Centralised control of Distributed Energy Resources for participation in electricity markets in presence of uncertainties

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Australia

Outline

- Introduction
- Research Objectives
- Motivation
- Literature Review and Gaps
- Proposed Methodology
- Progress up to date
- Timeline

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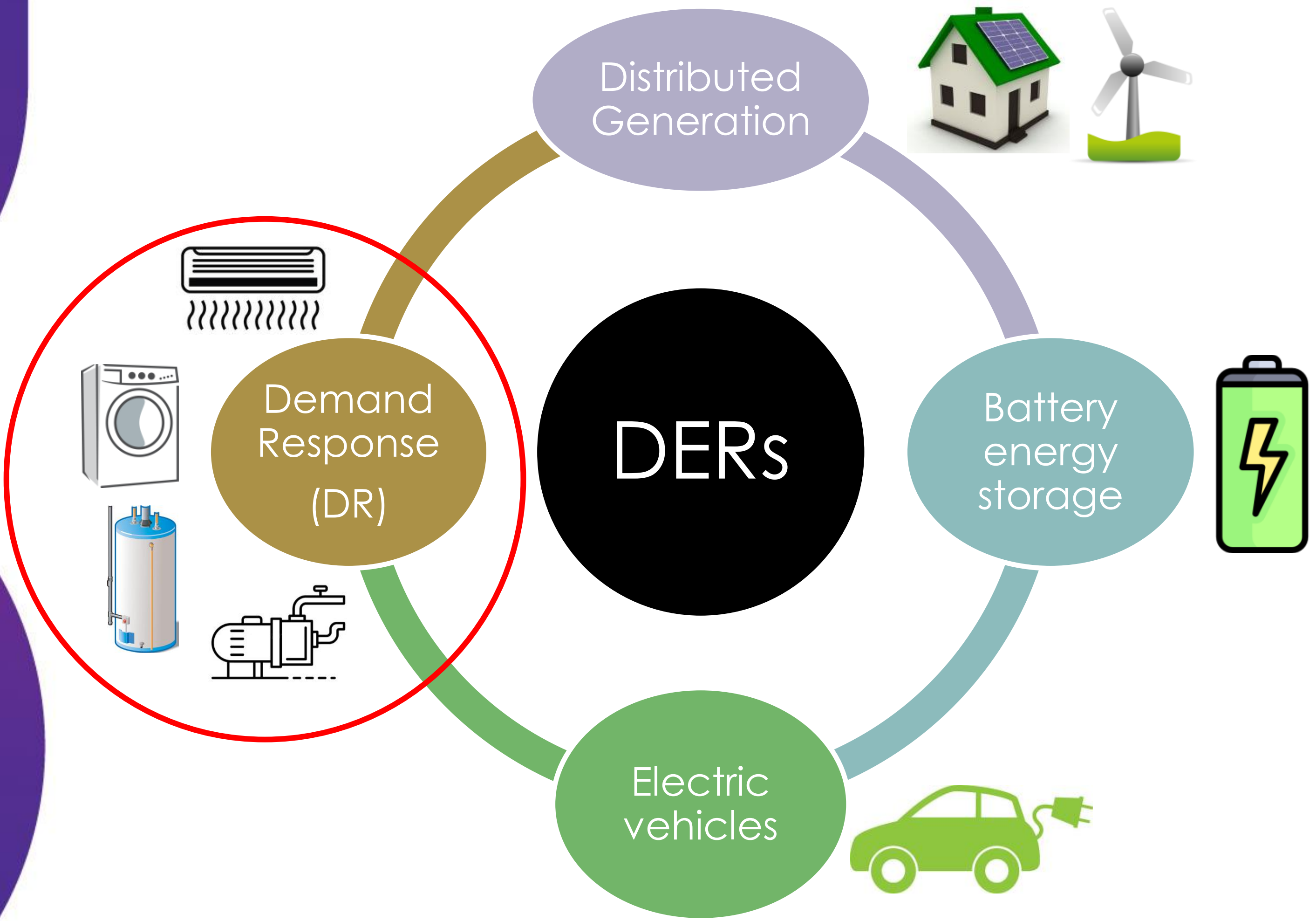
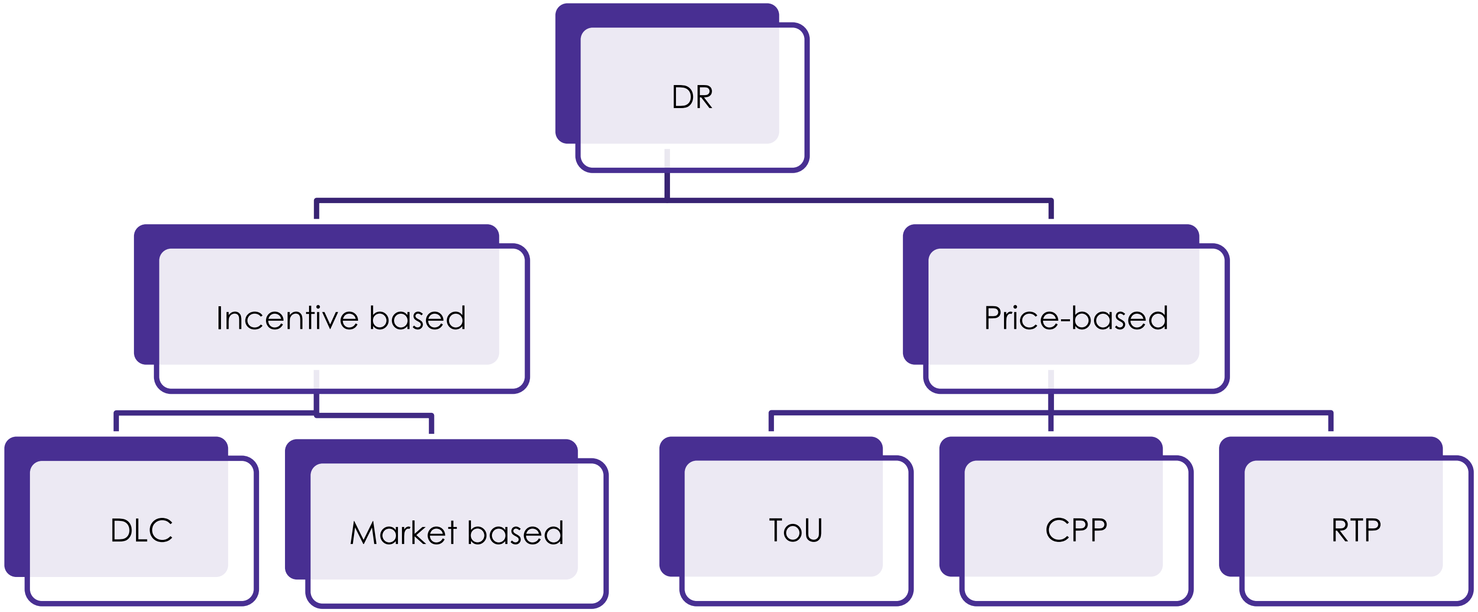
What are Distributed Energy Resources (DERs) ?

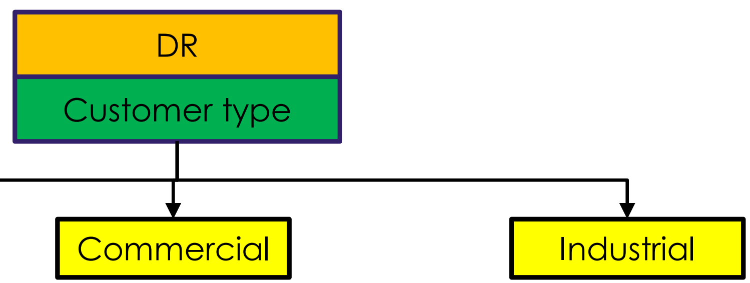


DERs are consumer owned devices that can generate, store or smartly manage energy demand.

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

Classification of DR





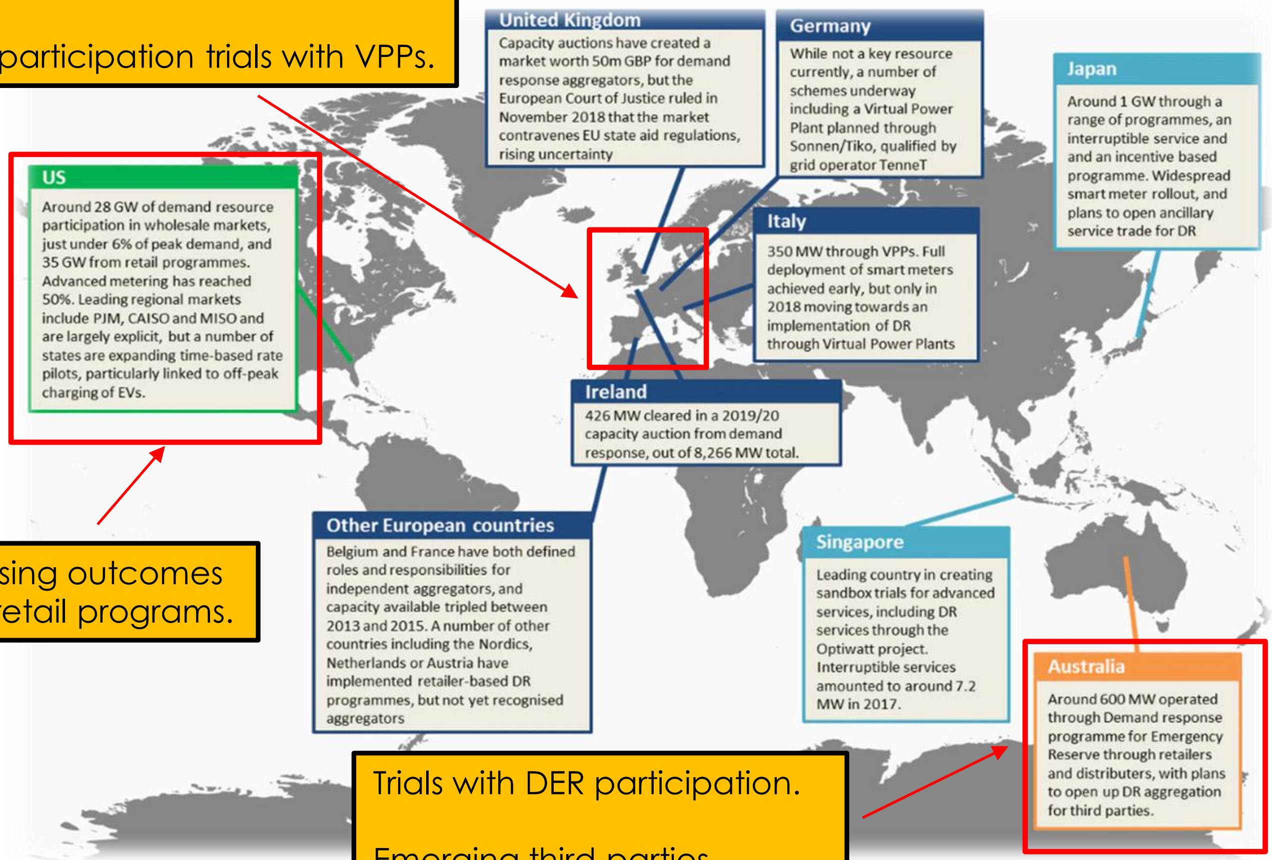
Residential DR is the driver behind most of the market based applications in the future.

Albadi, M.H. and El-Saadany, E.F., 2008. A summary of demand response in electricity markets. *Electric power systems research*, *78*(11), pp.1989-1996.

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.

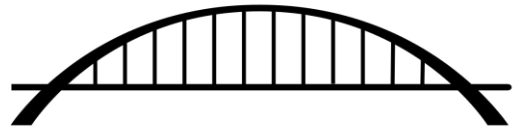
Trials have not been able to capture the residential DER aggregation.

IEA (2019), Tracking Energy Integration 2019, 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	✗	✓	✓



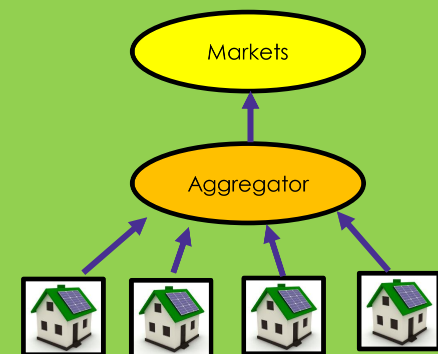
Issues

- 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.

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Research Objectives

1. To develop a control mechanism for the aggregator to accurately track the set-point power load reduction assigned by the system operator through aggregation of DERs.

2. To model the system uncertainties which could arise in the process of aggregator tracking the set-point power load reduction assigned by the system operator.

3. To develop a fully automated model-based control scheme that is robust enough to handle system uncertainties and successfully achieve provision of bids with precise load reductions in real-time under aggregated participation of DERs.

4. To analyse the performance of developed control schemes under different market scenarios and comparison with existing aggregator based DER management approaches.

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Outcomes of DR trials

Uncertainties in DER aggregation

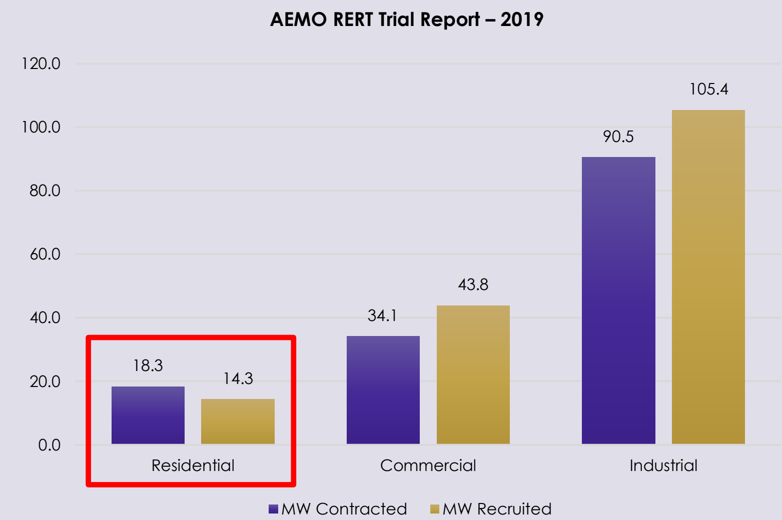
Lack of control algorithms

Compliance with existing standards

Learnings from existing Load Control Trials

- Low customer participation due to 'loss of perceived control'.
- Allowing flexibility at the consumer end, resulted in frequent overriding in trials.

Market participation trials

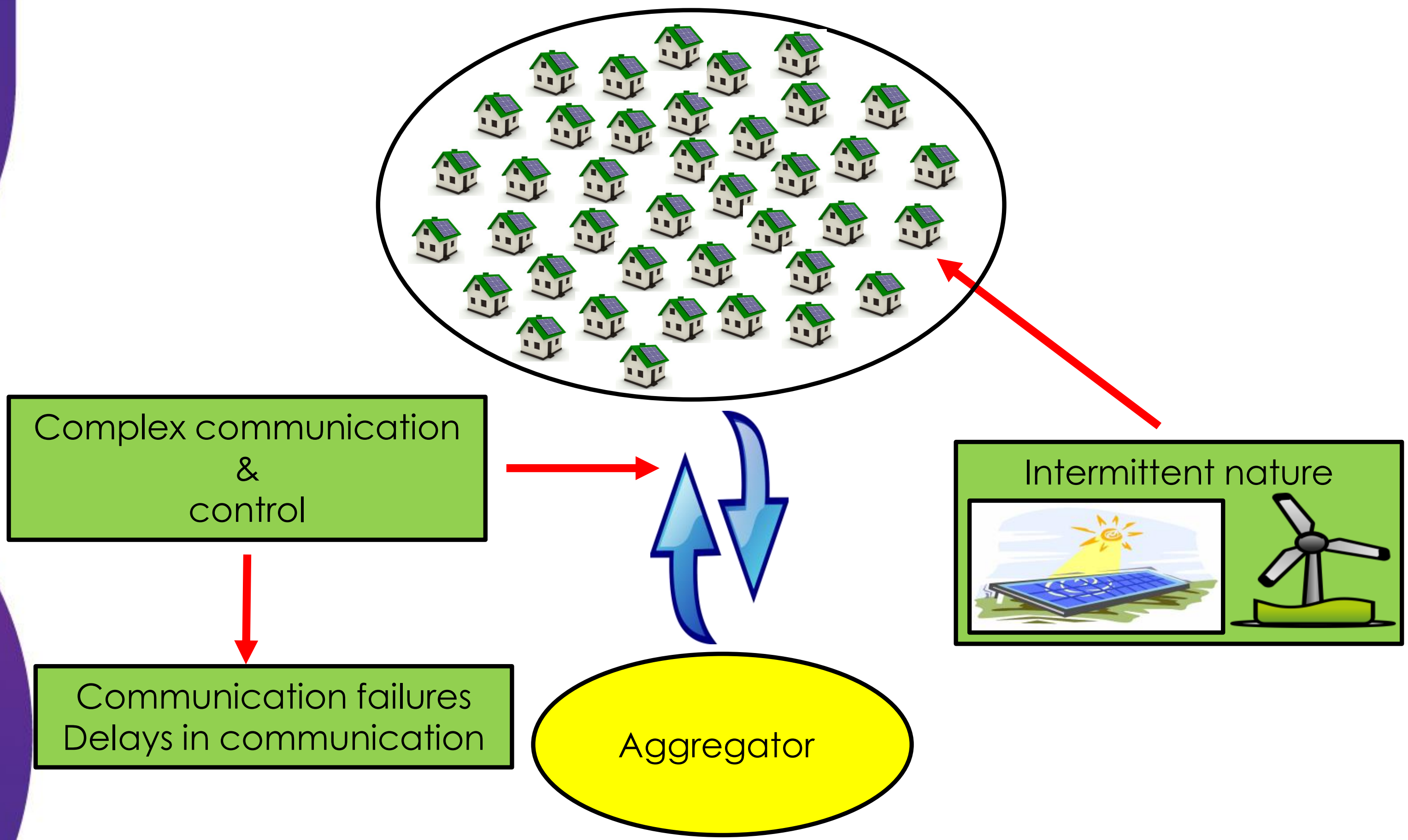


Significant mismatch in residential contribution.

<u>Customer overriding</u> poses challenges in the successful aggregation of DERs to participate in market events.

SDG&E "Smart Thermostat Pilot", ConEd Cool NYC program, Ausgrid *CoolSaver* program, ZEN ECOSYSTEMS ARENA/AEMO DR Trial
https://arena.gov.au/assets/2019/03/demand-response-rert-trial-year-1-report.pdf

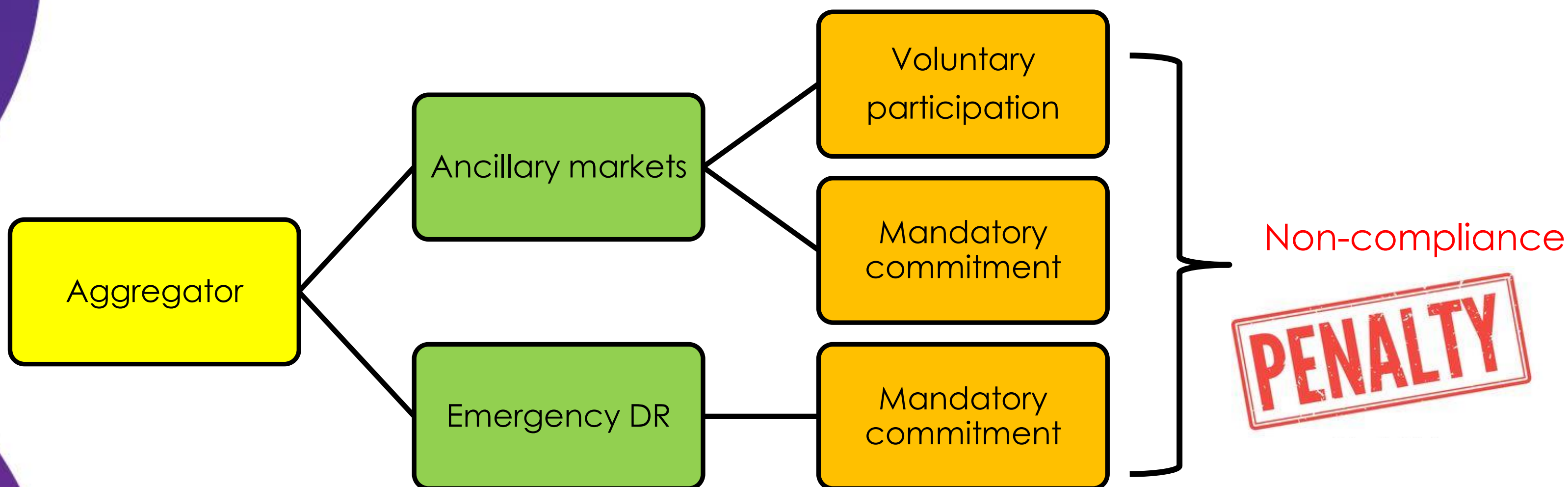
Large scale aggregation of DERs



<u>Complex communication and control</u> poses challenges in large scale DER aggregation.

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

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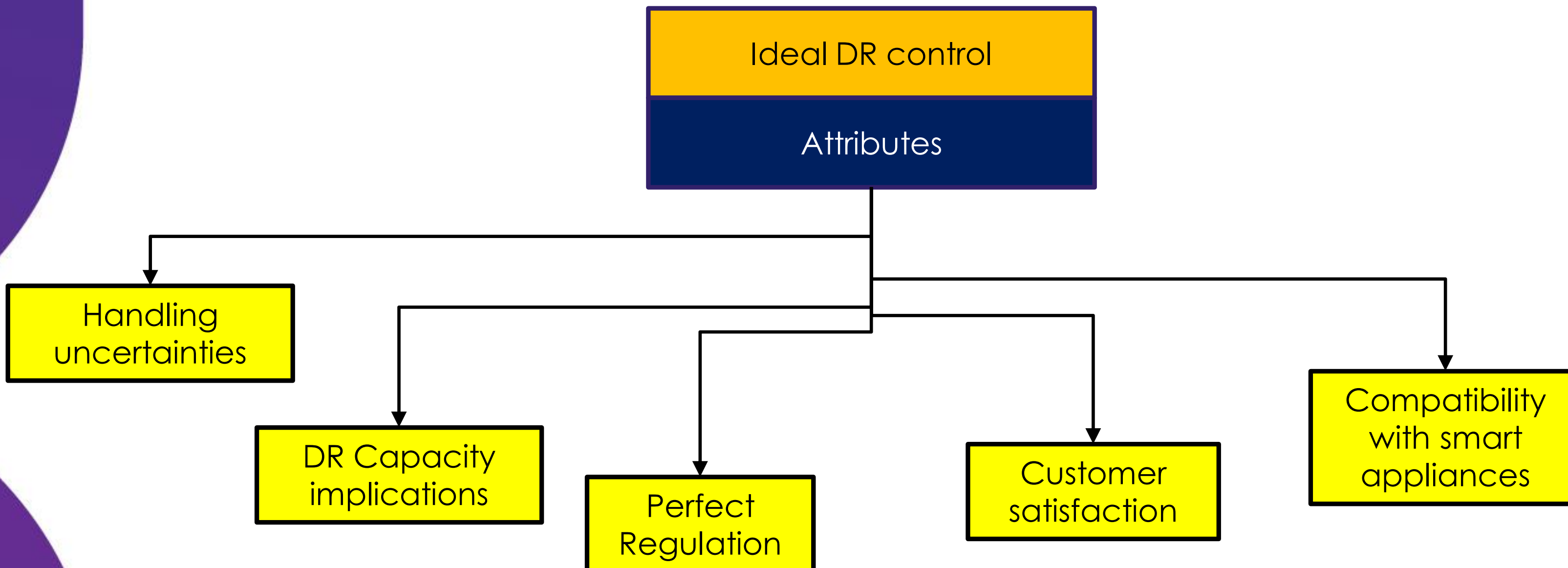
Uncertainties in DER aggregation
Lack of control algorithms
Compliance with existing standards

Drawbacks of existing load control programs



SDGE
A Sempra Energy utility
agl
Ausgrid
POSITIVE PAYBACK
conEdison, inc.

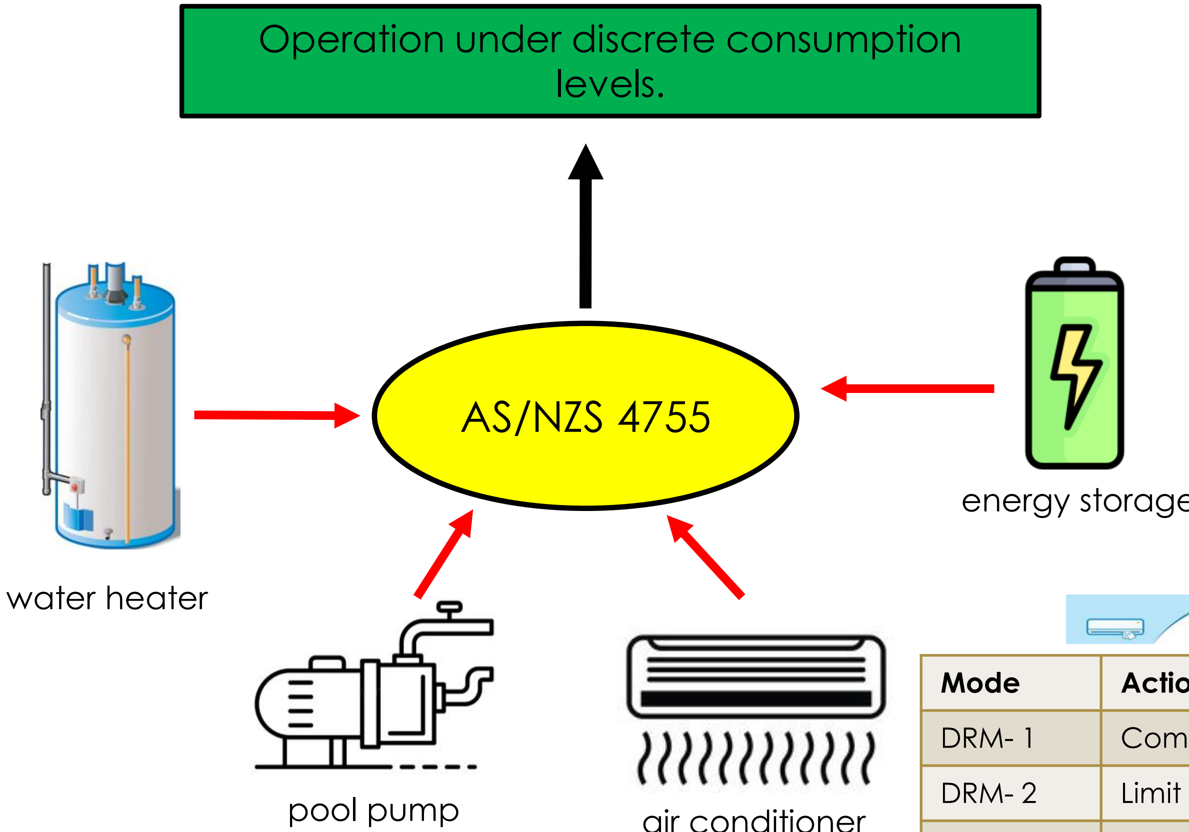
To what extent the existing algorithms account for market participation of DER is always a question.

Uncertainties in DER aggregation

Lack of control algorithms

Compliance with existing standards

Demand Response Standards



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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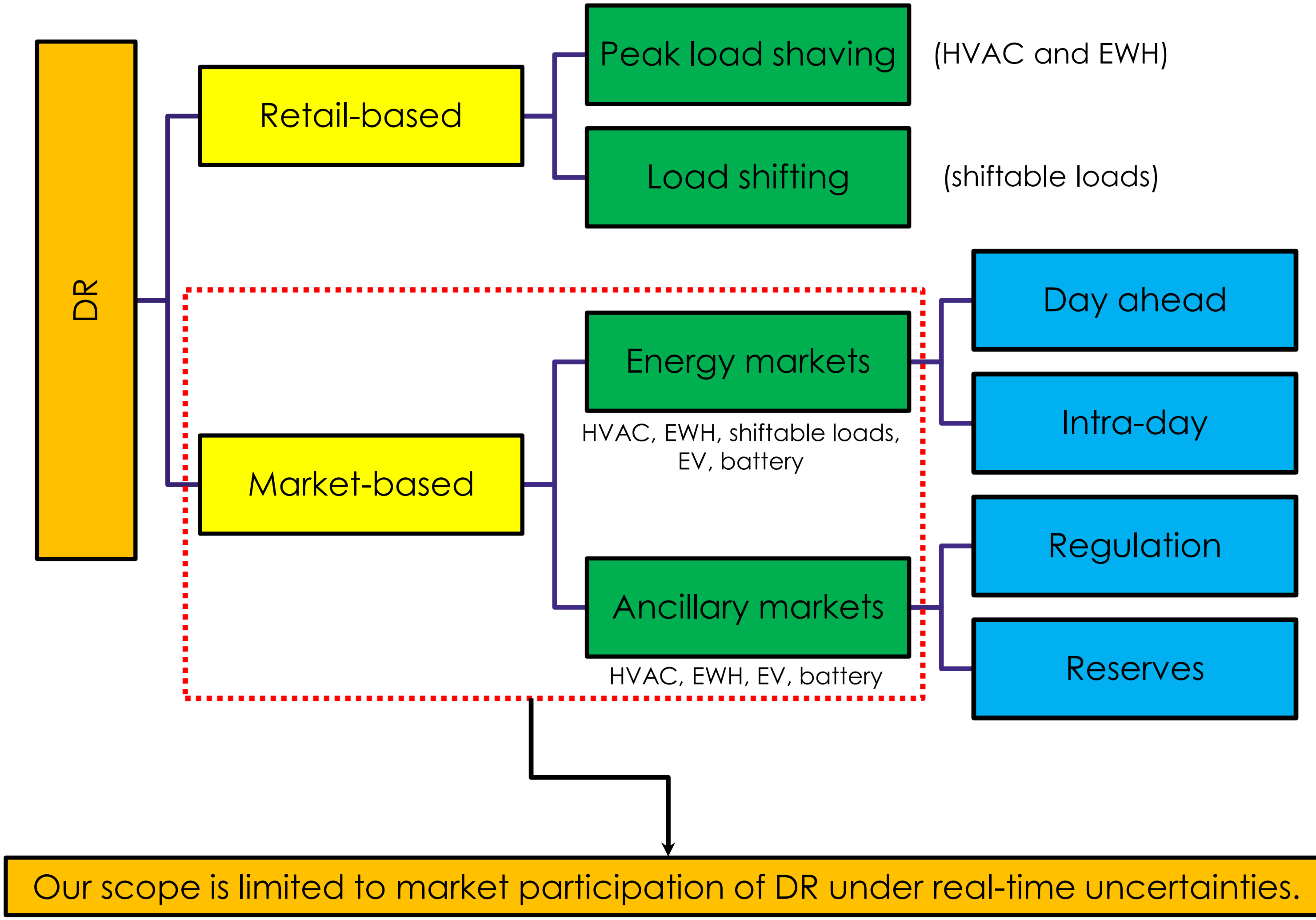
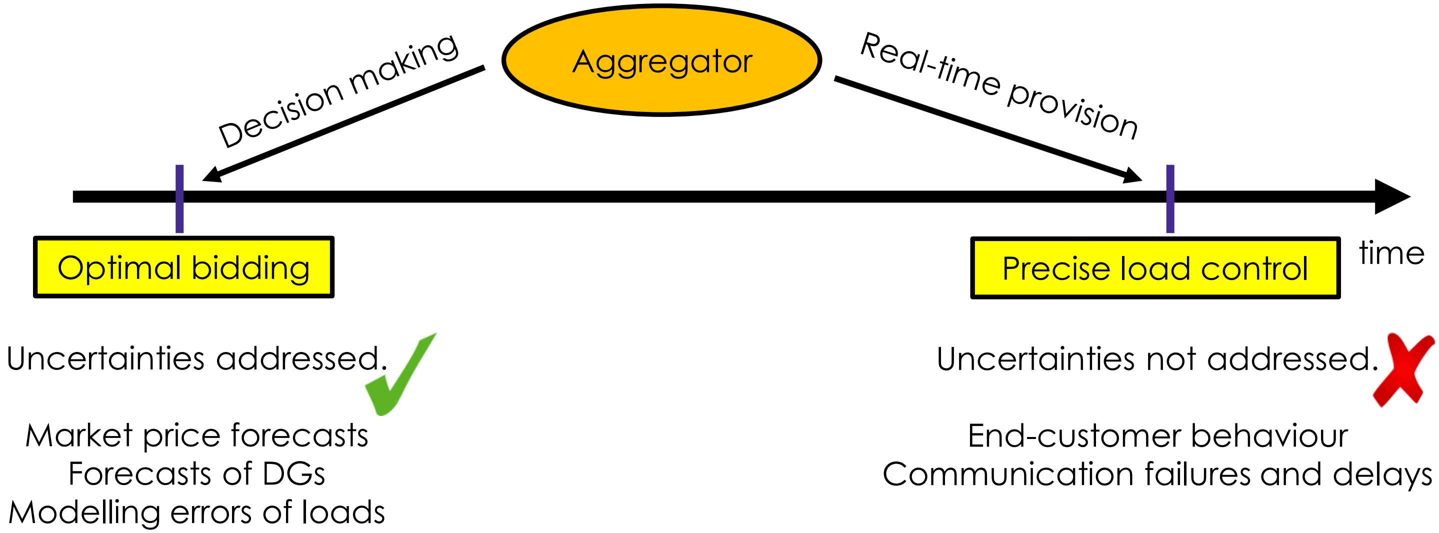
Literature Review



Gaps in Literature



Uncertainties are taken into account to determine the optimal bidding strategy, but not in developing control algorithms in real-time provision of bids.

Uncertainty modelling at bidding stage does not capture the dynamics in real-time operation.

Inadequacy of existing algorithms in resembling real-implementation under existing standards and policy related to DR.

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Proposed Methodology

- Stage1 — Heuristic control scheme
- Stage 2 — Systematic modelling of uncertainties
- Stage 3 — Predictive control scheme
- Stage 4 — Analysis in existing markets

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Stage 1: Heuristic control scheme

Developing control algorithms for thermostatically controllable loads to deliver a certain set-point reduction under uncertainties

Step 1: Development of the supply curve

↓

Step 2 : Formulation of the optimisation algorithm

↓

Step 3 : Modifications to the algorithm to account for customer override action

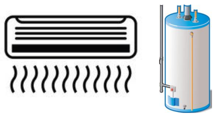
↓

Step 4 : Modifications to the algorithm to account for temperature changes

↓

Step 5 : Modifications to the algorithm to account for set-point load changes

Steps 1–2: Appliance selection



Steps 3–5: Algorithms under uncertainties

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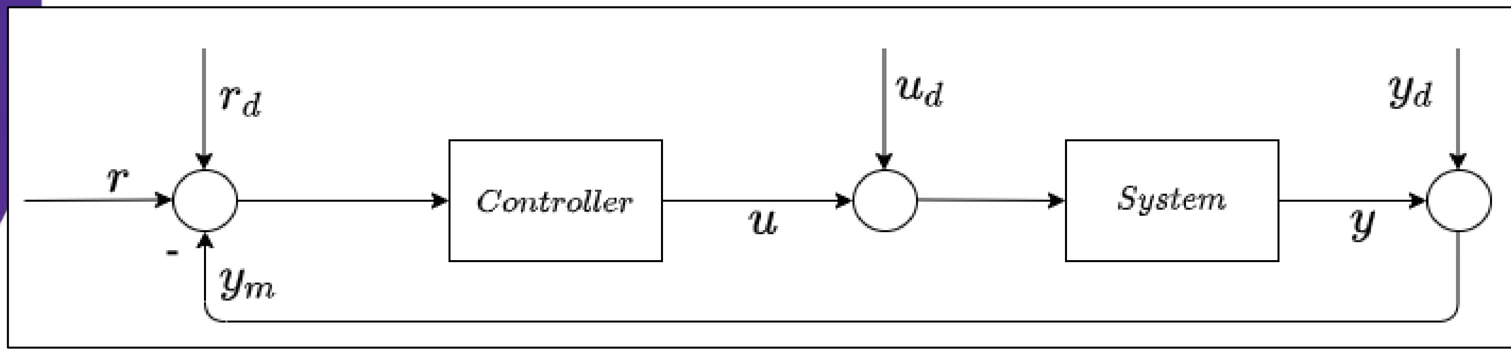
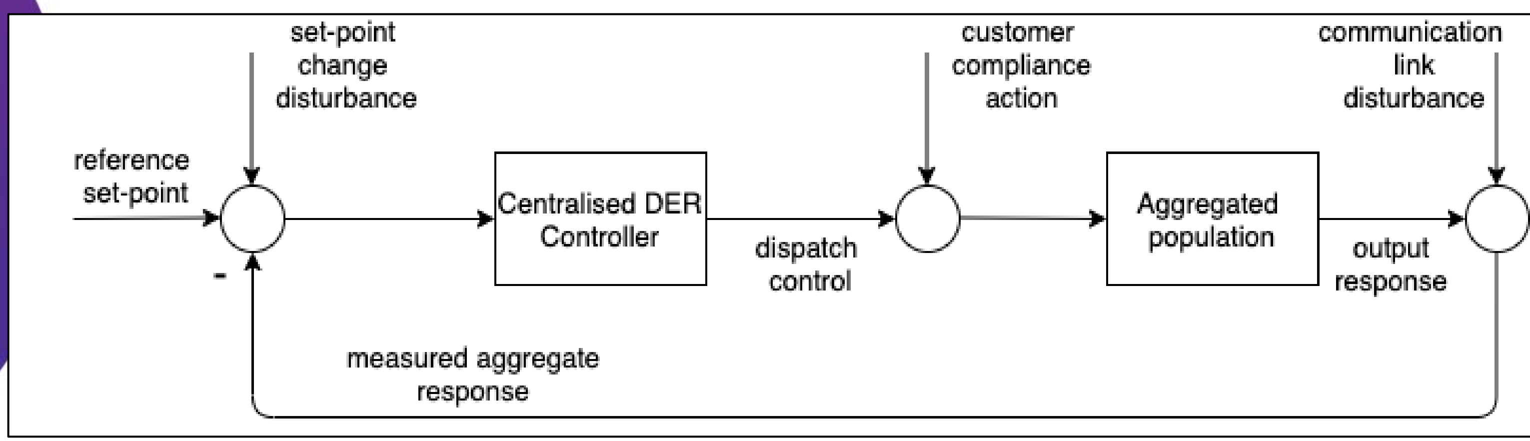
Stage 2: Uncertainty modelling

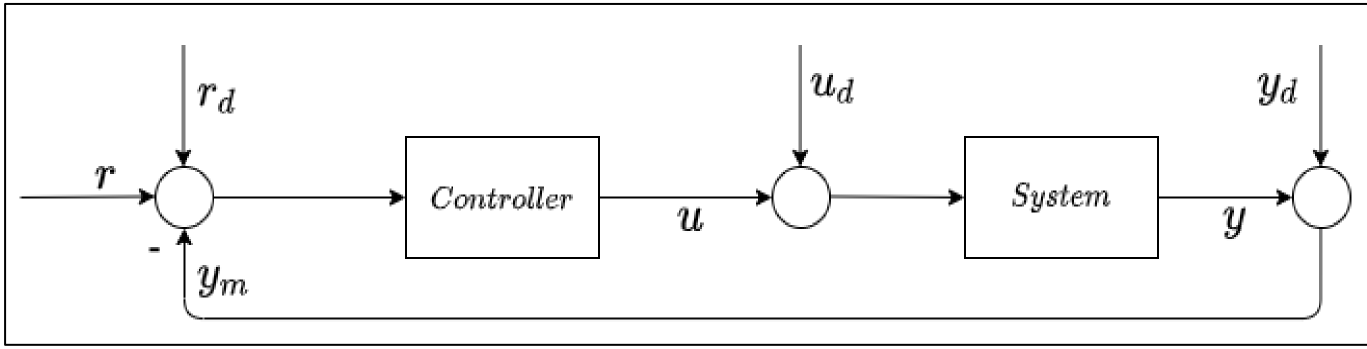
- Heuristic control scheme
- Systematic modelling of uncertainties
- Predictive control scheme
- Analysis in existing markets



Transformation to a real scenario



Stage 2: Uncertainty modelling



Mathematical modelling of uncertainties

$$\text{If } \mathbf{u} = \{u_1, u_2 \dots u_N\}^T \text{ where } u_i = \{0,1\} \quad \forall i \in \{1,2\dots N\}$$

$$u_i = \begin{cases} 1 & \text{if dispatch instructions sent} \\ 0 & \text{if not sent} \end{cases}$$

$$\text{If } \mathbf{y} = \{y_1, y_2 \dots y_N\}^T \text{ where } y_i = \{0,1\} \quad \forall i \in \{1,2\dots N\}$$

Customer overriding

$$u_{d,i} = \begin{cases} 0 & \text{if } y_i = u_i \\ 1 & \text{if } y_i \neq u_i \end{cases}$$

Communication failure

$$y_{d,i} = \begin{cases} 0 & \text{if } y_{m,i} = u_i \\ 1 & \text{if } y_{m,i} \neq u_i \end{cases}$$

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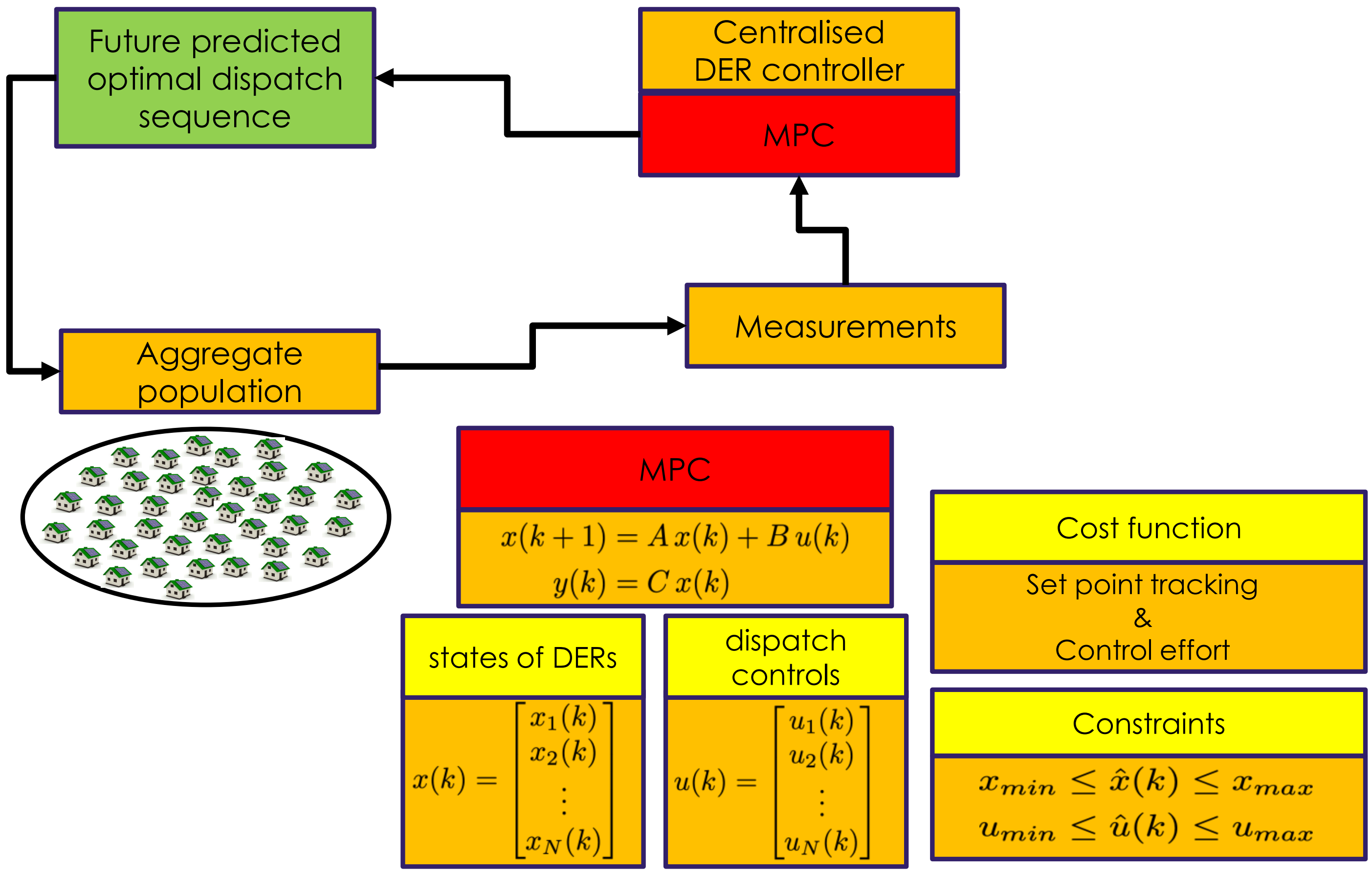
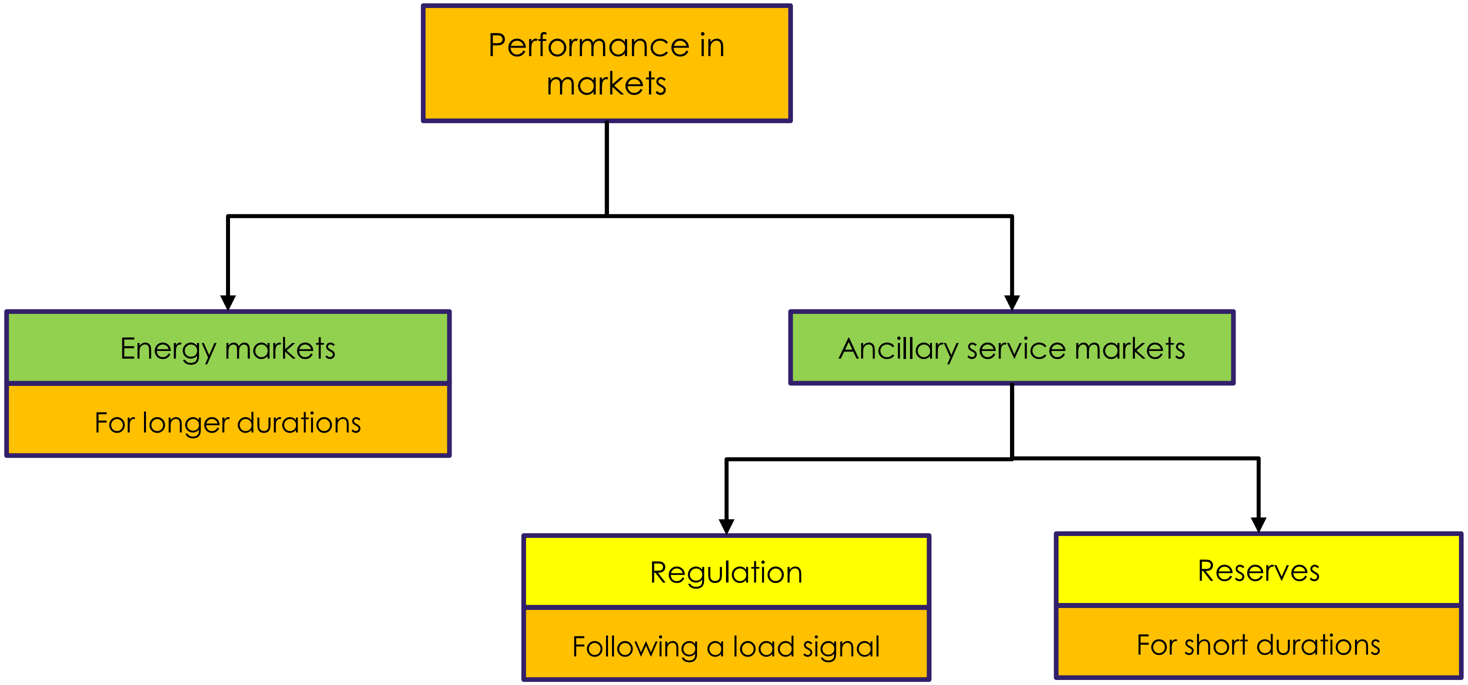
Stage 3: Predictive control scheme for aggregators

Model Predictive Control (MPC):

Solving a finite horizon optimal dispatch problem (subject to constraints of DERs) based on the current state of the aggregated population.



Stage 4: Analysis in existing markets



Performance criteria		
Robustness to uncertainties	Comparison with existing schemes	Practical commercial implementation

https://pjm.com/markets-and-operations.aspx

Data & Software tools

Data

Appliance specific consumption, generation data

Sensor measurements

Weather data : UQ weather stations

Market related data : from AEMO website, PJM and NordPool

Software

Data pre-processing

Control algorithm development

MATLAB
SIMULINK®

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Progress up to date

Work under stage 1 is almost completed.

Aim

Control of thermostatically controllable loads to deliver a certain set-point power reduction in the presence of uncertainties.

Thermostatically controllable loads (TCLs)

- Air conditioners
- Water heaters

Air conditioners:

$$T^{room}_{i,t+1} = T^{room}_{i,t} + t_s \cdot \frac{G_{i,t}}{\Delta c_i} - t_s \cdot \frac{Q^{AC}_{i,t}}{\Delta c_i}$$

Water heaters:

$$T^{outlet}_{i,t+1} = T^{outlet}_{i,t} \cdot \frac{(V_i^{tank} - f_i^r \cdot t_s)}{V_i^{tank}} + \frac{T_i^{inlet} \cdot f_i^r \cdot t_s}{V_i^{tank}} + \frac{1}{8.34} \cdot \left(P^{EWH}_{i,t} \times 3412 - \frac{A_i^{tank} \cdot (T^{outlet}_{i,t} - T_i^{amb})}{R_i^{tank}} \right) \cdot \frac{t_s}{60} \cdot \frac{1}{V_i^{tank}}$$

Realistic consumption data for air conditioners and water heaters used in modelling.

100 appliances for the study

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Methodology

Proposed Methodology

Appliance selection

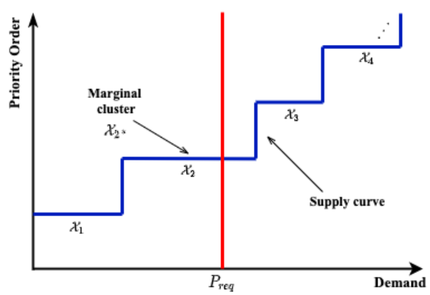
Supply curve formulation

Emulating a supply curve in electricity markets

→

Optimisation algorithm

In Marginal cluster



based on $\mathcal{X}_1$ and $\mathcal{X}_2$

Determining Marginal cluster

$$F = w_{cost} \cdot \sum_i C_{p,t} \cdot (P_{i,t} - \Delta P_{i,t}) \cdot t_s + w_{dis} \cdot \sum_i DI_{i,t}^2 \quad \forall i \in \mathcal{X}_{j^*}$$

$$\min \quad F(\Delta P_{i,t})$$

$$\sum_i \Delta P_{i,t} \le \overline{P}_{req,t}$$

$$P^{AC}_{min,i} \le P^{AC}_{i,t} \le P^{AC}_{max,i}$$

$$P^{EWH}_{min,i} \le P^{EWH}_{i,t} \le P^{EWH}_{max,i}$$

$$\underline{T}^{room}_i \le T^{room}_{i,t} \le \overline{T}^{room}_i$$

$$\underline{T}^{outlet}_i \le T^{outlet}_{i,t} \le \overline{T}^{outlet}_i$$

$$P_{i,t} = K_i \cdot P_{i,rated}$$

$$K_i \in \{0.25, 0.50, 0.75, 1.0\}$$

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

$$DI_{i,t} = \frac{2\,T_{i,t} - \underline{T}_i - \overline{T}_i}{\underline{T}_i - \overline{T}_i}$$

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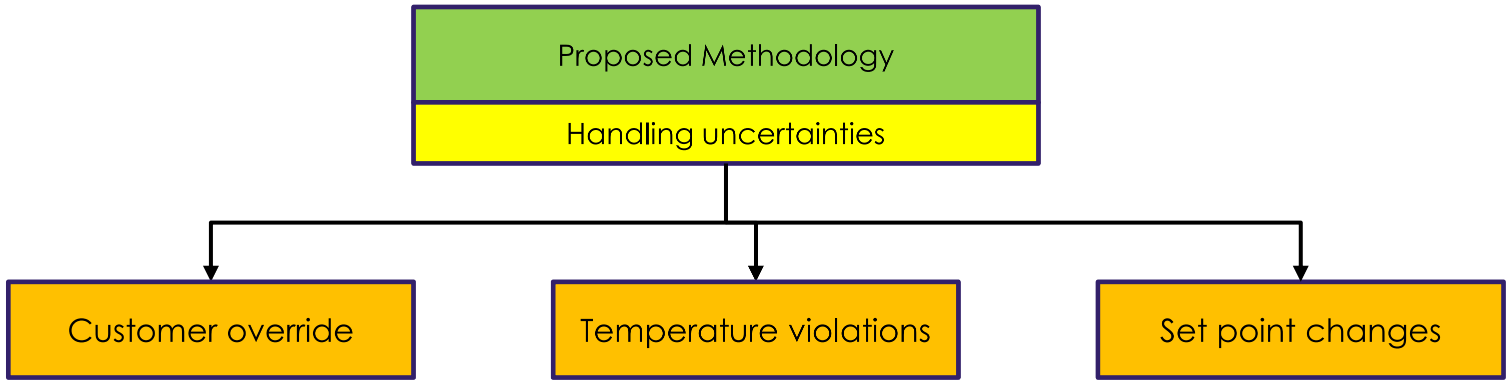
Methodology



Algorithm 1: Algorithm for customer non-compliance events

Data: P_{req}, T_{dur}, $P^{AC}_{i,t}$, $P^{EWH}_{i,t}$, $j\,\forall i$, input parameters;
Determine t_s based on T_{dur} and DR event;
Initialise $t = 0$;
Supply curve formation and determining $\mathcal{X}_{j^\star}$;
Performing optimisation to dispatch optimal appliances in $\mathcal{X}_{j^\star}$;
Update power consumption at time t;
Determine $P_{act,t}$ as in (21);
for $t = t + t_s;\ t \leq T_{dur}$ **do**
    if $P_{act,t} < P_{req,t}$ **then**
        Update $P_{req,t+t_s}$ as in (22) ;
        Determine $\mathcal{O}_t$ with (1);
        Set $P^{flex}_{i,t} = 0 \quad \forall i \in \mathcal{O}_{t-ts}$;
        Avoid sending control signals $\forall i \in \mathcal{O}_t$ for $[t, T_{dur}]$;
        Supply curve formulation and determine $\mathcal{X}_{j^\star}$ with $i \in \mathcal{A} \backslash \mathcal{O}_t$;
        Perform optimisation on $\mathcal{X}_{j^\star}$;
        Dispatch control on chosen appliances and determine $P_{act,t+t_s}$ from (21) ;
    if $P_{act,t} < P_{req,t}$ **then**
        Update $P_{req,t+t_s} = 0$;
        Skip $\mathcal{X}_{j^\star}$ selection and optimisation ;
        Allow $\forall i \in \mathcal{A}$ to operate at the power consumption at t;
        Determine $P_{act,t+t_s}$ from (21) ;
    end
end

Algorithm 2: Algorithm for temperature violations

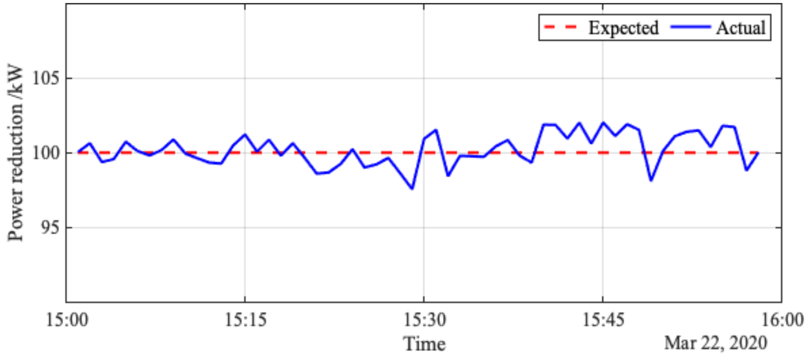
Data: t, $P^{AC}_{i,t}$, $P^{EWH}_{i,t}$, $T^{room}_{i,t}$, $T^{outlet}_{i,t}$, $\bar{T}^{room}_{i}$, T^{outlet} $\forall i$, input parameters;
Calculate $T^{room}_{i,t+t_s}$ with (4) ;
Calculate $T^{outlet}_{i,t+t_s}$ with (7) ;
for $i \in \Omega_{AC}$ **do**
    if $T^{room}_{i,t+t_s} > \bar{T}^{room}_{i}$ **then**
        Update $P^{AC}_{i,t} = P^{AC}_{i,rated}$;
    else
        Keep $P^{AC}_{i,t}$;
    end
end
for $i \in \Omega_{EWH}$ **do**
    if $T^{outlet}_{i,t+t_s} > \bar{T}^{outlet}_{i}$ **then**
        Update $P^{EWH}_{i,t} = P^{EWH}_{i,rated}$;
    else
        Keep $P^{EWH}_{i,t}$;
    end
end
Calculate $P_{act,t+t_s}$ as in (21);

Algorithm 3: Algorithm for a change in set point

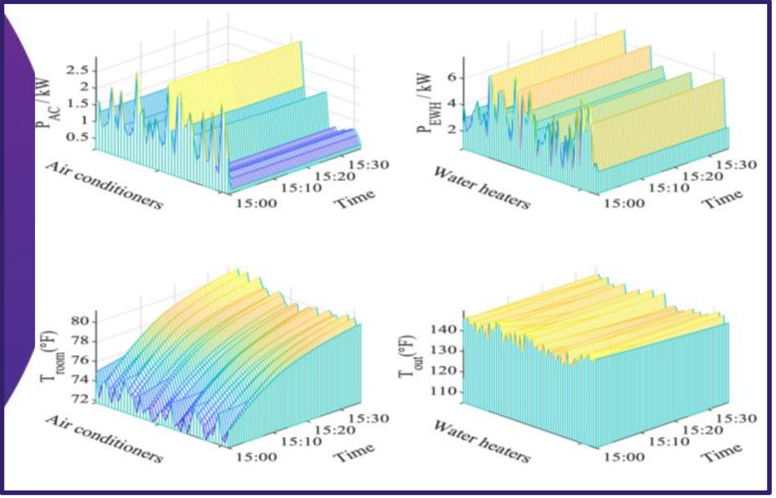
Data: $P_{req,t=0}$, T_{dur}, $P^{AC}_{i,t}$, $P^{EWH}_{i,t}$, $j\,\forall i$, input parameters;
Determine ts based on T_{dur} and DR event;
Initialise $t = 0$;
Supply curve formation and determining $\mathcal{X}_{j^\star}$;
Perform optimisation to dispatch appliances in $\mathcal{X}_{j^\star}$;
for $t = t + t_s;\ t \leq T_{dur}$ **do**
    Update $P_{req,t}$;
    if $P_{req,t} > P_{req,t-t_s}$ **then**
        Update $P^{new}_{req,t}$ as in (23) ;
        Formulate the supply curve and determine $\mathcal{X}_{j^\star}$;
        Perform optimisation on $\mathcal{X}_{j^\star}$ as in (9);
        Send control signals to chosen appliances ;
    if $P_{req,t} = P_{req,t-t_s}$ **then**
        Update $P^{*}_{req,t} = 0$;
        Skip marginal priority order selection and optimisation ;
        Allow $\forall i \in \mathcal{A}$ to operate at the power consumption at $t - t_s$;
    end
end

Results

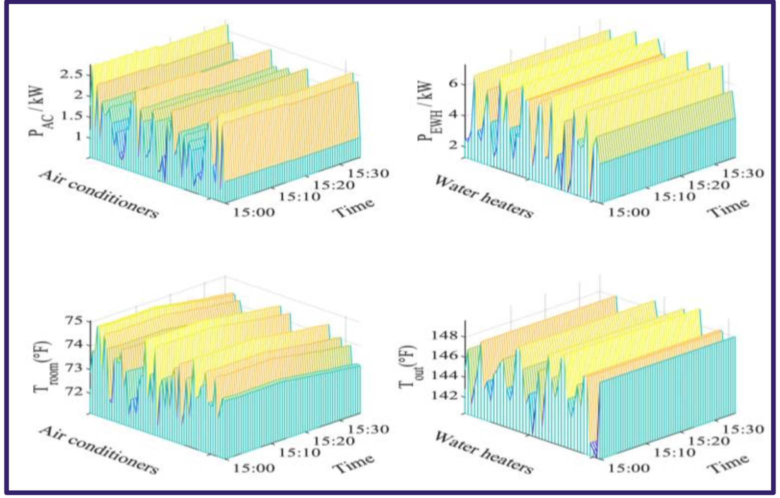
Objective : To obtain 100 kW load reduction from the TCLs in cluster 1 and cluster 2 in the absence of uncertainties in the system



Cluster 1

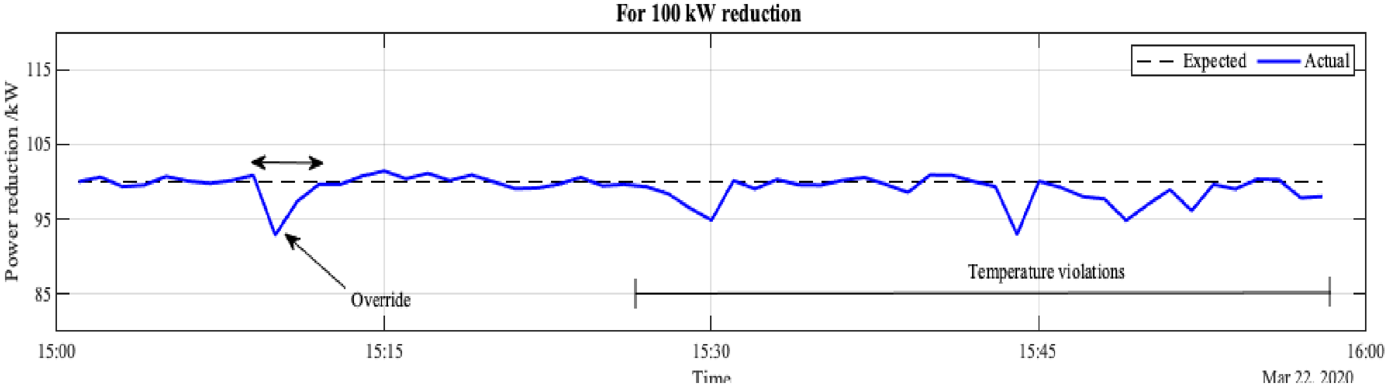


Cluster 2

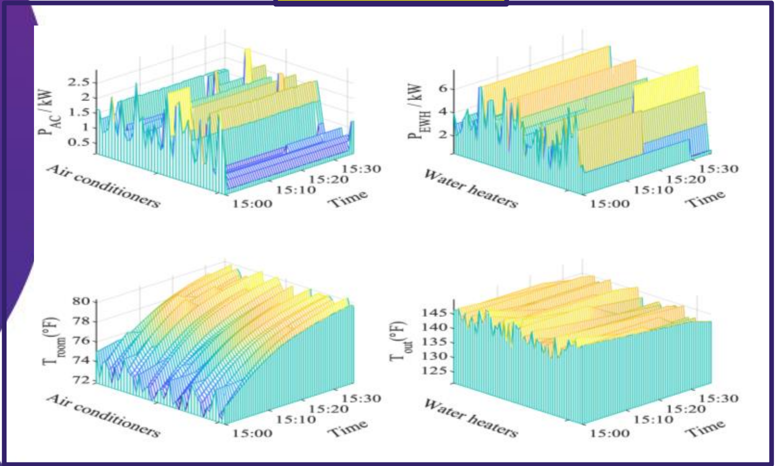


Results

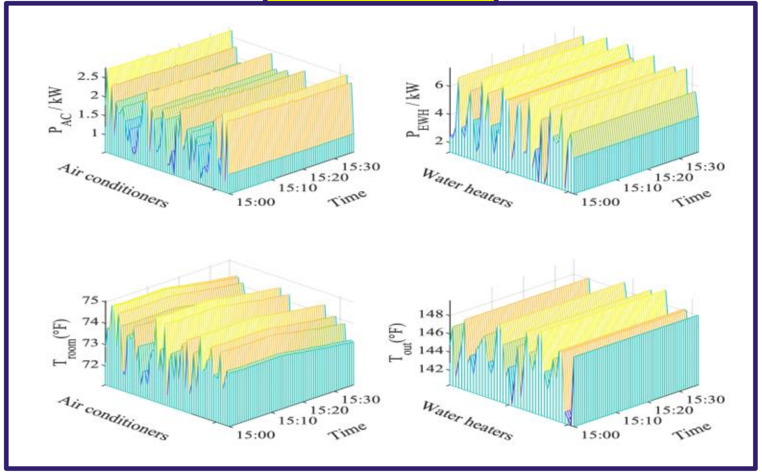
Objective : To obtain 100 kW load reduction from the TCLs in cluster 1 and cluster 2 in the presence of uncertainties due to customer override action and temperature violations



Cluster 1

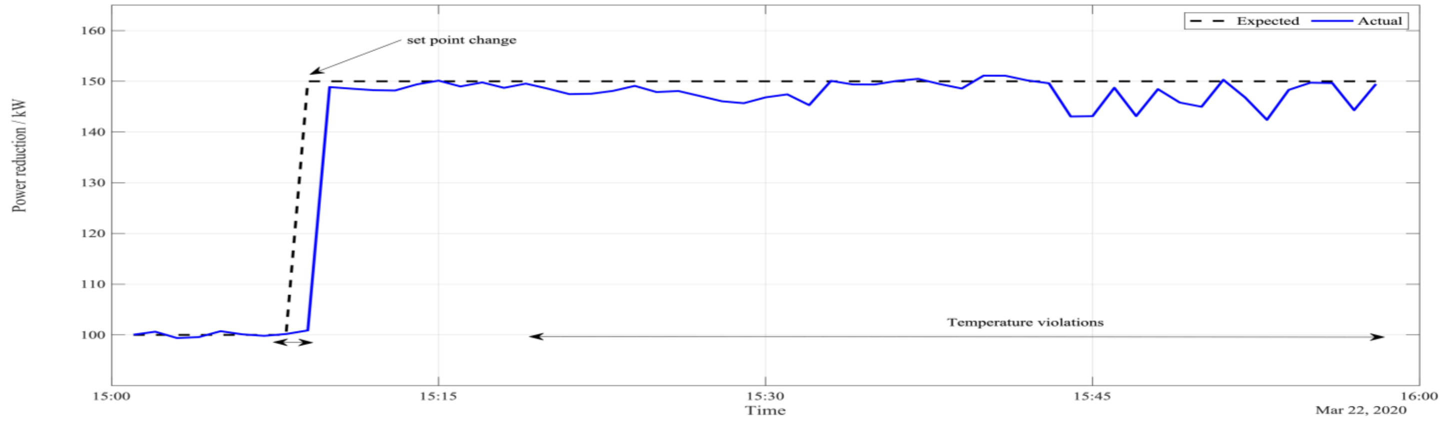


Cluster 2

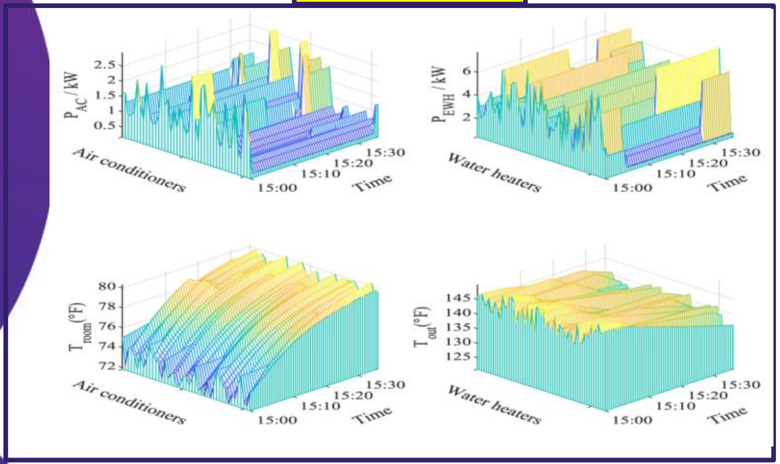


Results

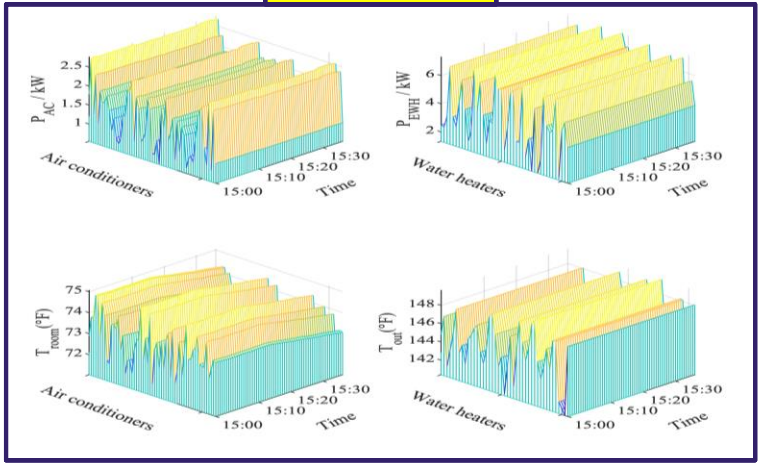
Objective : To follow the load reduction signal when the set–point changes from 100 kW to 150 kW at a certain time step, while taking into account the uncertainties arising from temperature violations.



Cluster 1

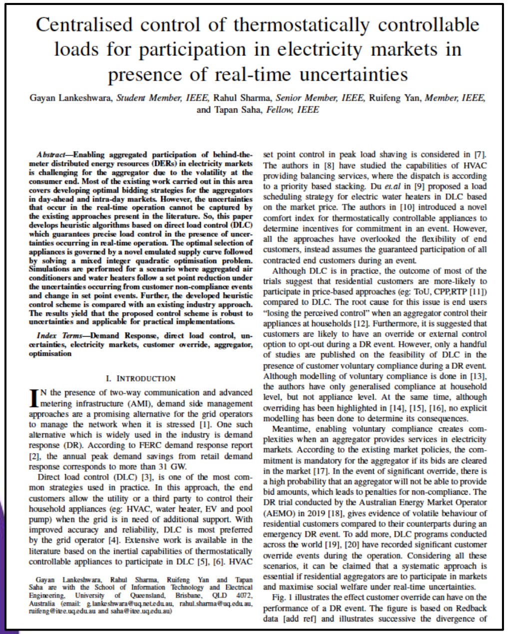


Cluster 2



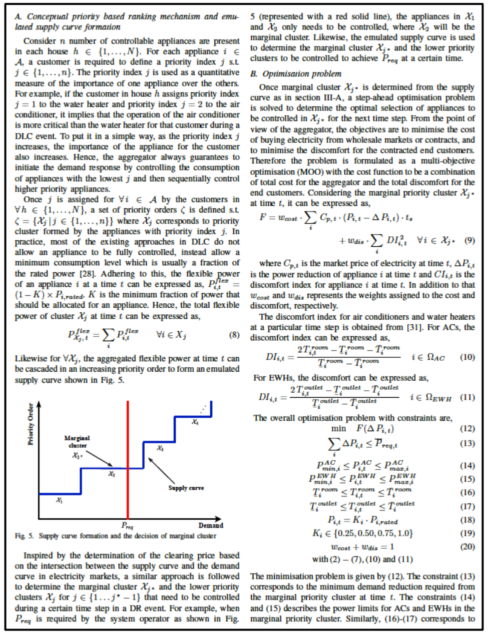
Results

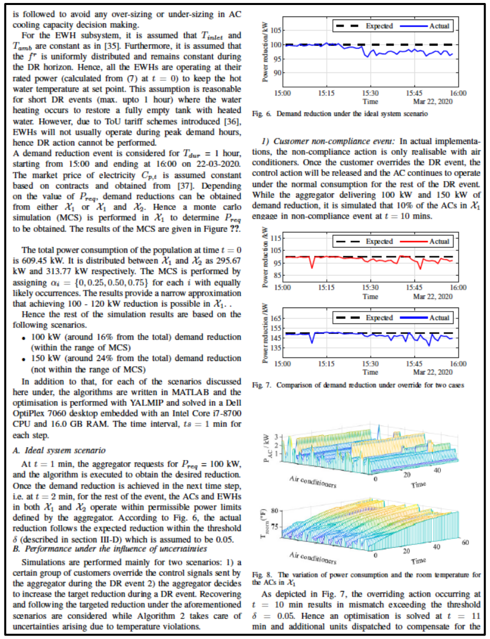
This work is nearly ready for submission in *IEEE Transactions on Sustainable Energy*.



Centralised control of thermostatically controllable loads for participation in electricity markets in presence of real-time uncertainties

Gayan Lankeshwara, *Student Member, IEEE*, Rahul Sharma, *Senior Member, IEEE*, Ruifeng Yan, *Member, IEEE*, and Tapan Saha, *Fellow, IEEE*





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Timeline

	Activity/Milestone	2019		2020				2021				2022		
		RQ3	RQ4	RQ1	RQ2	RQ3	RQ4	RQ1	RQ2	RQ3	RQ4	RQ1	RQ2	RQ3
1	Literature Review	■	■	■	■	■	■	■	■	■	■	■	■	
2	Modelling of Thermostatically controllable loads for direct load control		■	■										
3	Developing the heuristic control algorithm			■	■									
4	Journal publication			■	■									
5	Confirmation					■								
6	Systematic modelling of uncertainties					■								
7	Conference publication						■							
8	Modelling of shiftable appliances							■						
9	Developing the predictive control algorithm							■	■					
10	Journal publication								■	■				
11	Mid-candidature									■				
12	Modelling distributed energy resources									■	■			
13	Conference publication											■		
14	Extending the predictive control algorithm to DERs										■	■		
15	Journal publication										■	■	■	
16	Thesis writing										■	■	■	■
17	Thesis Review													■

Thank You !

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