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

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# Outline

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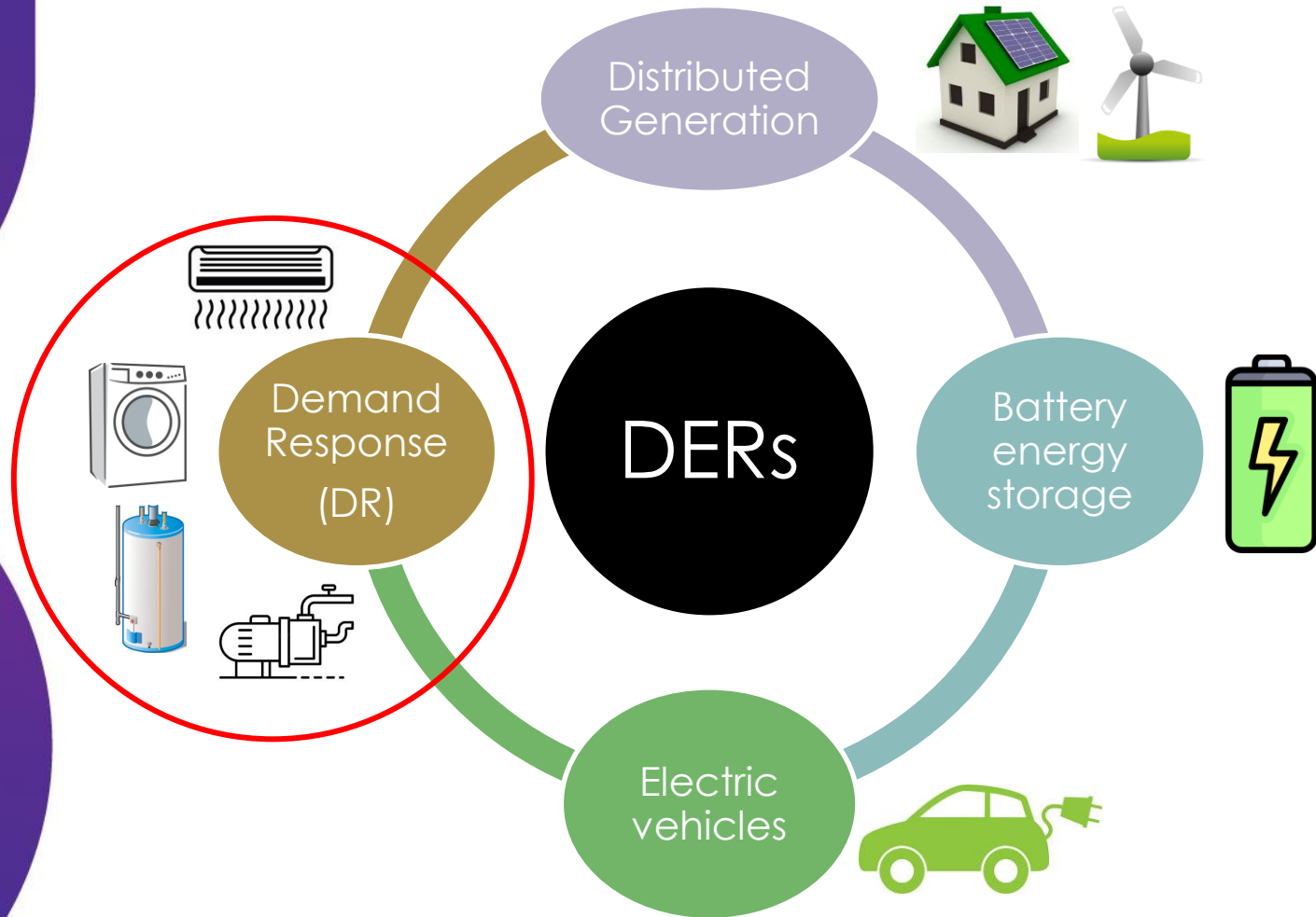
- Introduction
- Research Objectives
- Motivation
- Literature Review and Gaps
- Proposed Methodology
- Progress up to date
- Timeline

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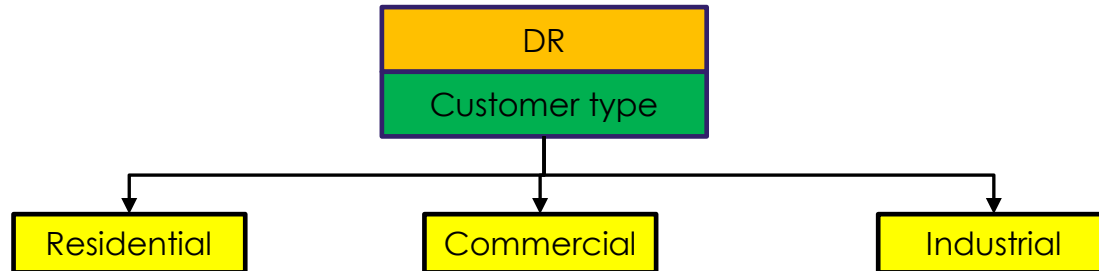
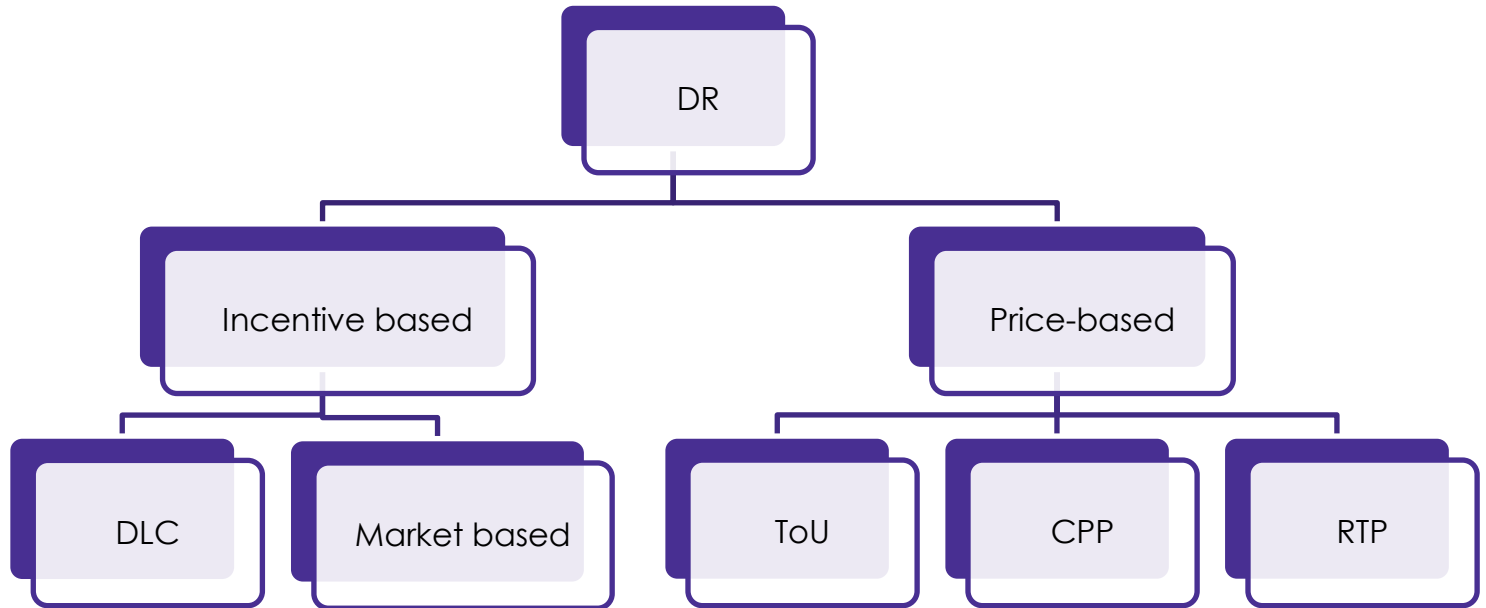
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# What are Distributed Energy Resources (DERs) ?



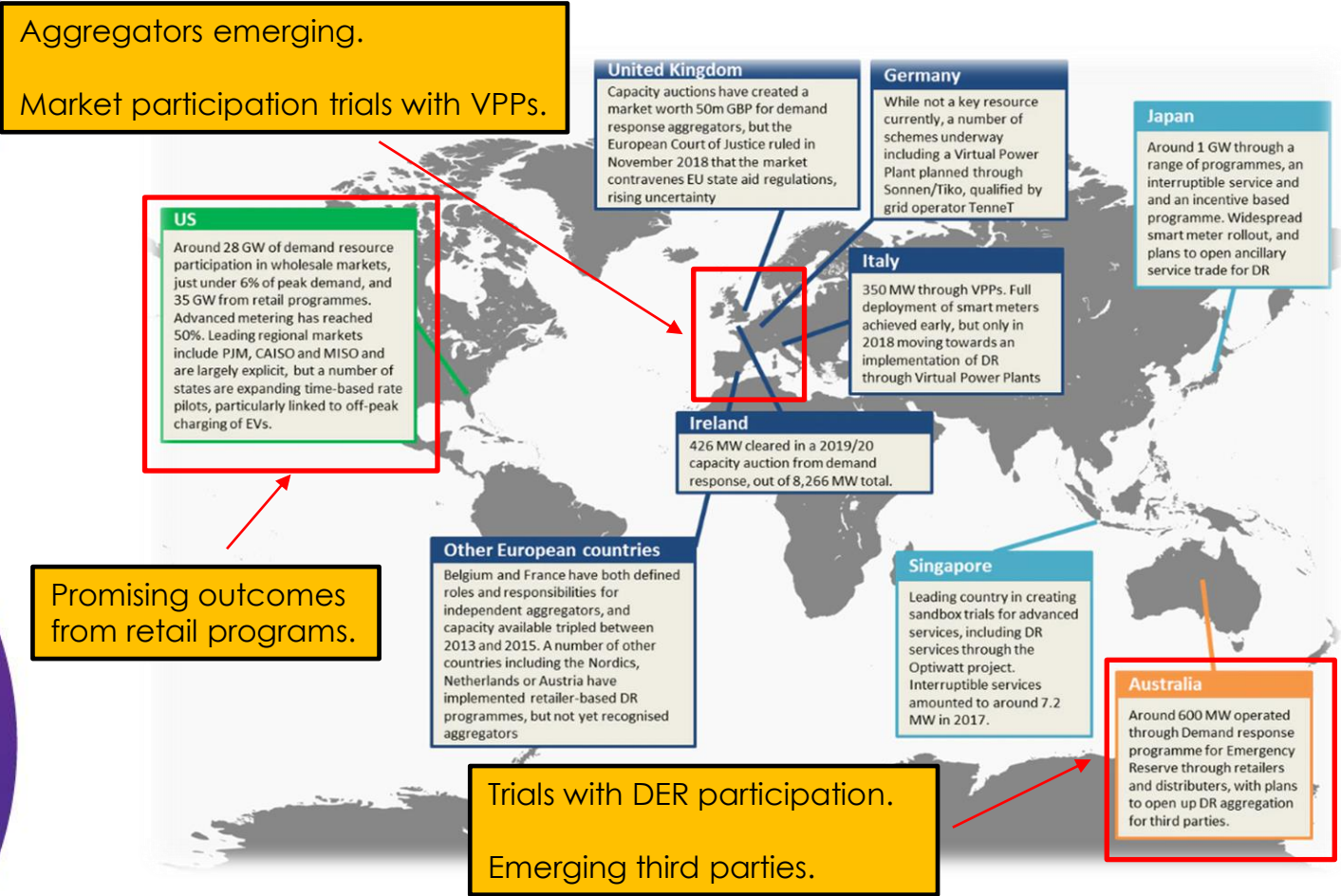
DERs are consumer owned devices that can generate, store or smartly manage energy demand.

# Classification of DR



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

# A glimpse of DR initiatives around the world

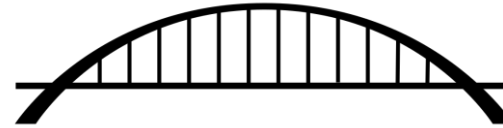


Trials have not been able to capture the residential DER aggregation.

# Existing vs. Future prospects

## Current applications of DR

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



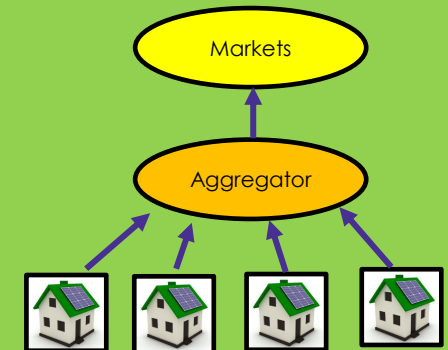
## Issues

- 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

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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

AEMO RERT Trial Report – 2019

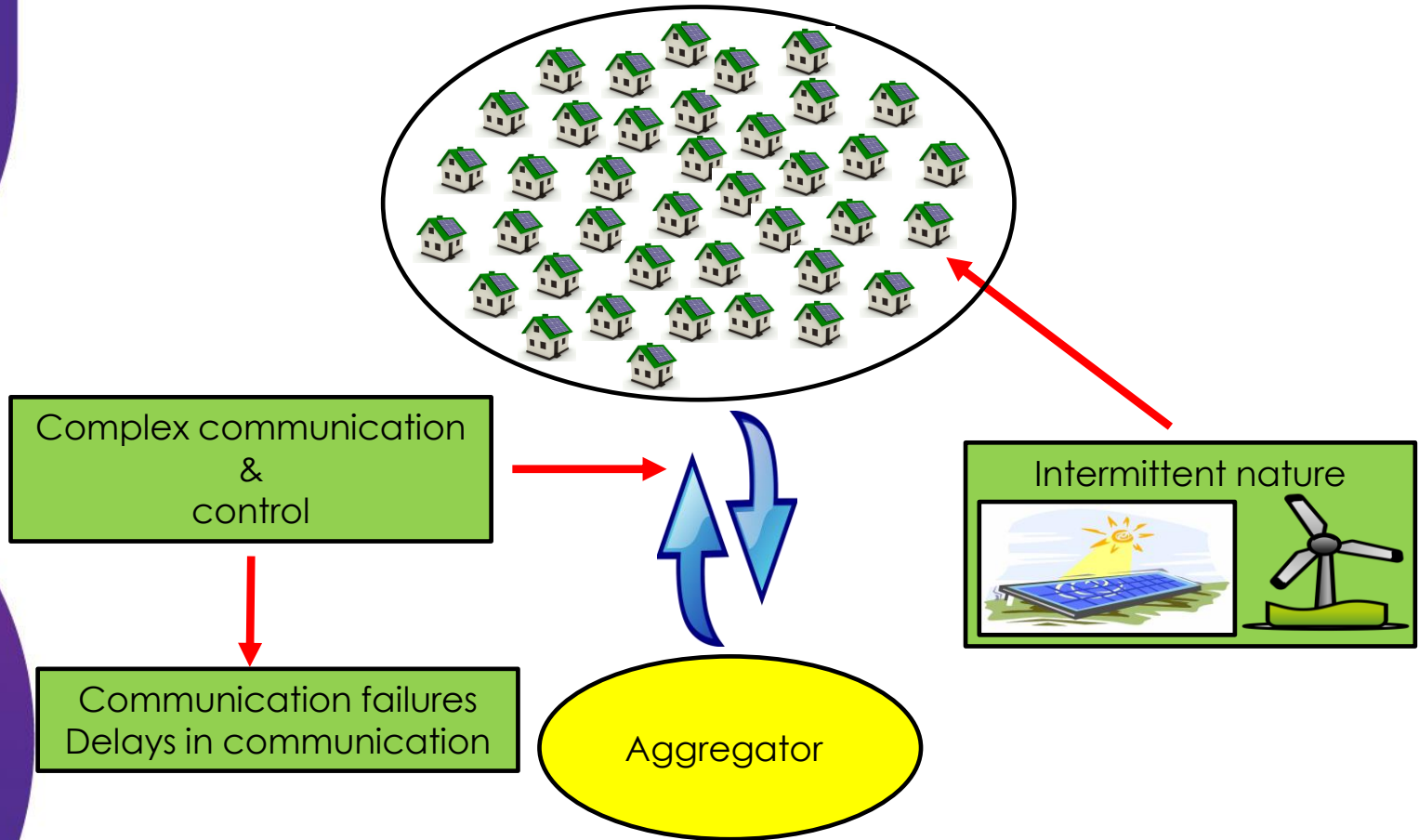


Significant mismatch in residential contribution.

Customer overriding poses challenges in the successful aggregation of DERs to participate in market events.

# Large scale aggregation of DERs

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



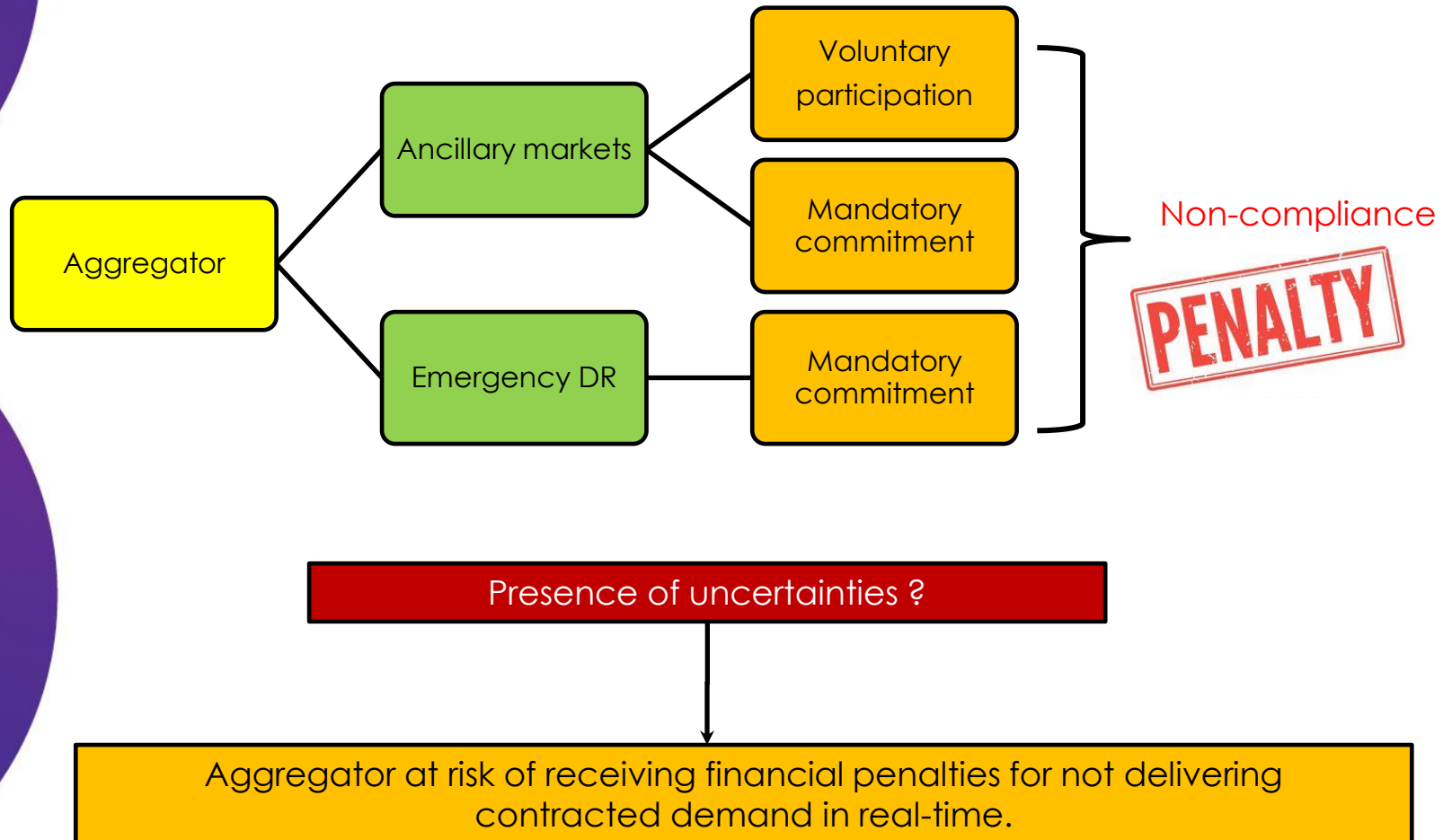
Complex communication and control poses challenges in large scale DER aggregation.

# Why uncertainties need to be addressed?

Uncertainties in DER aggregation

- Lack of control algorithms
- Compliance with existing standards

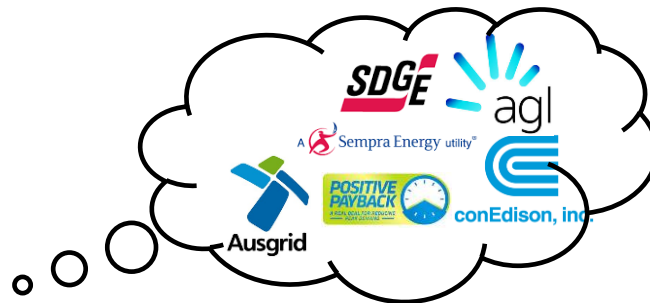
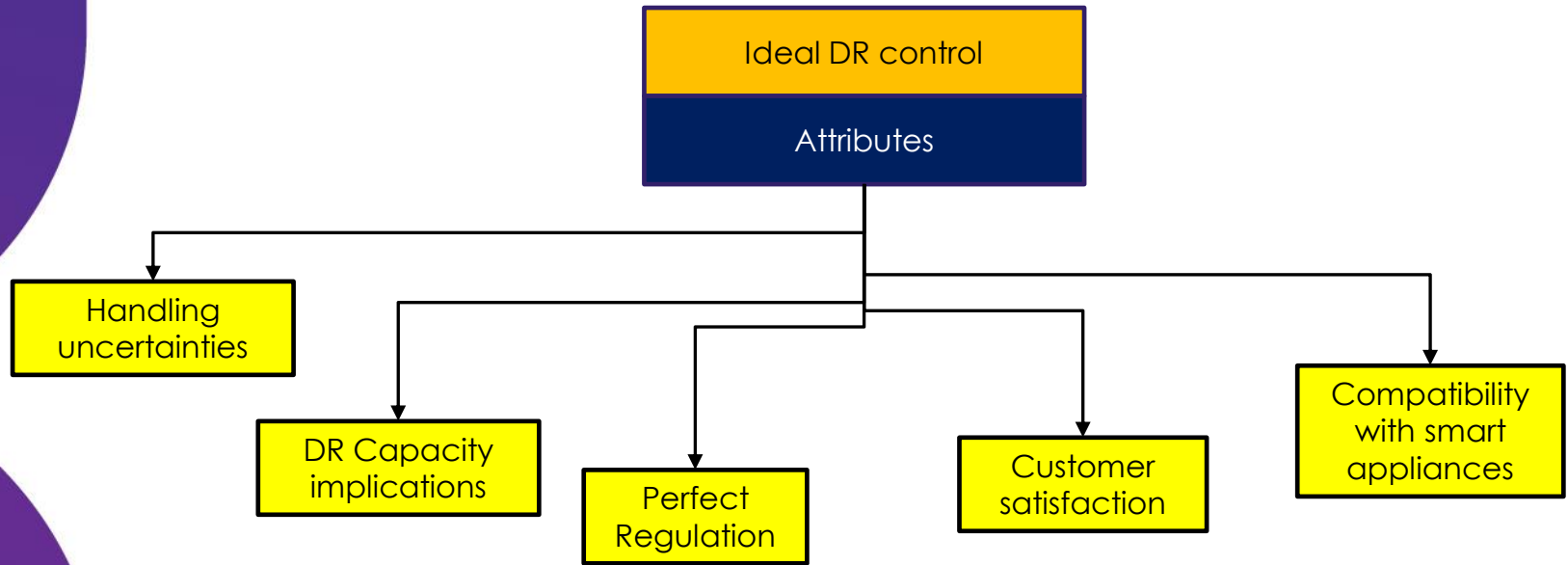
According to market policies [1],



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

# Drawbacks of existing load control programs

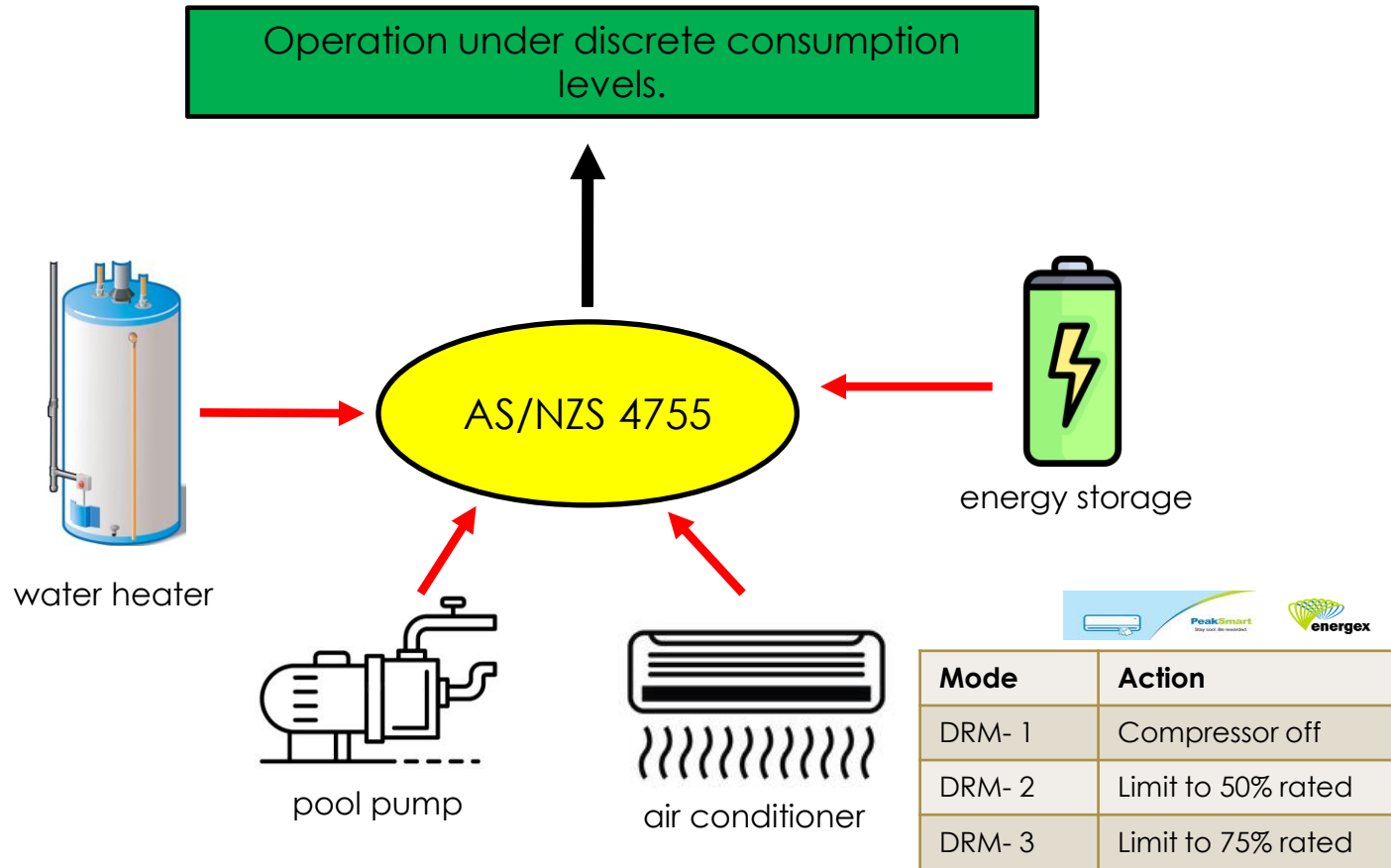
Uncertainties in DER aggregation  
Lack of control algorithms  
Compliance with existing standards



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

# Demand Response Standards

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



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

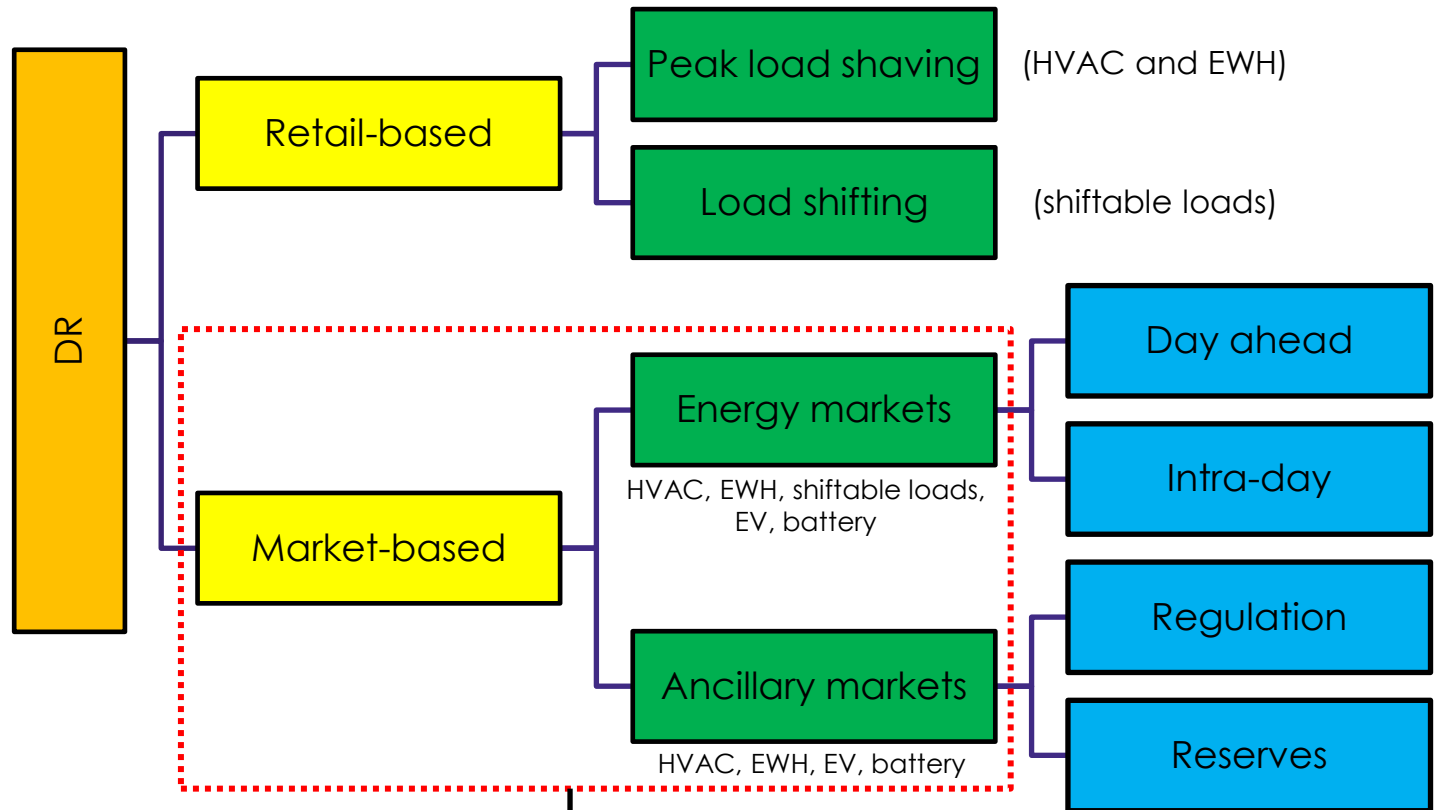
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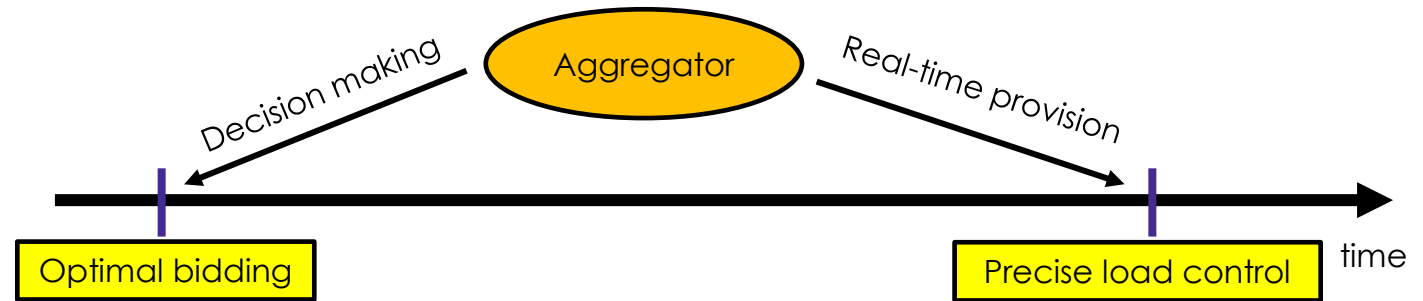


# Literature Review



Our scope is limited to market participation of DR under real-time uncertainties.

# Gaps in Literature



Uncertainties addressed. ✓

- Market price forecasts
- Forecasts of DGs
- Modelling errors of loads

Uncertainties not addressed. ✗

- End-customer behaviour
- Communication failures and delays

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.

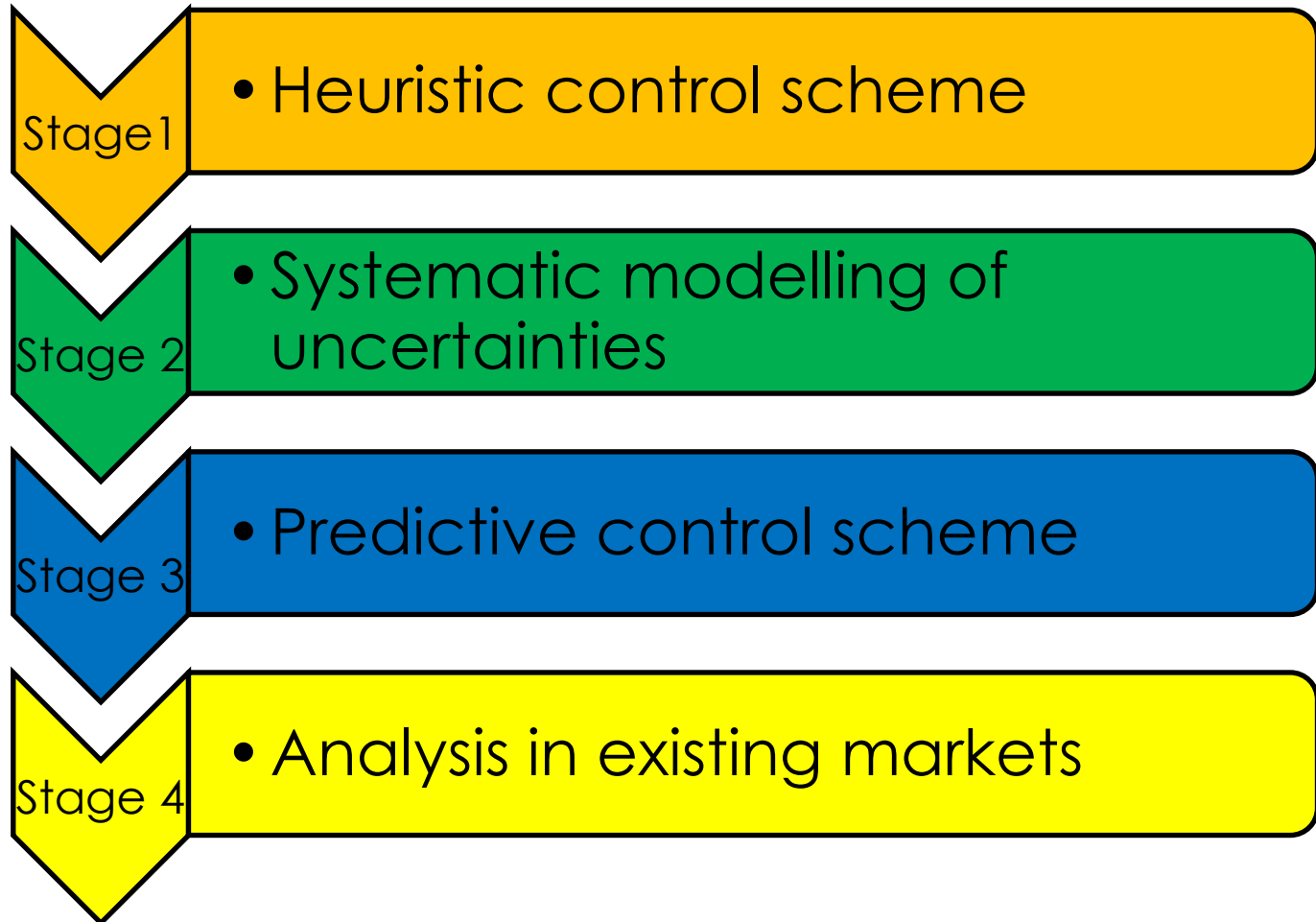
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# Proposed Methodology

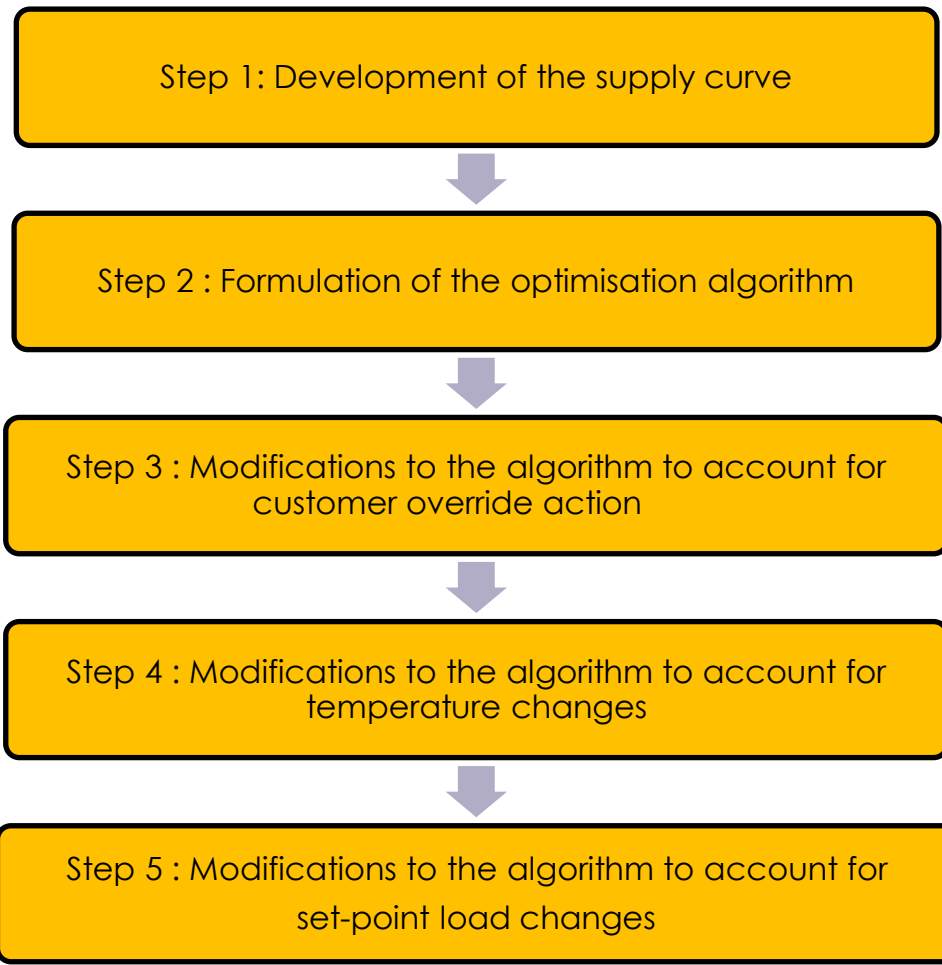
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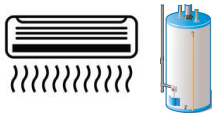
# Stage 1: Heuristic control scheme

- Stage 1: Heuristic control scheme
- Systematic modelling of uncertainties
- Predictive control scheme
- Analysis in existing markets

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



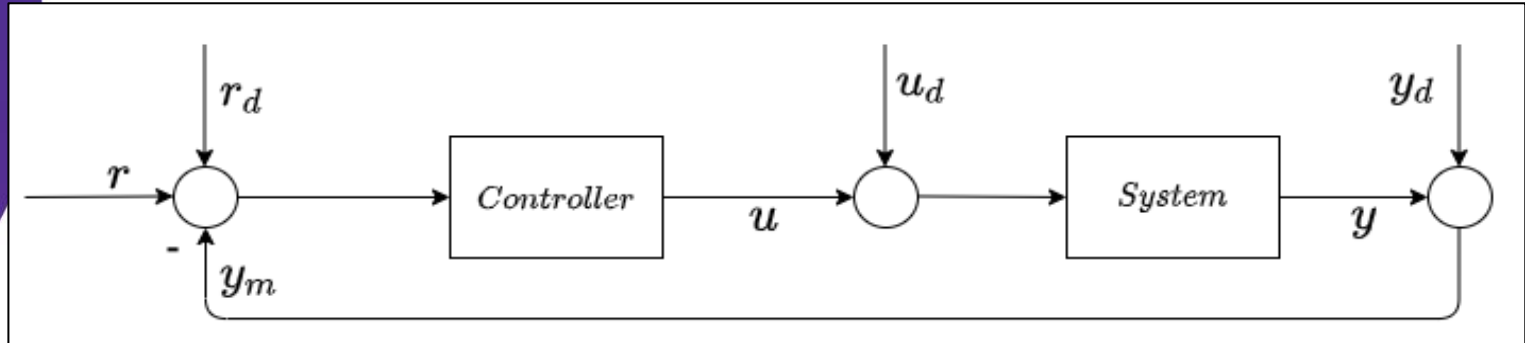
Appliance selection



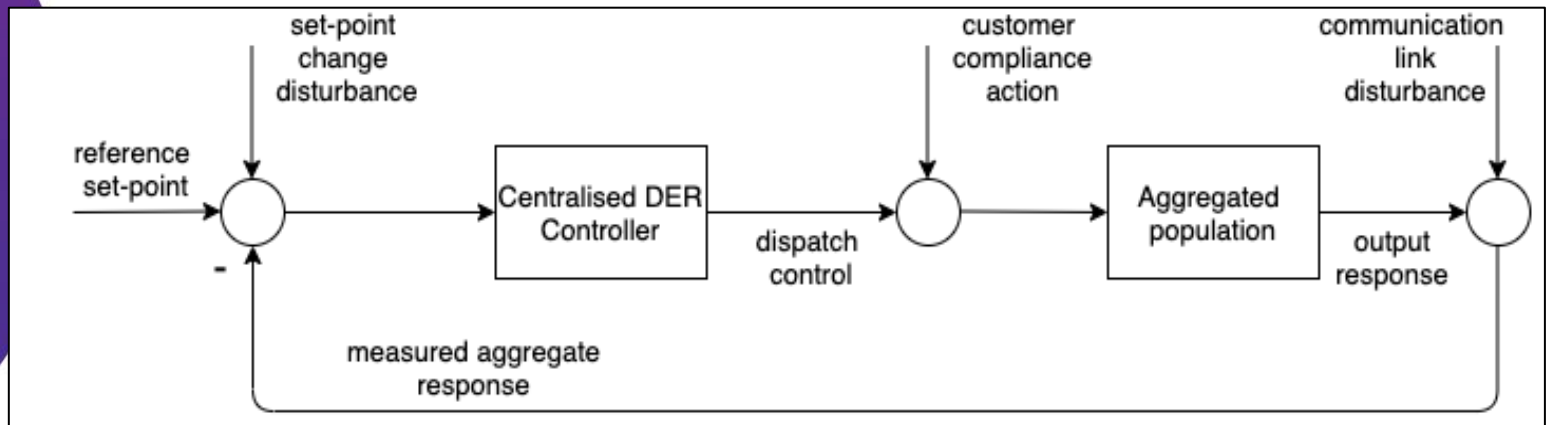
Algorithms under uncertainties

# Stage 2: Uncertainty modelling

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

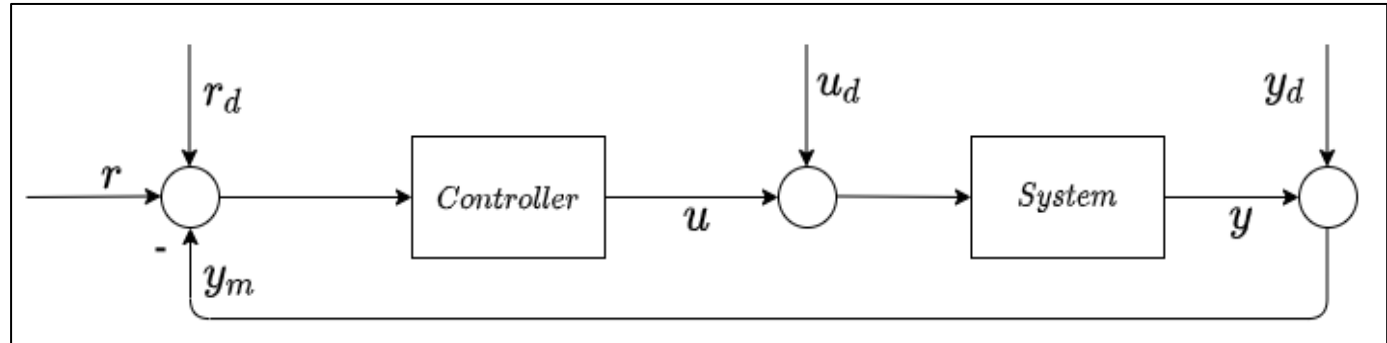


Transformation to a real scenario



# Stage 2: Uncertainty modelling

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



## Mathematical modelling of uncertainties

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

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

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

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

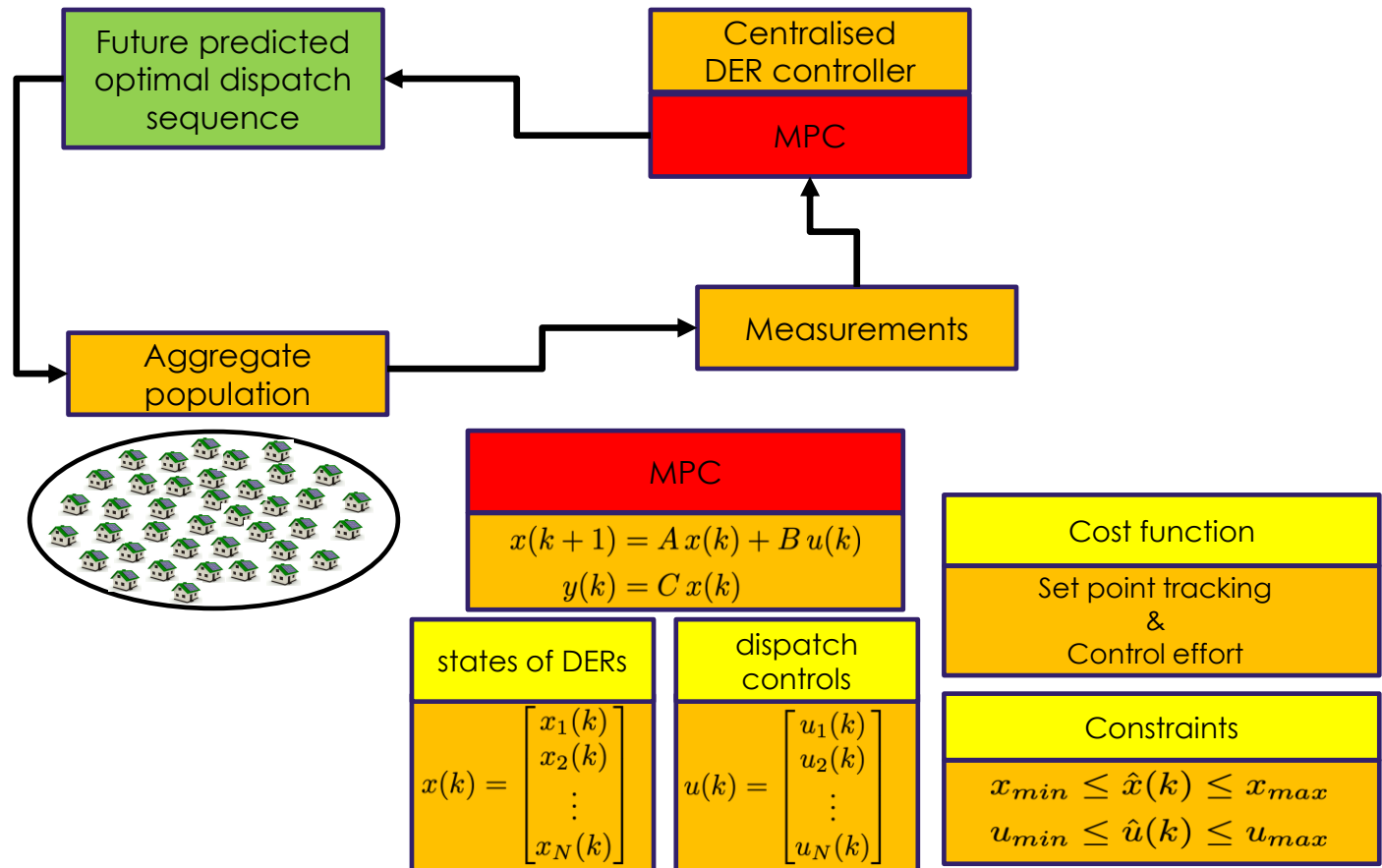
Communication failure	
$y_{d,i} =$	$\begin{cases} 0 & \text{if } y_{m,i} = u_i \\ 1 & \text{if } y_{m,i} \neq u_i \end{cases}$

# Stage 3: Predictive control scheme for aggregators

- Heuristic control scheme
- Systematic modelling of uncertainties
- Stage 3: Predictive control scheme**
- Analysis in existing markets

Model Predictive Control (MPC):

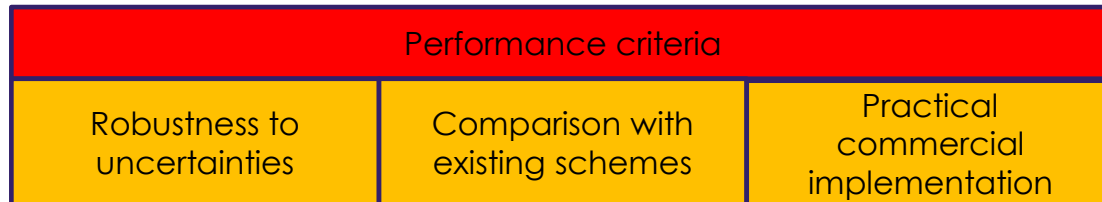
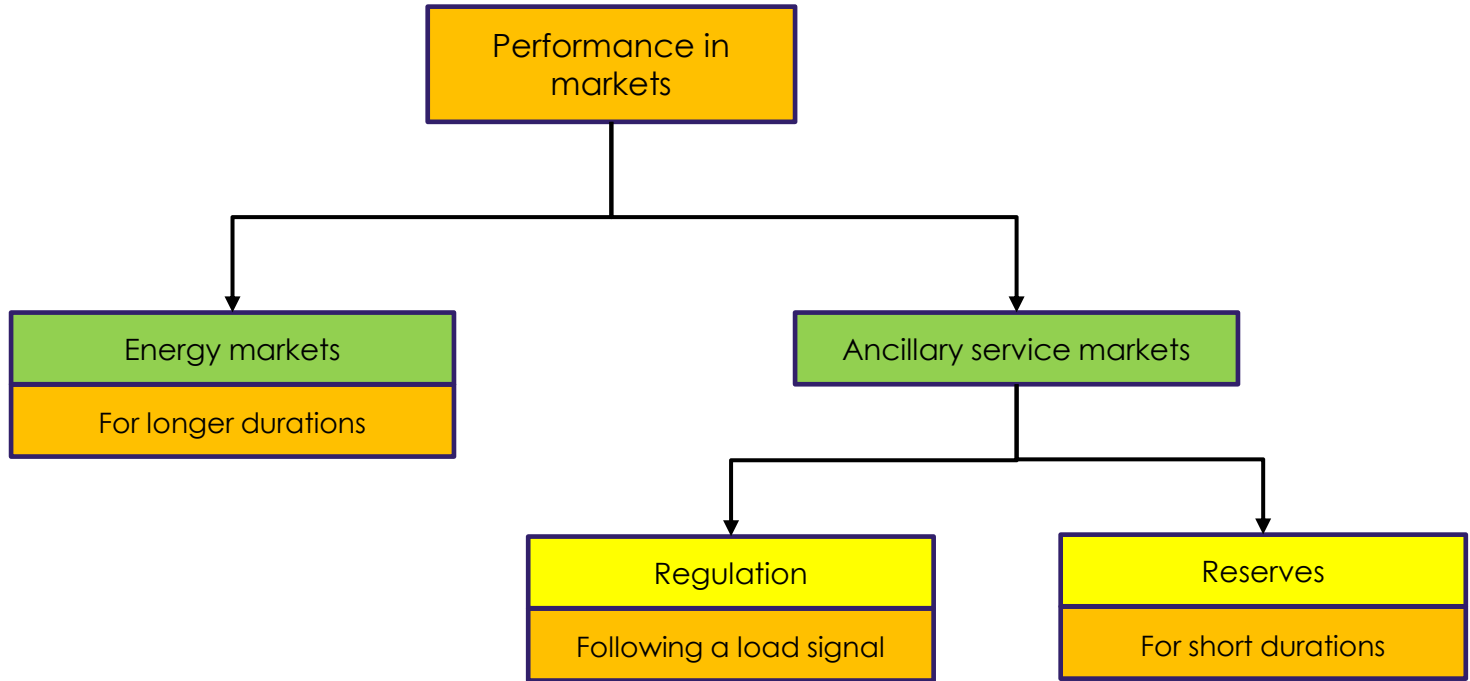
Solving a finite horizon optimal dispatch problem (subject to constraints of DERs) based on the current state of the aggregated population.





# Stage 4: Analysis in existing markets

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



# 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



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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

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

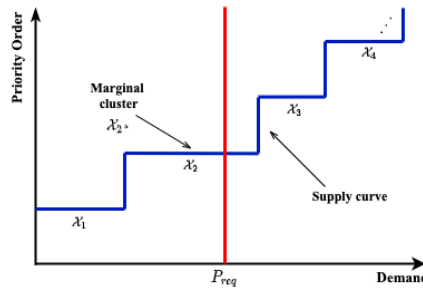
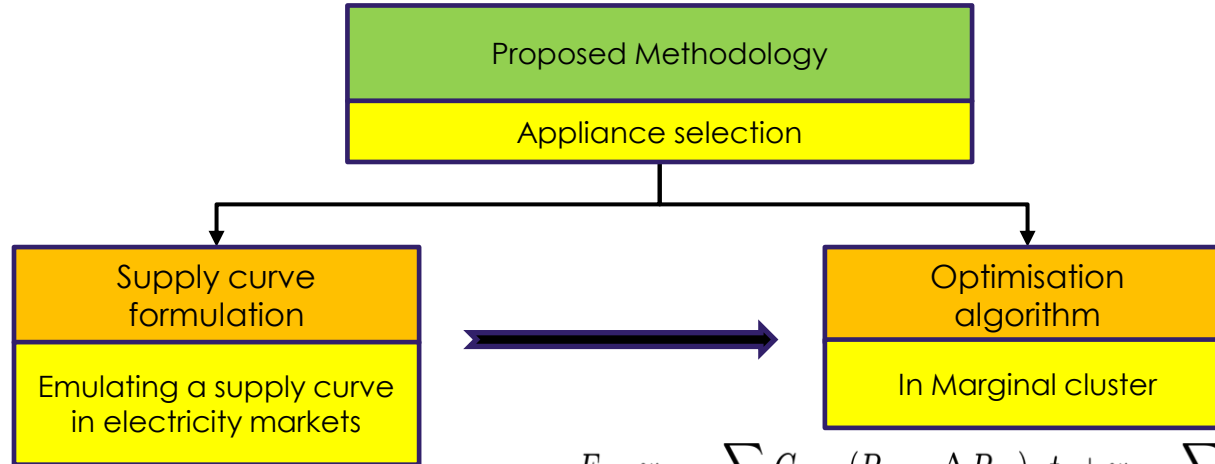
Water heaters

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

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

100 appliances for the study

# Methodology



based on  $\lambda_1$  and  $\lambda_2$

Determining Marginal cluster

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

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

$$\sum_i \Delta P_{i,t} \leq \bar{P}_{req,t}$$

$$P_{min,i}^{AC} \leq P_{i,t}^{AC} \leq P_{max,i}^{AC}$$

$$P_{min,i}^{EWH} \leq P_{i,t}^{EWH} \leq P_{max,i}^{EWH}$$

$$\underline{T}_i^{room} \leq T_{i,t}^{room} \leq \bar{T}_i^{room}$$

$$\underline{T}_i^{outlet} \leq T_{i,t}^{outlet} \leq \bar{T}_i^{outlet}$$

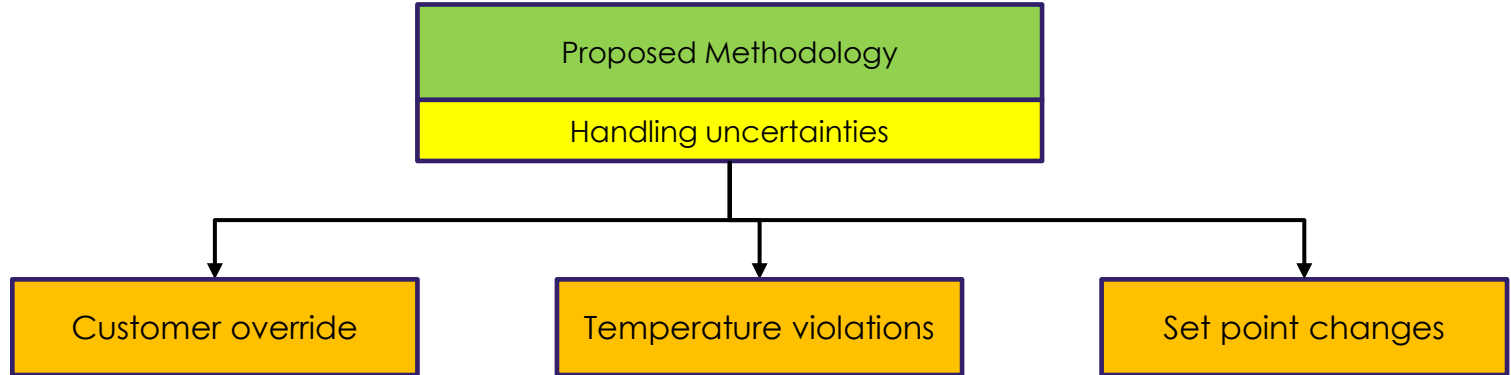
$$P_{i,t} = K_i \cdot P_{i,rated}$$

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

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

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

# Methodology



**Algorithm 1:** Algorithm for customer non-compliance events

```

1 Data:  $P_{req}, T_{dur}, P_{i,t}^{AC}, P_{i,t}^{EWH}, j \forall i$ , input parameters;
2 Determine  $t_s$  based on  $T_{dur}$  and DR event;
3 Initialise  $t = 0$ ;
4 Supply curve formation and determining  $\mathcal{X}_{j^*}$ ;
5 Performing optimisation to dispatch optimal appliances in  $\mathcal{X}_{j^*}$ ;
6 Update power consumption at time  $t$ ;
7 Determine  $P_{act,t}$  as in (21);
8 for  $t = t + t_s; t \leq T_{dur}$  do
9   if  $P_{act,t} < P_{req,t}$  then
10     Update  $P_{req,t+t_s}$  as in (22);
11     Determine  $\mathcal{O}_t$  with (1);
12     Set  $P_{i,t}^{flex} = 0 \quad \forall i \in \mathcal{O}_{t-t_s}$ ;
13     Avoid sending control signals  $\forall i \in \mathcal{O}_t$  for  $[t, T_{dur}]$ ;
14     Supply curve formulation and determine  $\mathcal{X}_{j^*}$  with  $i \in \mathcal{A} \setminus \mathcal{O}_t$ ;
15     Perform optimisation on  $\mathcal{X}_{j^*}$ ;
16     Dispatch control on chosen appliances and determine  $P_{act,t+t_s}$  from (21);
17   if  $P_{act,t} < P_{req,t}$  then
18     Update  $P_{req,t+t_s} = 0$ ;
19     Skip  $\mathcal{X}_{j^*}$  selection and optimisation;
20     Allow  $\forall i \in \mathcal{A}$  to operate at the power consumption at  $t$ ;
21     Determine  $P_{act,t+t_s}$  from (21);
22   end
23 end
  
```

**Algorithm 2:** Algorithm for temperature violations

```

1 Data:  $t, P_{i,t}^{AC}, P_{i,t}^{EWH}, T_{i,t}^{room}, T_{i,t}^{outlet}, T_{i,t}^{room}, T_{i,t}^{outlet} \forall i$ , input parameters;
2 Calculate  $T_{i,t+t_s}^{room}$  with (4);
3 Calculate  $T_{i,t+t_s}^{outlet}$  with (7);
4 for  $i \in \Omega_{AC}$  do
5   if  $T_{i,t+t_s}^{room} > T_{i,t}^{room}$  then
6     Update  $P_{i,t}^{AC} = P_{i,t}^{AC_{rated}}$ ;
7   else
8     Keep  $P_{i,t}^{AC}$ ;
9   end
10 end
11 for  $i \in \Omega_{EWH}$  do
12   if  $T_{i,t+t_s}^{outlet} > T_{i,t}^{outlet}$  then
13     Update  $P_{i,t}^{EWH} = P_{i,t}^{EWH_{rated}}$ ;
14   else
15     Keep  $P_{i,t}^{EWH}$ ;
16   end
17 end
18 Calculate  $P_{act,t+t_s}$  as in (21);
  
```

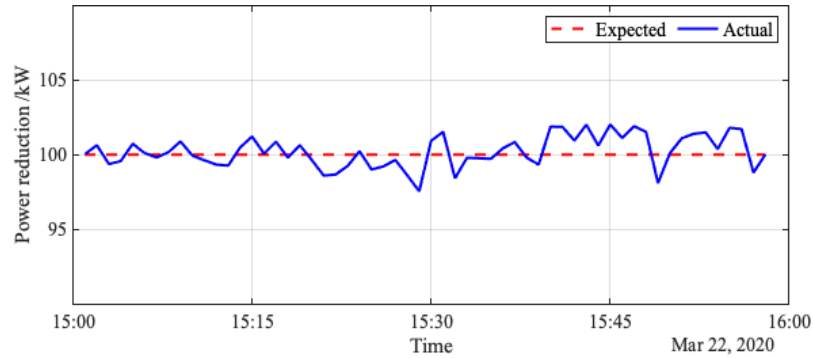
**Algorithm 3:** Algorithm for a change in set point

```

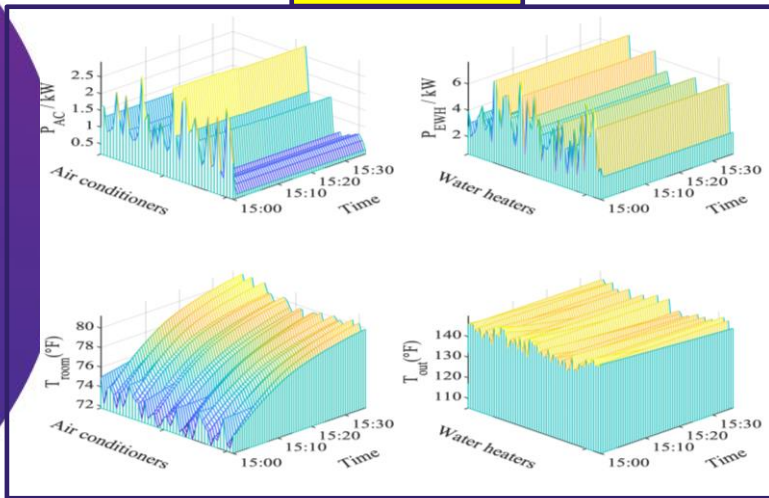
1 Data:  $P_{req,t=0}, T_{dur}, P_{i,t}^{AC}, P_{i,t}^{EWH}, j \forall i$ , input parameters;
2 Determine  $t_s$  based on  $T_{dur}$  and DR event;
3 Initialise  $t = 0$ ;
4 Supply curve formation and determining  $\mathcal{X}_{j^*}$ ;
5 Perform optimisation to dispatch appliances in  $\mathcal{X}_{j^*}$ ;
6 for  $t = t + t_s; t \leq T_{dur}$  do
7   Update  $P_{req,t}$ ;
8   if  $P_{req,t} > P_{req,t-t_s}$  then
9     Update  $P_{req,t}^{new}$  as in (23);
10    Formulate the supply curve and determine  $\mathcal{X}_{j^*}$ ;
11    Perform optimisation on  $\mathcal{X}_{j^*}$  as in (9);
12    Send control signals to chosen appliances;
13   if  $P_{req,t} = P_{req,t-t_s}$  then
14     Update  $P_{req,t}^* = 0$ ;
15     Skip marginal priority order selection and optimisation;
16     Allow  $\forall i \in \mathcal{A}$  to operate at the power consumption at  $t - t_s$ ;
17   end
18 end
  
```

# Results

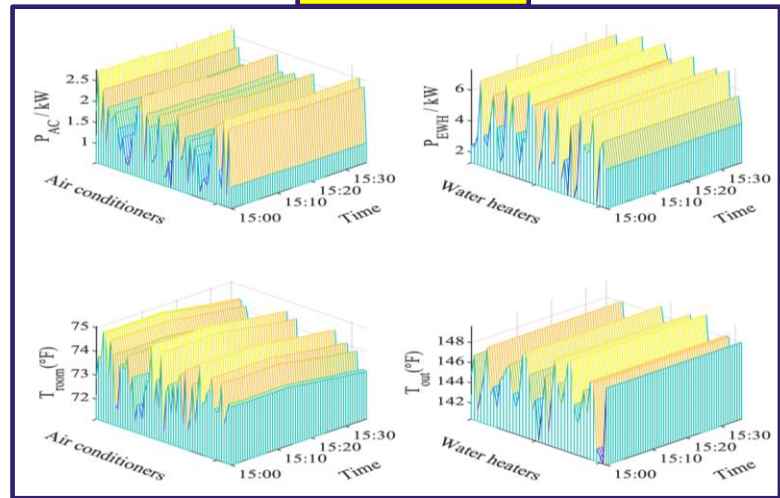
Objective : To obtain 100 kW load reduction from the TCLs in cluster 1 and cluster 2 in the absence of uncertainties in the system



Cluster 1

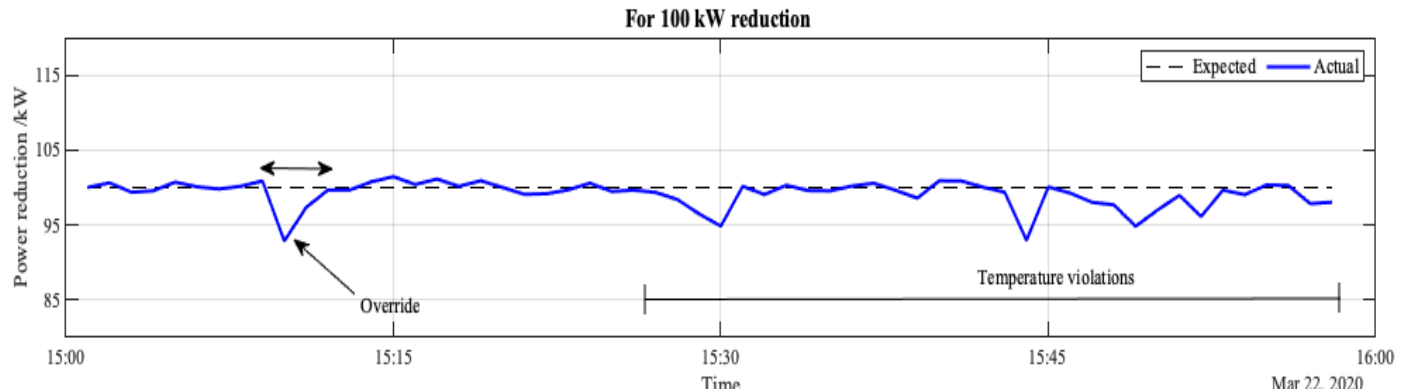


Cluster 2

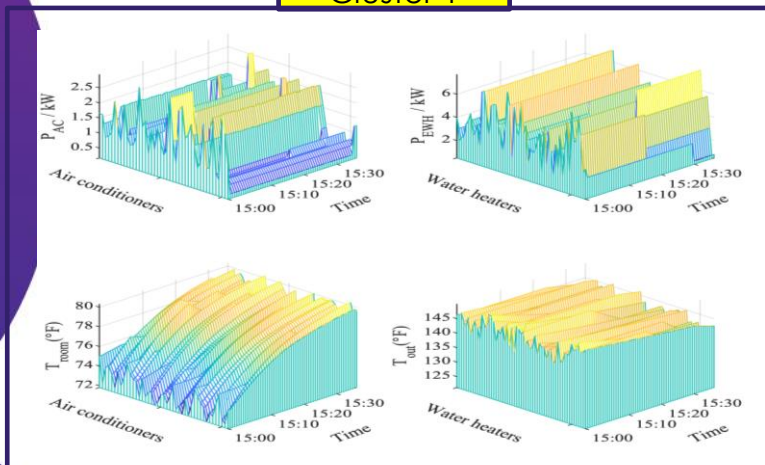


# Results

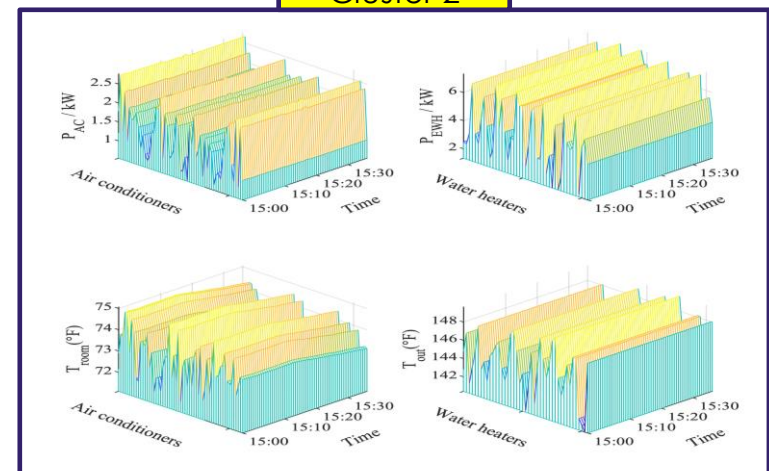
Objective : To obtain 100 kW load reduction from the TCLs in cluster 1 and cluster 2 in the presence of uncertainties due to customer override action and temperature violations



**Cluster 1**



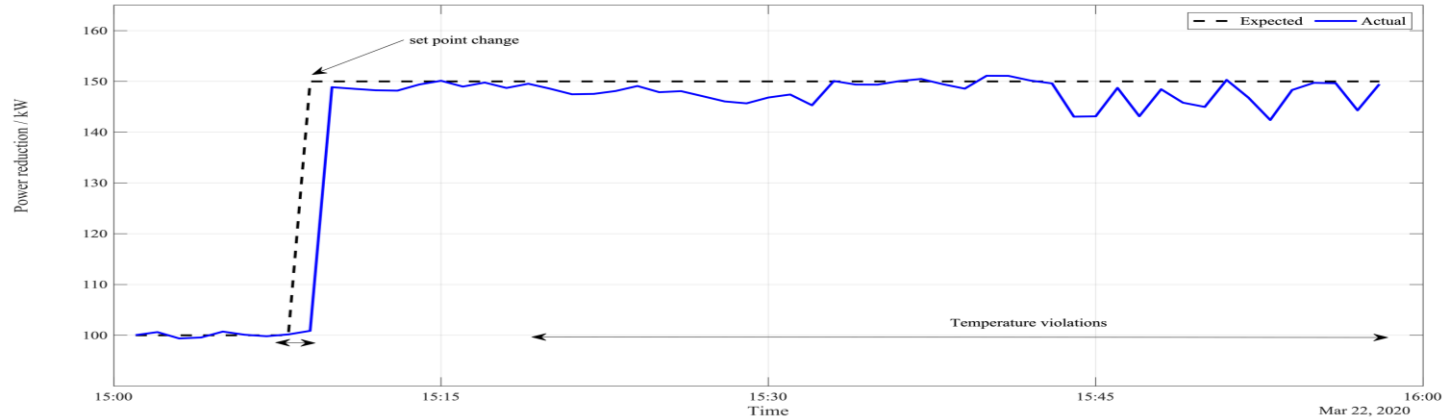
**Cluster 2**



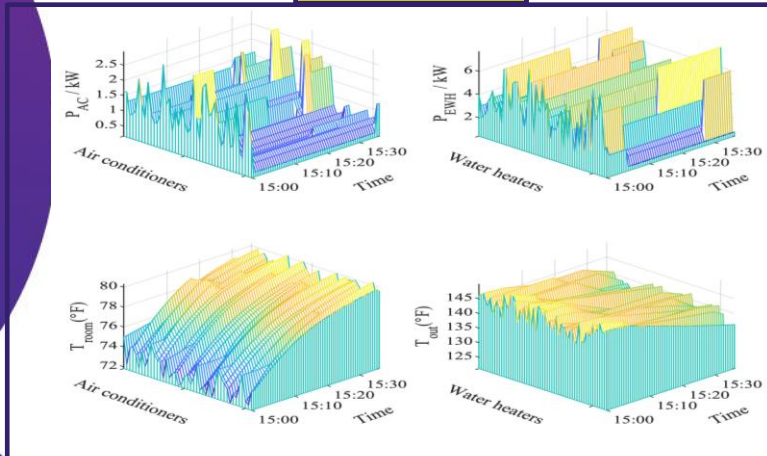


# Results

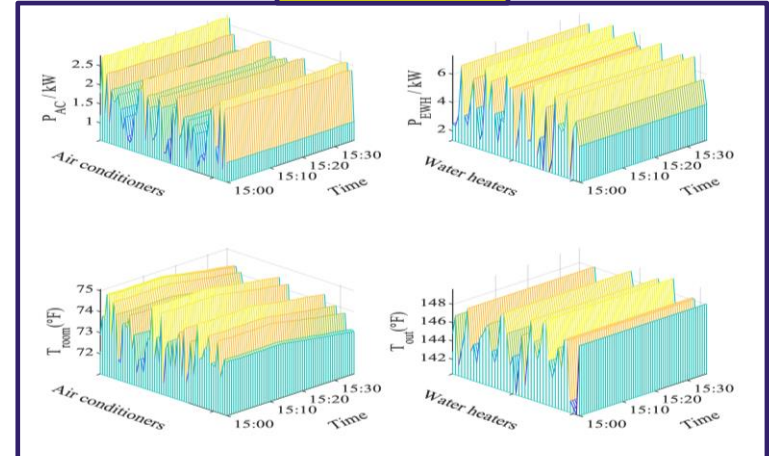
Objective : To follow the load reduction signal when the set-point changes from 100 kW to 150 kW at a certain time step, while taking into account the uncertainties arising from temperature violations.



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

Gagan Lankeshwara, Student Member, IEEE, Rahul Sharma, Senior Member, IEEE, Ruiting Yan, Member, IEEE, and Tapan Saha, Fellow, IEEE

**Abstract**—Enabling aggregated participation of behind-the-meter distributed energy resources (DERs) in electricity markets is challenging for the aggregator due to the volatility at the consumer end. Most of the existing work carried out in this area covers developing optimal bidding strategies for the aggregators in day-ahead and intra-day markets. However, the uncertainties that occur in the real-time operation cannot be captured by the existing approaches present in the literature. So, this paper develops heuristic algorithms based on direct load control (DLC) which guarantees precise load control in the presence of uncertainties occurring in real-time operation. The optimal selection of appliances is governed by a novel simulated supply curve followed by solving a mixed integer quadratic optimisation problem. Simulations are performed for a scenario where aggregated air conditioners and water heaters follow a set point reduction under the uncertainties occurring from customer non-compliance events and changes in set point events. Further, the developed heuristic control scheme is compared with an existing industry approach. The results yield that the proposed control scheme is robust to uncertainties and applicable for practical implementations.

**Index Terms**—Demand Response, direct load control, uncertainties, electricity markets, customer override, aggregator, optimisation

### I. INTRODUCTION

IN the presence of two-way communication and advanced metering infrastructure (AMI), demand side management approaches are a promising alternative for the grid operators to manage the network when it is stressed [1]. One such alternative which is widely used in the industry is demand response (DR). According to FEREC demand response report [2], the annual peak demand savings from retail demand response corresponds to more than 31 GW.

Direct load control (DLC) [3], is one of the most common strategies used in practice. In this approach, the end customers allow the utility or a third party to control their household appliances (eg: HVAC, water heater, EV and pool pump) when the grid is in need of additional support. With improved accuracy and reliability, DLC is most preferred by the grid operator [4]. Extensive work is available in the literature based on the inertial capabilities of thermostatically controllable appliances to participate in DLC [5], [6]. HVAC

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set point control in peak load shaving is considered in [7]. The authors in [8] have studied the capabilities of HVAC providing balancing services, where the dispatch is according to a priority based stacking. Du *et al* in [9] proposed a load scheduling strategy for electric water heaters in DLC based on the market price. The authors in [10] introduced a novel comfort index for thermostatically controllable appliances to determine incentives for commitment in an event. However, all the approaches have overlooked the flexibility of end customers, instead assumes the guaranteed participation of all contracted end customers during an event.

Although DLC is in practice, the outcome of most of the trials suggest that residential customers are more likely to participate in price-based approaches (eg: DSM, CPP/RT) [11] compared to DLC. The root cause for this issue is end users “losing the perceived control” when an aggregator control their appliances at households [12]. Furthermore, it is suggested that customers are likely to have an override or external control option to opt-out during a DR event. However, only a handful of studies are published on the feasibility of DLC in the presence of customer voluntary compliance during a DR event.

Although modelling of voluntary compliance is done in [13], the authors here only generalised compliance at household level, but not appliance level. At the same time, although overriding has been highlighted in [14], [15], [16], no explicit modelling has been done to determine its consequences.

Meanwhile, enabling voluntary compliance creates complexities when an aggregator provides services in electricity markets. According to the existing market policies, the commitment is mandatory for the aggregator if its bids are cleared in the market [17]. In the event of significant override, there is a high probability that an aggregator will not be able to provide bid amounts, which leads to penalties for non-compliance. The DR trial conducted by the Australian Energy Market Operator (AEMO) in 2019 [18], gives evidence of volatile behaviour of residential customers compared to their counterparts during an emergency DR event. To add more, DLC programs conducted across the world [19], [20] have recorded significant customer override events during the operation. Considering all these scenarios, it can be claimed that a systematic approach is essential if residential aggregators are to participate in markets and maximise social welfare under real-time uncertainties.

Fig. 1 illustrates the effect customer override can have on the performance of a DR event. The figure is based on Redback data [add ref] and illustrates successive the divergence of

### A. Conceptual priority based ranking mechanism and emulated supply curve formation

Consider a number of controllable appliances are present in each house  $h \in \{1, \dots, N\}$ . For each appliance  $i \in A$ , a customer is required to define a priority index  $j$  s.t.  $j \in \{1, \dots, n\}$ . The priority index  $j$  is used as a quantitative measure of the importance of one appliance over the others. For example, if the customer in house  $h$  assigns priority index  $j = 1$  to the water heater and priority index  $j = 2$  to the air conditioner, it implies that the operation of the air conditioner is more critical than the water heater for that customer during a DLC event. To put it in a simple way, as the priority index  $i$  increases, the importance of the appliance for the customer also increases. Hence, the aggregator always guarantees to initiate the demand response by controlling the consumption of appliances with the lowest  $j$  and then sequentially control higher priority appliances.

Once  $j$  is assigned for  $\forall i \in A$  by the customers in  $\forall h \in \{1, \dots, N\}$ , a set of priority orders  $\zeta$  is defined s.t.  $\zeta = \{X_j^i | j \in \{1, \dots, n\}\}$  where  $X_j^i$  corresponds to priority cluster formed by the appliances with priority index  $j$ . In practice, most of the existing approaches in DLC do not allow an appliance to be fully controlled, instead allow a minimum consumption level which is usually a fraction of the rated power [28]. Adhering to this, the flexible power of an appliance  $i$  at a time  $t$  can be expressed as,  $P_{i,t}^{flex} = (1 - K_i) P_{i,rated}$ .  $K_i$  is the minimum fraction of power that should be allocated for an appliance. Hence, the total flexible power of cluster  $X_j^i$  at time  $t$  can be expressed as,

$$P_{X_j^i,t}^{flex} = \sum_{i \in X_j^i} P_{i,t}^{flex} \quad \forall i \in X_j^i \quad (8)$$

Likewise for  $\forall X_j^i$ , the aggregated flexible power at time  $t$  can be cascaded in an increasing priority order to form an emulated supply curve as shown in Fig. 5.

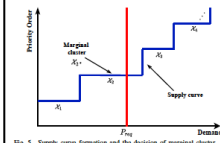


Fig. 5. Supply curve formation and the decision of marginal cluster

Impaired by the determination of the clearing price based on the intersection between the supply curve and the demand curve in electricity markets, a similar approach is followed to determine the marginal cluster  $X_j^i$  and the lower priority clusters  $X_j^i$  for  $j \in \{1, \dots, j-1\}$  that need to be controlled during a certain time step in a DR event. For example, when  $P_{req}$  is required by the system operator as shown in Fig.

5 (represented with a red solid line), the appliances in  $X_1$  and  $X_2$  only need to be controlled, where  $X_2$  will be the marginal cluster. Likewise, the emulated supply curve is used to determine the marginal cluster  $X_j^i$  and the lower priority clusters to be controlled to achieve  $P_{req}$  at a certain time.

### B. Optimisation problem

Once marginal cluster  $X_j^i$  is determined from the supply curve as in section III.A, a step-based optimisation problem is solved to determine the optimal selection of appliances to be controlled in  $X_j^i$  for the next time step. From the point of view of the aggregator, the objectives are to minimise the cost of buying electricity from wholesale markets or contracts, and to minimise the discomfort for the contracted end customers. Therefore the problem is formulated as a multi-objective optimisation (MOO) with the cost function to be a combination of total cost for the aggregator and the total discomfort for the end customers. Considering the marginal priority cluster  $X_j^i$  at time  $t$ , it can be expressed as,

$$F = \min_{\omega} \sum_{i \in X_j^i} C_{p,i} (P_{i,t} - \Delta P_{i,t}) + \sum_{i \in X_j^i} D_{i,t}^d \quad \forall i \in X_j^i \quad (9)$$

where  $C_{p,i}$  is the market price of electricity at time  $t$ ,  $\Delta P_{i,t}$  is the power reduction of appliance  $i$  at time  $t$ , and  $D_{i,t}^d$  is the discomfort index for appliance  $i$  at time  $t$ . In addition to that  $\omega_{i,t}$  and  $\omega_{i,t}$  represents the weights assigned to the cost and discomfort, respectively.

The discomfort index for air conditioners and water heaters at a particular time step is obtained from [31]. For ACs, the discomfort index can be expressed as,

$$D_{i,t}^d = \frac{2(T_{i,t}^{room} - T_{i,t}^{min})}{T_{i,t}^{max} - T_{i,t}^{min}} \quad i \in \Omega_{AC} \quad (10)$$

For EWHs, the discomfort can be expressed as,

$$D_{i,t}^d = \frac{2(T_{i,t}^{water} - T_{i,t}^{min})}{T_{i,t}^{max} - T_{i,t}^{min}} \quad i \in \Omega_{EWH} \quad (11)$$

The overall optimisation problem with constraints are,

$$\min F(\Delta P_{i,t}) \quad (12)$$

$$\sum_{i \in X_j^i} \Delta P_{i,t} \leq P_{req,t} \quad (13)$$

$$P_{i,t}^{AC} \leq P_{i,t}^{AC} \leq P_{i,t}^{AC} \quad (14)$$

$$P_{i,t}^{EWH} \leq P_{i,t}^{EWH} \leq P_{i,t}^{EWH} \quad (15)$$

$$T_{i,t}^{room} \leq T_{i,t}^{room} \leq T_{i,t}^{room} \quad (16)$$

$$T_{i,t}^{water} \leq T_{i,t}^{water} \leq T_{i,t}^{water} \quad (17)$$

$$P_{i,t} = K_i P_{i,t}^{rated} \quad (18)$$

$$K_i \in \{0.25, 0.50, 0.75, 1.0\} \quad (19)$$

$$\min_{\omega} + \min_{\omega} = 1 \quad (20)$$

$$\text{with (2) - (7), (10) and (11)}$$

The minimisation problem is given by (12). The constraint (13) corresponds to the minimum demand reduction required from the marginal priority cluster at time  $t$ . The constraints (14) and (15) describes the power limits for ACs and EWHs in the marginal priority cluster. Similarly, (16)-(17) corresponds to

is followed to avoid any over-sizing or under-sizing in AC cooling capacity decision making.

For the EWH subsystem, it is assumed that  $T_{i,t}^{water}$  and  $T_{i,t}^{room}$  are constant as in [35]. Furthermore, it is assumed that the  $P_{i,t}$  is uniformly distributed and remains constant during the DR horizon. Hence, all the EWHs are operating at their rated power (calculated from (7)) at  $t = 0$  to keep the hot water temperature at set point. This assumption is reasonable for short DR events (max. upto 1 hour) where the water heating occurs to restore a fully empty tank with heated water. However, due to ToU tariff schemes introduced [36], EWHs will not usually operate during peak demand hours, hence DR action cannot be performed.

A demand reduction event is considered for  $T_{dur} = 1$  hour, starting from 15:00 and ending at 16:00 on 22-03-2020. The market price of electricity ( $C_{p,t}$ ) is assumed constant based on contracts and obtained from [37]. Depending on the value of  $P_{req}$ , demand reductions can be obtained from either  $X_1$  or  $X_2$  and  $X_3$ . Hence a Monte Carlo simulation (MCS) is performed in  $X_1$  to determine  $P_{req}$  to be obtained. The results of the MCS are given in Figure ??

The total power consumption of the population at time  $t = 0$  is 600.45 kW. It is distributed between  $X_1$  and  $X_2$  as 295.67 kW and 315.77 kW respectively. The MCS is performed by assigning  $\omega_i \in \{0, 0.25, 0.50, 0.75\}$  for each  $i$  with equally likely occurrences. The results provide a narrow approximation that achieving 100 - 120 kW reduction is possible in  $X_1$ .

Hence the rest of the simulation results are based on the following scenarios.

- 100 kW (around 16% from the total) demand reduction (within the range of MCS)
- 150 kW (around 24% from the total) demand reduction (just within the range of MCS)

In addition to that, for each of the scenarios discussed here under, the algorithms are written in MATLAB and the optimisation is performed with YALMIP and solved in a Dell Optiplex 7600 desktop embedded with an Intel Core i7-6700 CPU and 16.0 GB RAM. The time interval,  $\Delta t = 1$  min for each step.

### A. Ideal system scenario

At  $t = 1$  min, the aggregator requests for  $P_{req} = 100$  kW, and the algorithm is executed to obtain the demand reduction. Once the demand reduction is achieved in the next time step, i.e. at  $t = 2$  min, for the rest of the event, the ACs and EWHs in both  $X_1$  and  $X_2$  operate within permissible power limits defined by the aggregator. According to Fig. 6, the actual reduction follows the expected reduction within the threshold  $\delta$  (described in section III.D) which is assumed to be 0.05.

### B. Performance under the influence of uncertainties

Simulations are performed mainly for two scenarios: 1) a certain group of customers override the control signals sent by the aggregator during the DR event 2) the aggregator decides to increase the target reduction during a DR event. Recovering and following the targeted reduction under the aforementioned scenarios are considered while Algorithm 2 takes care of the uncertainties arising due to temperature violations.

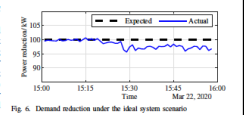


Fig. 6. Demand reduction under the ideal system scenario

1) Customer non-compliance event: In actual implementations, the non-compliance action is only realisable with air conditioners. Once the customer overrides the DR event, the control action will be released and the AC continues to operate under the normal consumption for the rest of the DR event. While the aggregator delivering 100 kW and 150 kW of demand reduction, it is simulated that 10% of the ACs in  $X_1$  override in non-compliance event at  $t = 10$  mins.

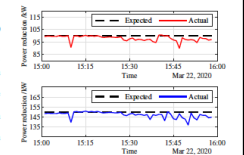


Fig. 7. Comparison of demand reduction under override for two cases

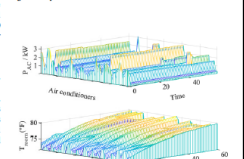


Fig. 8. The variation of power consumption and the room temperature for the ACs in  $X_1$

As depicted in Fig. 7, the overriding action occurring at  $t = 10$  min results in mismatch exceeding the threshold  $\delta = 0.05$ . Hence an optimisation is solved at  $t = 11$  min and additional units dispatched to compensate for the

# Outline

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

# 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 !

