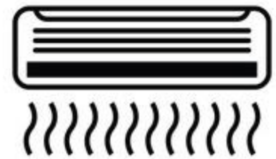
Drawbacks of existing load control programs



To what extent the existing algorithms account for market participation of DER is always a question.

Why our primary focus is on Air-conditioning loads?

Why Air conditioning loads ?



High thermal inertia

Minimum effect on temperature even controlled for longer durations

Existing literature

- Rarely consider inverter-type air conditioners
- Most of the approaches based on setpoint control of ON-OFF type air conditioners
- Incompatible with existing demand response standards

The capabilities of inverter-type air conditioners operating under demand response standards for regulation services requires further study.

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System Model

Using a first order thermal model (ETP model) for inverter-type air conditioners,

$$T_i(k+1) = a_i T_i(k) + (1-a_i)\left[T_i^{\text{out}}(k) - \eta_i R_i P_i(k)\right]$$

$T_i(k)$: indoor temperature at time k

$T_i^{out}(k)$: outdoor temperature at time k

$P_i(k)$: power consumption at time k

R_i : thermal resistance

C_i : thermal capacitance

η_i : coefficient of performance

$$a_i = e^{-h/R_i C_i}$$

obtained from [1]

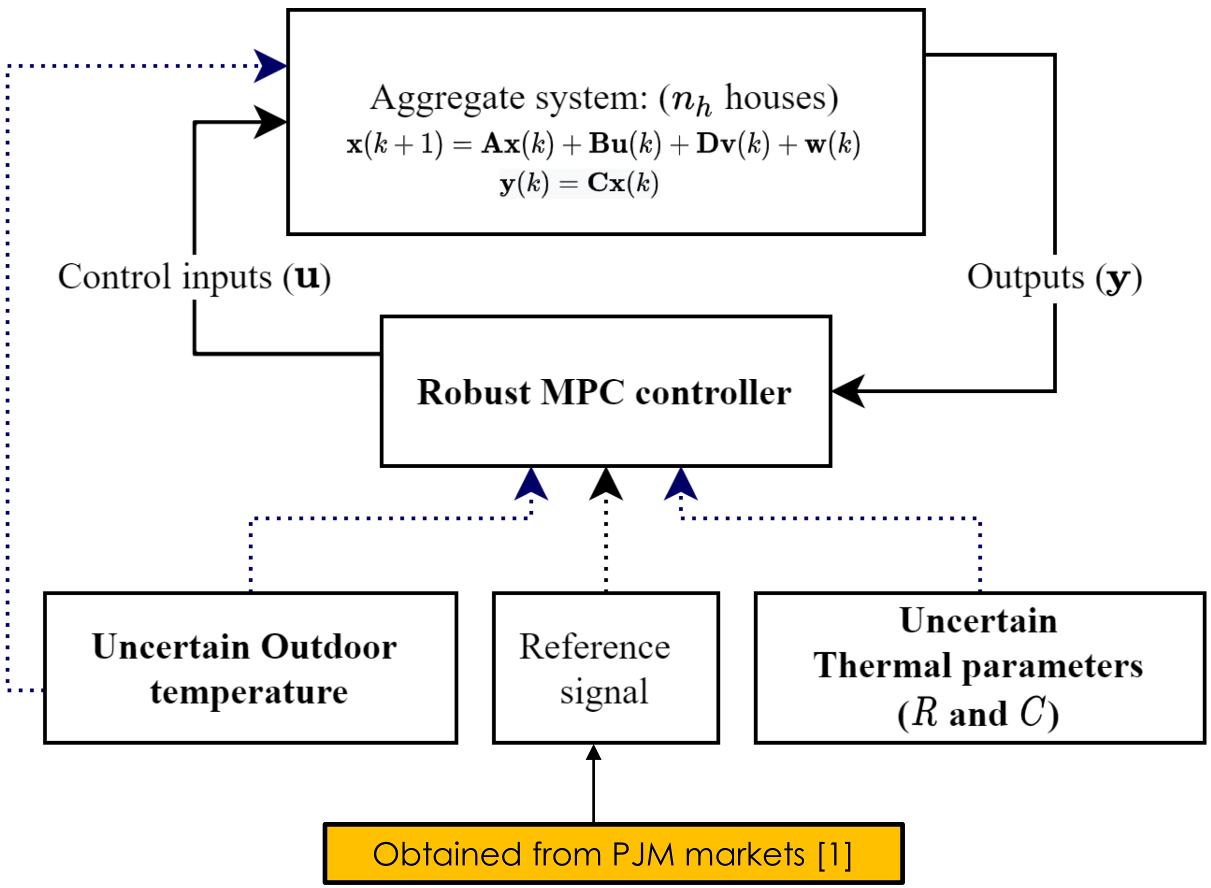
Parameter	Value
R	1.5 -2.5°C/kW
C	1.5 -2.5 kWh/°C
η	2.5

Individual models can be stacked together to obtain the aggregate model of the population of air conditioners (dynamically-decoupled).

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

[1] J. Mathieu, S. Koch and D. Callaway, "State estimation and control of electric loads to manage real-time energy imbalance," 2013 IEEE Power & Energy Society General Meeting, Vancouver, BC, 2013, pp. 1-1, doi: 10.1109/PESMG.2013.6672144.

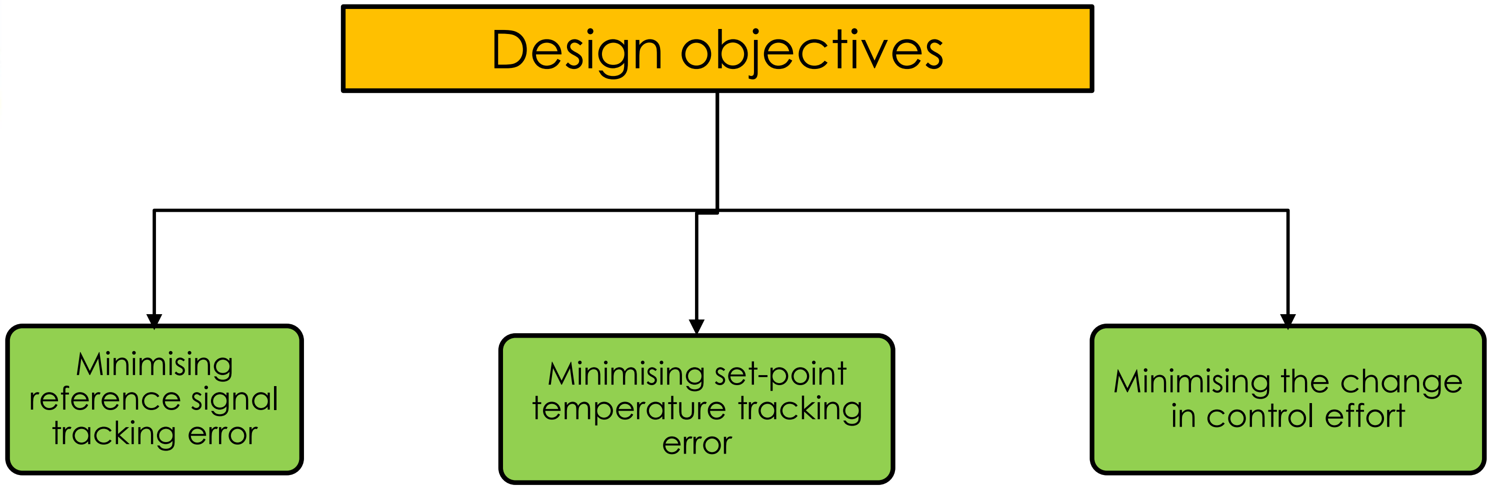
Overall Robust Model Predictive Control (MPC) scheme



Control inputs: power consumption set-points of air conditioners
Outputs: Indoor temperature measurements

[1] https://pjm.com/markets-and-operations.aspx

Centralised control scheme



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

Constraints of the problem

$$\mathbf{x}(k+j+1|k) = A\mathbf{x}(k+j|k) + B\mathbf{u}(k+j|k) + D\mathbf{v}(k+j|k) + \mathbf{w}(k+j|k)$$

$$P_{\text{agg}}(k+j|k) = \mathbf{P}_{\text{rated}}{}^{\text{T}}\mathbf{u}(k+j|k)$$

$$\underline{\mathcal{X}} \leq \mathbf{x}(k+j|k) \leq \overline{\mathcal{X}}$$

Thermal comfort constraints

$$\Delta\mathbf{u}(k+j|k) = \mathbf{u}(k+j+1|k) - \mathbf{u}(k+j|k)$$

$$\mathbf{u}(k+j|k) = \{0.5, 0.75, 1.0\}$$

DRM levels

$$\mathbf{w}(k+j|k) \in \mathbb{W}$$

$$\text{for } j = 0, 1, 2 \ldots N-1$$

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

Worst-case disturbance

How to find the worst-case disturbance for Robust MPC scheme ? (w_0)

Deriving from first principles,

$$R_i = R_{\text{nom},i} + \Delta R_i$$
$$C_i = C_{\text{nom},i} + \Delta C_i$$

$$a_i = e^{-h/(R_i C_i)} = e^{-h/(R_{\text{nom},i}+\Delta R_i)(C_{\text{nom},i}+\Delta C_i)}$$
$$= e^{-h/(R_{\text{nom},i}C_{\text{nom},i}+R_{\text{nom},i}\Delta C_i+C_{\text{nom},i}\Delta R_i+\Delta R_i \Delta C_i)}$$

$$a_i = a_{\text{nom},i} + \Delta a_i$$

$$a_{\text{nom},i} = e^{-h/(R_{\text{nom},i}C_{\text{nom},i})}$$

$$T_i(k+1) = (a_{\text{nom},i} + \Delta a_i)T_i(k) + (1 - (a_{\text{nom},i} + \Delta a_i)) \left[(T_i^{\text{out}}(k) + \Delta T_i^{\text{out}}(k)) - \eta_i (R_{\text{nom},i} + \Delta R_i) P_i(k) \right]$$

$$\boxed{w_i(k) = (1 - a_{\text{nom},i})(\Delta T_i^{\text{out}}(k) - \eta_i \, \Delta R_i \, P_i(k)) - \Delta a_i \cdot \left(T_i^{\text{out}}(k) - \Delta T_i^{\text{out}}(k) - \eta_i (R_{\text{nom},i} + \Delta R_i) P_i(k) \right)}$$

How to find the worst-case disturbance for Robust MPC scheme ? (w_0)

If we can estimate,

$$\Delta C_i = |\Delta C_i|_{\max}$$

$$\Delta R_i = |\Delta R_i|_{\max}$$

Remember !

Parameter	Value
R	1.5 -2.5°C/kW
C	1.5 -2.5 kWh/°C
η	2.5

Analysing historical data, we can estimate outdoor temperature prediction error

$$\Delta T_i^{\mathrm{out}}(k) = |\Delta T_i^{\mathrm{out}}|_{\max}$$

Finally, we have an estimation of (w_0)

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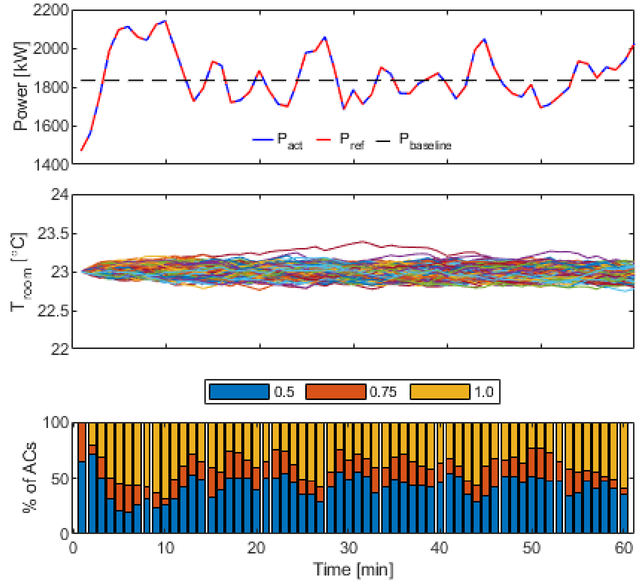
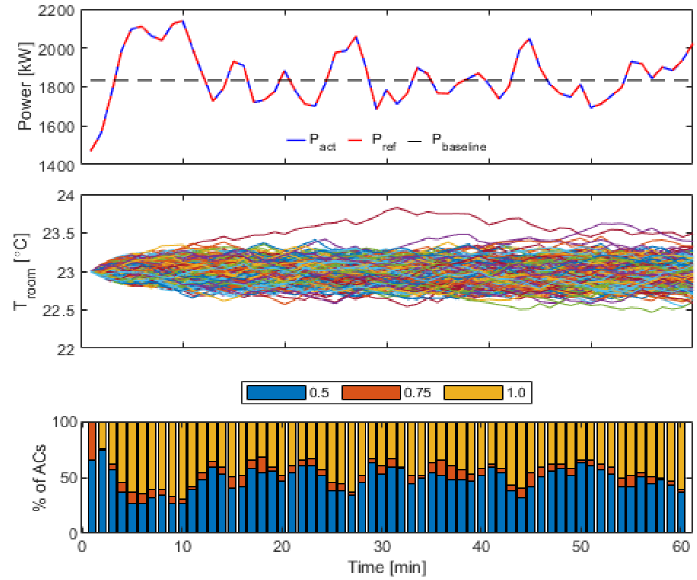
Simulation data

Parameter/ Variable	Value
P_{rated}	2.5 kW
Temp constraints	[22, 24]°C
T_{set}	23°C
Simulation step size	1 min
MPC prediction horizon (*N*)	3 mins
$T_{duration}$	1 hour
No. houses (n_h)	1000

Results



w0 = 0.05°C



w0 = 0.075°C

As the degree of uncertainty increases, most of the air conditioners tend to operate at their extreme limits to avoid temperature violations.

However, tracking is maintained.

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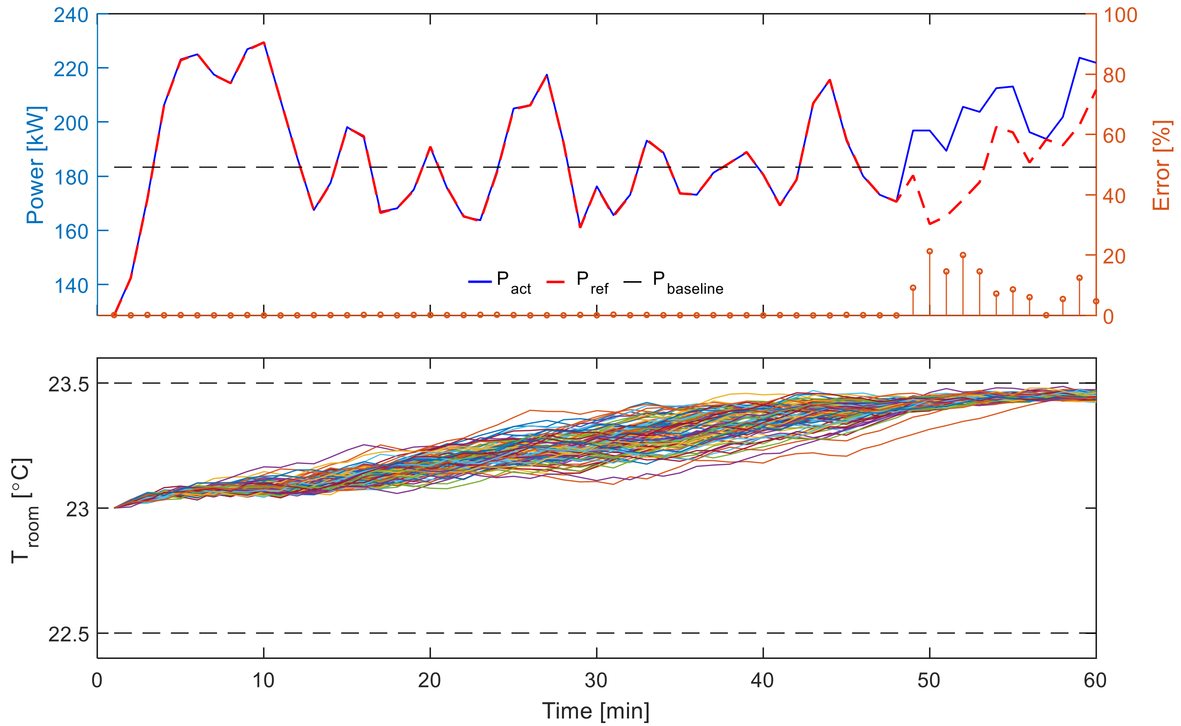
Results (continued)

Under tightened temperature constraints and additive uncertainties assumed to be positive



w0 = 0.02°C

Towards the end of the event, the tracking performance degrades in order to maintain the indoor temperature within the limits

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Future work

✓ Distributed control of air conditioners instead of centralised control

- end-user privacy-preserving
- thermal comfort preserving
- taking into account uncertainties at household level

Thank You !

Acknowledgement : REDBACK TECHNOLOGIES