# Net-Zero distribution networks and distribution system operation – challenges and opportunities


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# Outline of presentation*

- Characteristics of the evolving and future net-zero distribution power and energy networks
- Operation, modelling and control challenges of net-zero distribution networks
- Examples of the latest research results in some of the relevant areas
- Current developments in the UK related to the Electricity Distribution Price Control 2023-2028

* Contrary to all advices that I (and others) give to students regarding the number of slides that they should prepare for a presentation, I have probably double of that number

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# Evolving Power & Energy Network

- Evolving/new market structures/operation
  - Increasingly liberalised market
  - Increased cross-boarder bulk power transfers to facilitate effectiveness of market mechanisms
  - Introduction of market at DN level

- **(D)** New generation/storage technologies (mostly **PE** interfaced and often not visible to system operator, ie, <100 MW typically invisible to SO)
  - Proliferation of non-conventional, largely stochastic and intermittent renewable generation (large on-shore & off-shore wind farms & PV) and storage at all voltage levels with small scale (widely dispersed) technologies in DN


# Evolving Power & Energy Network

- Proliferation of PE based “transmission facilitating” technologies
  - Increased use of HVDC lines of both, LCC and predominantly VSC MMC technology (in meshed networks and as a super grid)
  - Increased presence of static and active shunt and series compensation
  - Increased deployment of FACTS devices in general









- **(D)** New types and operational patterns of mostly **PE** connected load
  - New types of PE based/connected loads within customer premises (e.g. heat pumps, HVAC, lighting)
  - EVs (spatial and temporal uncertainty)

# Evolving Power & Energy Network




- **(D)** Energy & information security of integrated systems require integrated approach
  - Integrated ICT - Information extraction challenges
  - Integrated “intelligent” PE devices enabling bi-directional information flow
  - Different energy carriers (whole energy system)
  - Cyber security




# Evolving Power & Energy Network

- **(D)** Workforce & customers
  - Available skilled, trained and content workforce
    - re-training to ensure adequate skills are available
    - recruitment of people with new technical skills
    - recruitment form diverse backgrounds, technical, social, cultural, faith…
- Ensuring no-one is left behind
    - Priority customer registers
    - Special care of vulnerable customers

# This development leads to…

## Power electronics rich networks

Power electronics devices, on the other hand, are known to be:

- Major contributors of non-sinusoidal (due to semiconductor device switching which occurs within a single cycle of the power system fundamental frequency) to the network, hence

**These changes are clearly affecting both, transmission and (possibly to a larger extent) distribution network**

So, this new network will not be short of the sources of harmonics nor the devices affected by harmonics

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# Challenges - 1

- **DATA:** Efficient use and reliance on existing and newly acquired data through deployed local measurement devices and two-way communications enabled meters (primarily smart meters) for increased observability, state estimation, forecasting, operation and control (including real time control)
  - Efficient data management (signal processing, aggregation, transmission) and ICT network reliability are essential for both static and dynamic observability as well as for operation and control of the system
  - Data exchange (format & accessibility), security and privacy

**Data Analitics –**

**Efficient knowledge extraction form data**

# Challenges - 2

- **MODELLING**: for steady state & dynamic studies
  - Variable, and to extent stochastic, operating conditions influenced by market forces and uncertainty in renewable generation and load
  - Clusters of RES (generation and storage) of the same or different type some of those not visible at transmission level
  - Demand, including new types of energy efficient and PE controlled loads, heat pumps, EVs, customer participation and behavioural patterns, etc.
  - Storage technologies for provision of ancillary services
  - Modelling/analysis of efficient and effective integration of different energy carriers into self sufficient energy module/cell
  - Interconnected DN and TN as well as critical infrastructure systems, "system of systems"
  - Power Quality related phenomena resulting from integration of LCTs (harmonic sources and propagation, unbalance, voltage regulation)

**Probabilistic modelling**

**to mange increasing uncertainties**

# Challenges - 3

- **CONTROL**: Design of advanced controllers and control structures – increased network automation
  - Design of effici

**Particular challenge for DNOs due to the lack of past operational experience in some, if not many of these areas**

Risk is an uncertain event or condition that, if it occurs, has an effect on at least one objective, it is the probability of something happening multiplied by the resulting cost or benefit if it does.

# Addressing identified challenges

**DATA:** Introduce Data analytics for planning, operation and control

- New skills of the workforce are required: re-training, re-skilling and employment of people from non-engineering (e.g., *computer science, mathematics, communications, social science,* etc.) backgrounds

**MODELLING:** Strong emphasis will need to be put on developing appropriate, most likely probabilistic models of components, processes and events

- New skills of the workforce are required: re-training, re-skilling and employment of people from non-engineering (e.g., *mathematics, social science*) backgrounds

**CONTROL:** New control approaches (stochastic distributed control), greater network automation, to deliver real time risk limiting control of the system.

- New skills of the workforce are required: re-training, re-skilling and employment of people from non-engineering (e.g., *control systems, mathematics, communications*) backgrounds

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# Acknowledgement

Many examples, figures and some slides in this presentation are adopted from the work of my numerous undergraduate, MSc and PhD students, PDRAs and visitors who worked with me on these topics since 2011. In particular

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4. Mr Lingyue Zhang (FY)
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6. Miss Yaxin Su (MSc)
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10. Mr Jiawei Cai (FY)
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12. Dr Pablo Rodríguez-Pajarón (visitor)
13. Assoc. Prof. Araceli Hernández (visitor)

References to some of their publications are shown throughout this presentation.

# Demand Profiling (and management)

Identification/estimation and forecasting of static composition (in terms of load categories and load controllability) and demand side management

# Demand profiling

| Load controllability | Load categories | Residential appliances |
|---|---|---|
| Controllable | CTIM1 | Dish washer, tumble dryer, washing machine, washer-dryer, vacuum cleaner |
| | QTIM1 | Chest freezer, fridge-freezer, fridge, upright freezer |
| | $R_C$ | Water heater, electrical shower, storage heater, electrical space heating |
| Uncontrollable | $R_{UC}$ | Iron, hob, oven |
| | SMPS | Answer machine, CD player, Clock, telephone, high fidelity (HiFi) appliances, Fax machine, PC, printer, TV, VCR-DVD, receiver, microwave |
| | Lighting | Lighting |

**Load categories:**

CTIM1 - Single-phase constant torque induction motors

CTIM3 - Three-phase constant torque induction motors

QTIM1 - Single-phase quadratic induction motors

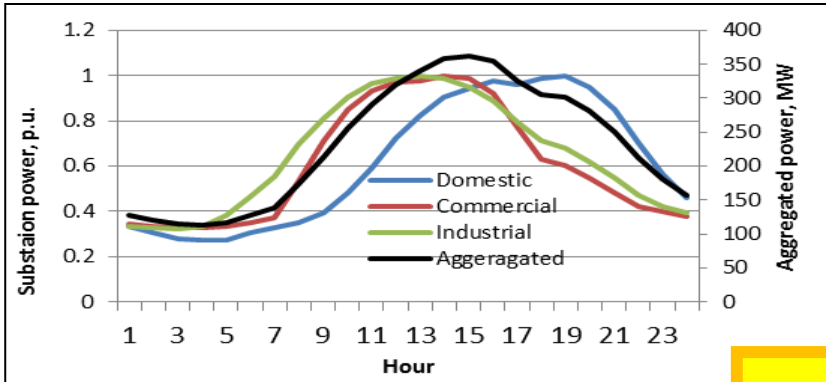
$R_C$- controllable resistive loads

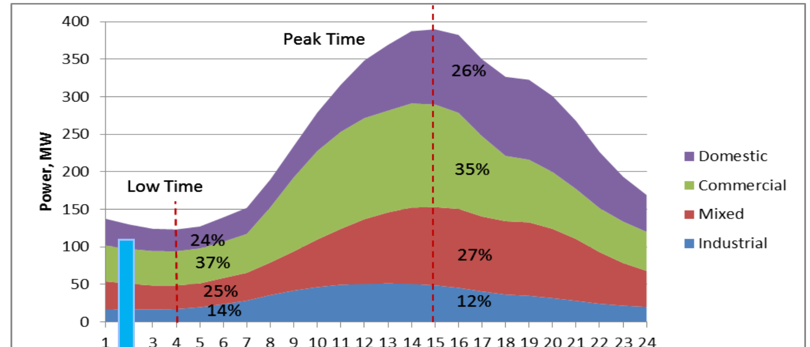
$R_{UC}$- uncontrollable resistive loads

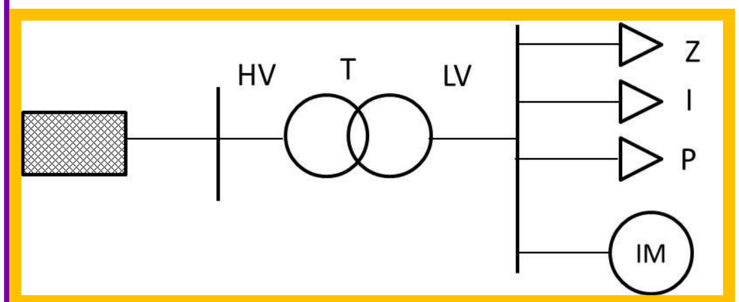
SMPS - Switch-mode power supply

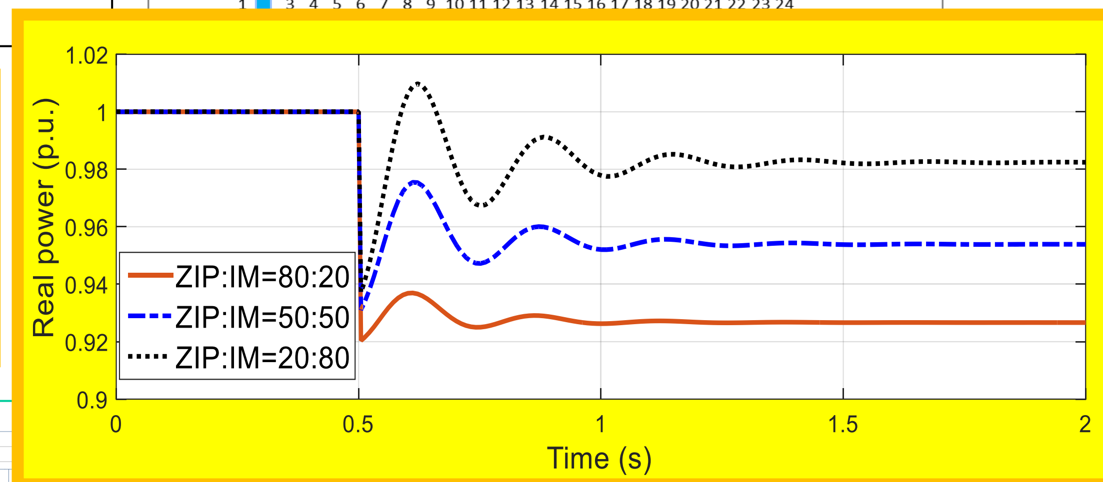
Lighting

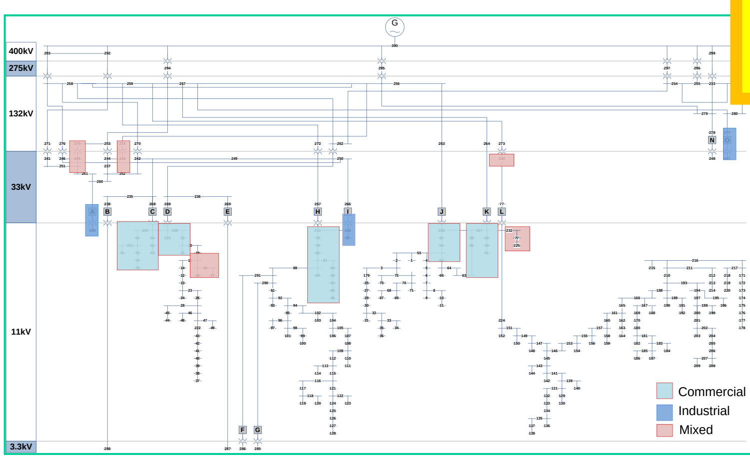
# Effect of demand management

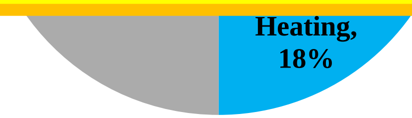



Domestic electricity consumption broken down by end use.

Domestic electricity consumption broken down by load category

# Practical application within EU H2020 project “Nobel Grid”

## (€12million, 42 months, 1/1/2015 - 30/6/2018)

**Illustration of the process of demand forecasting and disaggregation**

J. Ponocko, Jiawei Cai, Yusong Sun and J. V. Milanović, “Real-time visualisation of residential load flexibility for advanced demand side management”, 19th IEEE Mediterranean Electrotechnical Conference (MELECON 2018), Marrakesh, Morocco May 2-7, 2018, (1570409786)

K. Li, J. Ponoćko, L. Zhang and J. V. Milanović, “Methodology for Close to Real Time Profiling of Aggregated Demand Using Data Streams from Smart Meters”, 10th Mediterranean Conference on Power Generation, Transmission Distribution and Energy Conversion, Medpower 2016, Belgrade, Serbia, 6-9 November 2016.

Yizheng Xu and J.V. Milanović, “Artificial intelligence based methodology for load disaggregation at bulk supply point”, IEEE Transactions on Power Systems, Vol. 30, No 2, 2015, pp. 795 – 803

J.V. Milanović and Yizheng Xu, “Methodology for estimation of dynamic response of demand using limited data”, IEEE Transactions on Power Systems, Vol. 30, No 3, 2015, pp. 1288 – 1297

Yizheng Xu and J.V. Milanović, “Day-ahead Prediction and Shaping of Dynamic Response of Demand at Bulk Supply Points ”, IEEE Transactions on Power Systems, Vol. 31, No. 4, 2016, pp. 3100 - 3108.

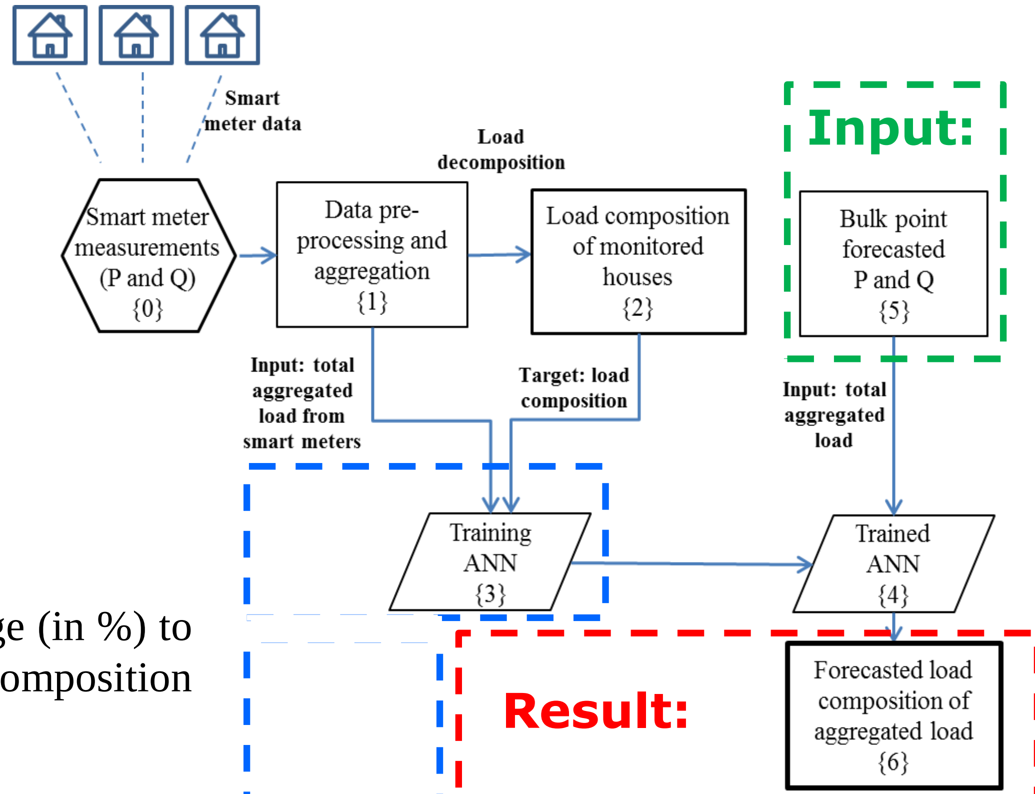
Jelena Ponoćko and J. V. Milanović,”Forecasting demand flexibility of aggregated residential load using smart meter data", IEEE Transactions on Power Systems, Vol. 33, No. 5, Sep. 2018, pp. 5446 - 5455.

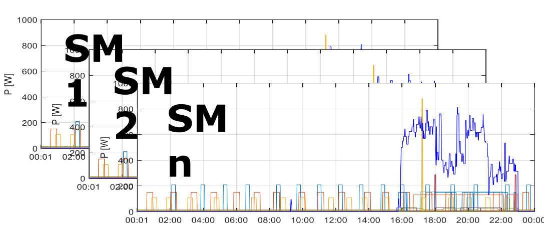
# Assessing demand composition with a few smart meters?

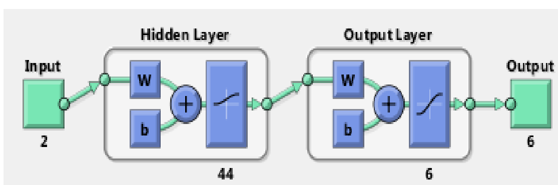
Assumptions:

- Some smart meters have sub-metering capabilities
- Day-ahead forecast of active and reactive demand is available at the aggregation level (substation)
- There are missing data samples and time series are provided with different time steps

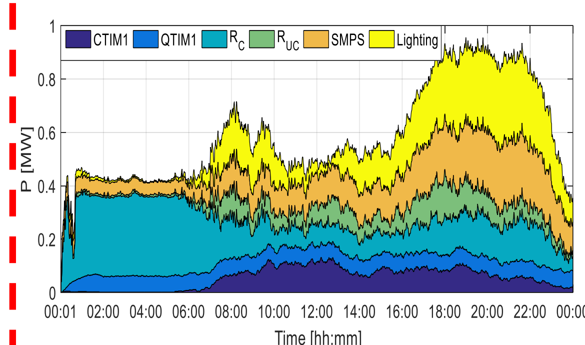
Aim: Assess the required smart meter coverage (in %) to estimate with acceptable accuracy the load composition at the aggregation point



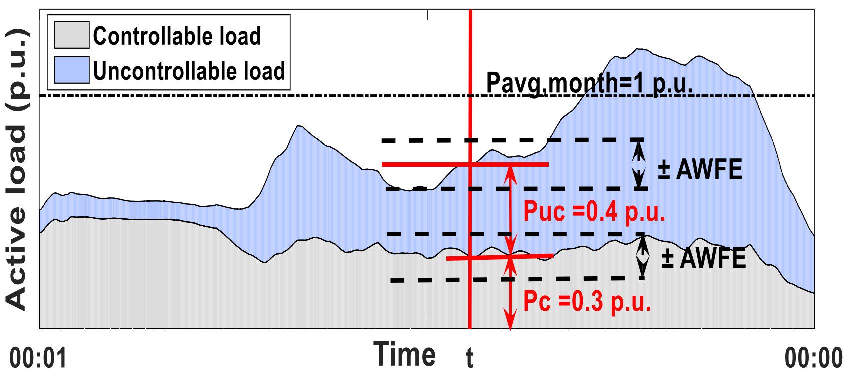




Training the ANN

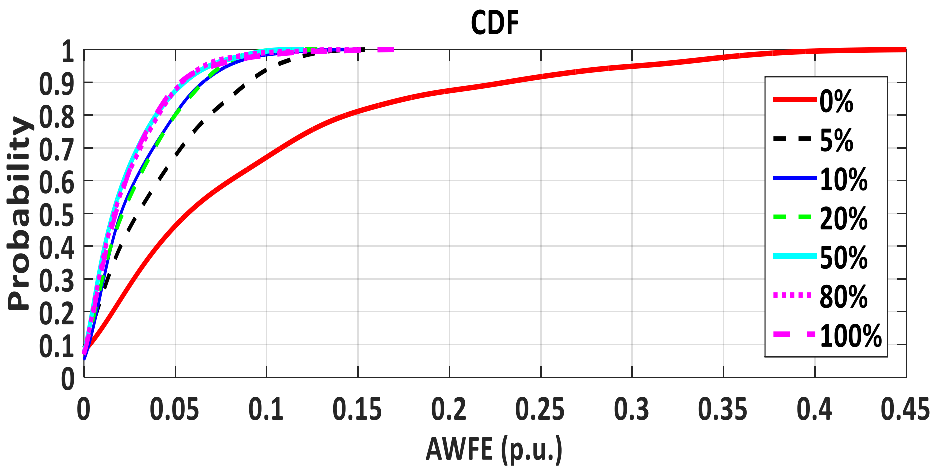


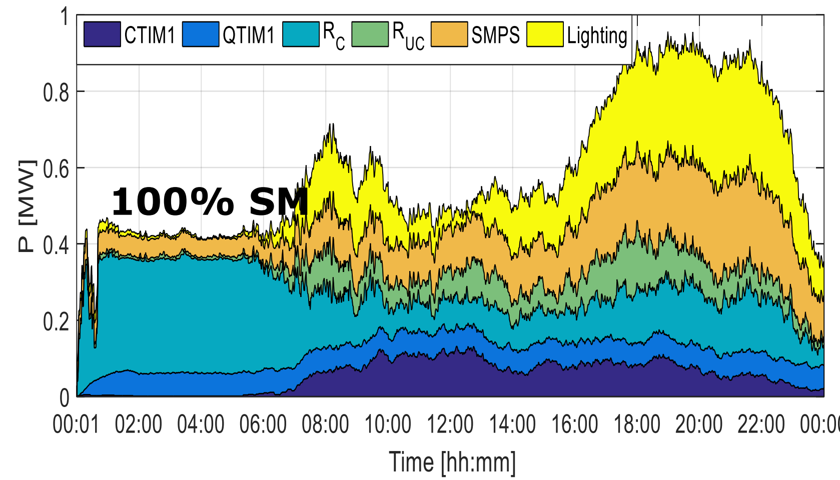
# Validation of the methodology

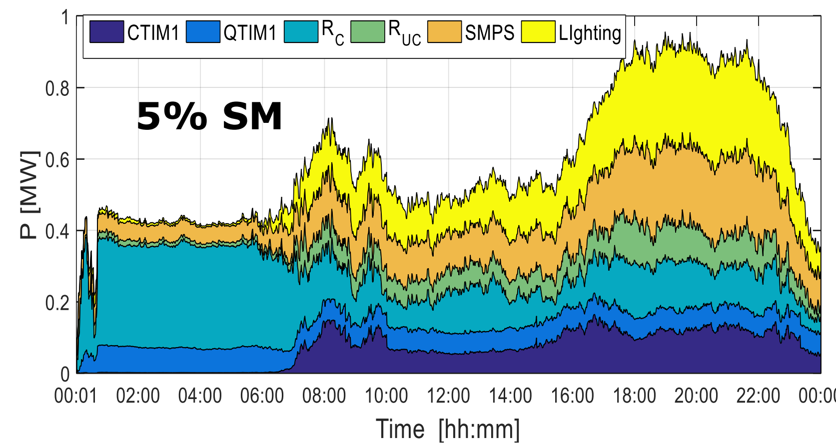
## Validation of the methodology was performed using CREST* load model




$$AWFE_{cat} = \left| WF_{cat,ANN} - WF_{cat,\,real} \right|$$




**Controllable:**
CTIM1
QTIM1
$R_C$

**Uncontrollable:**
$R_{UC}$
SMPS
Lighting

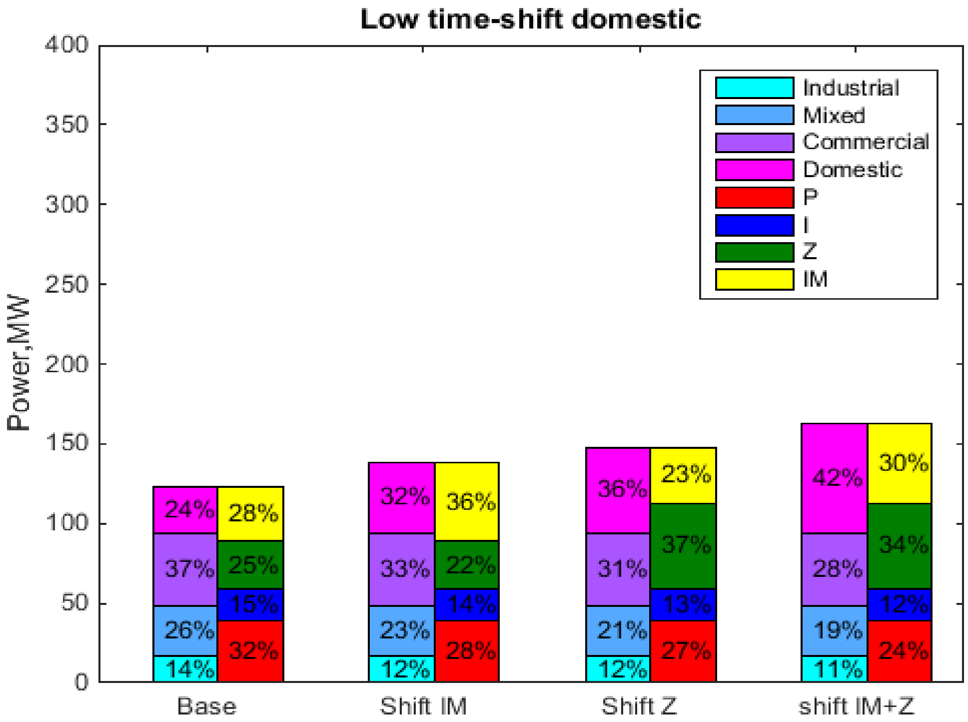
** I. Richardson, M. Thomson, D. Infield, and C. Clifford, "Domestic electricity use: A high-resolution energy demand model," Energy and Buildings, vol. 42, pp. 1878-1887, 2010.*

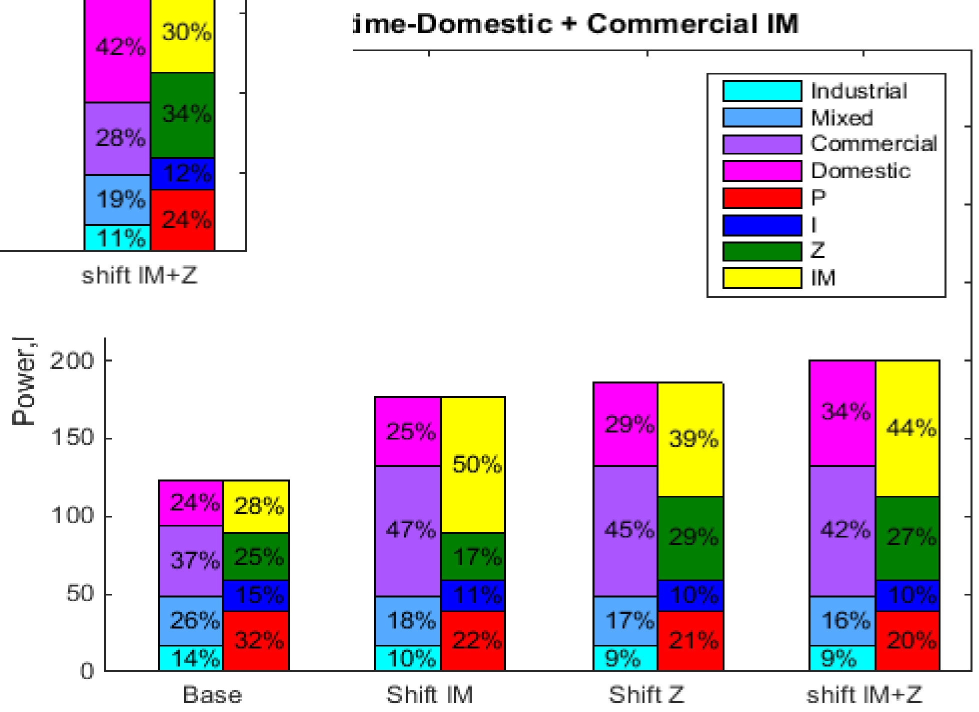
# Unintended consequences of DSM

Large sale DSM (large number of small users, few large users, combination of the two) can be used as a flexibility resource, however:

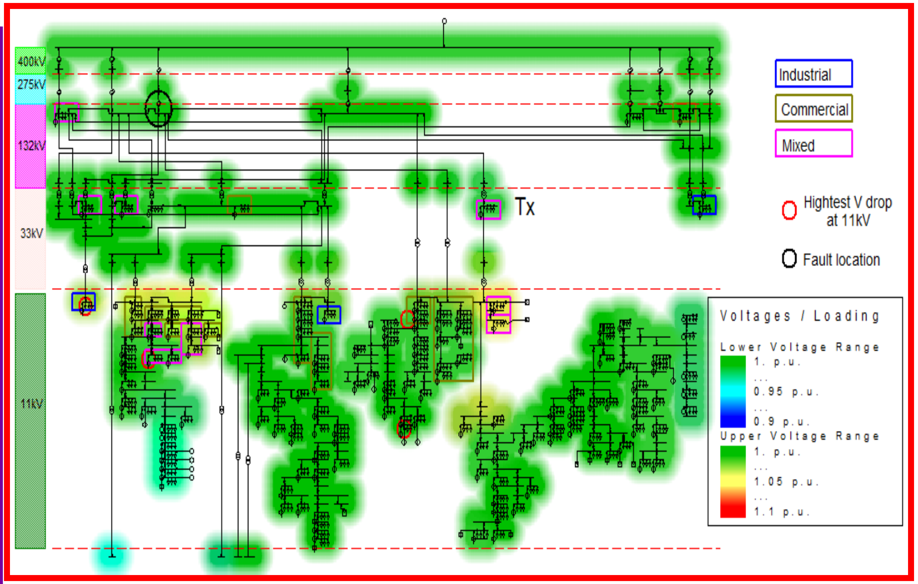
- Shifting a large number of different types of load from one time period to another changes not only the total load, but also the **composition** of the load during the day at different busses
- Change in total demand and demand composition affects distribution, and ultimately transmission network steady state and dynamic performance
- Different load demand and composition at network buses
  - results in different dynamic response of demand to disturbances
  - affects the network loadability, voltage profiles and network losses

# Change in demand composition

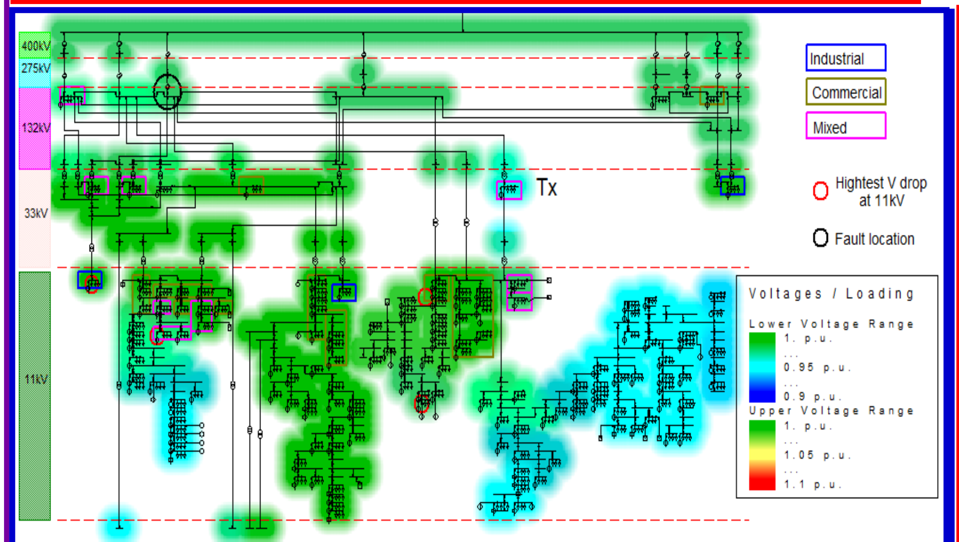


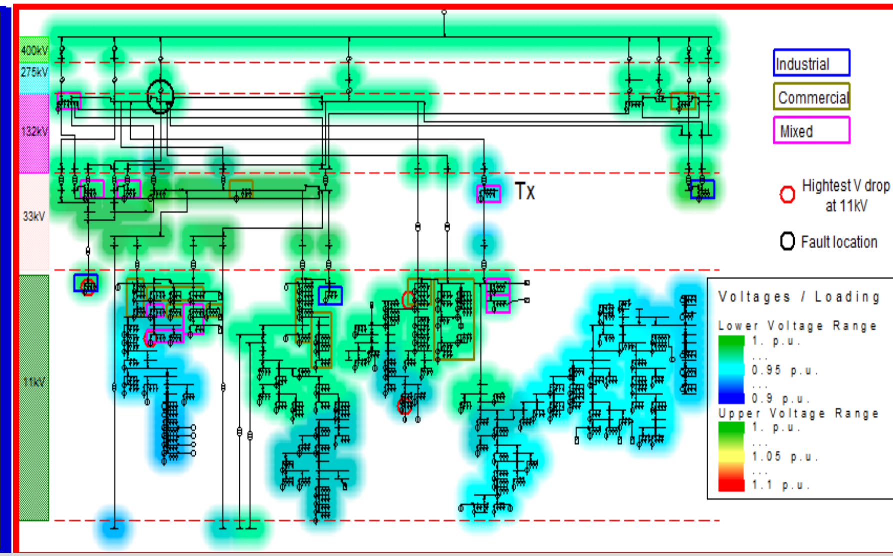



# Effect on voltage levels




Voltage levels in distribution network before DSM at **peak time**

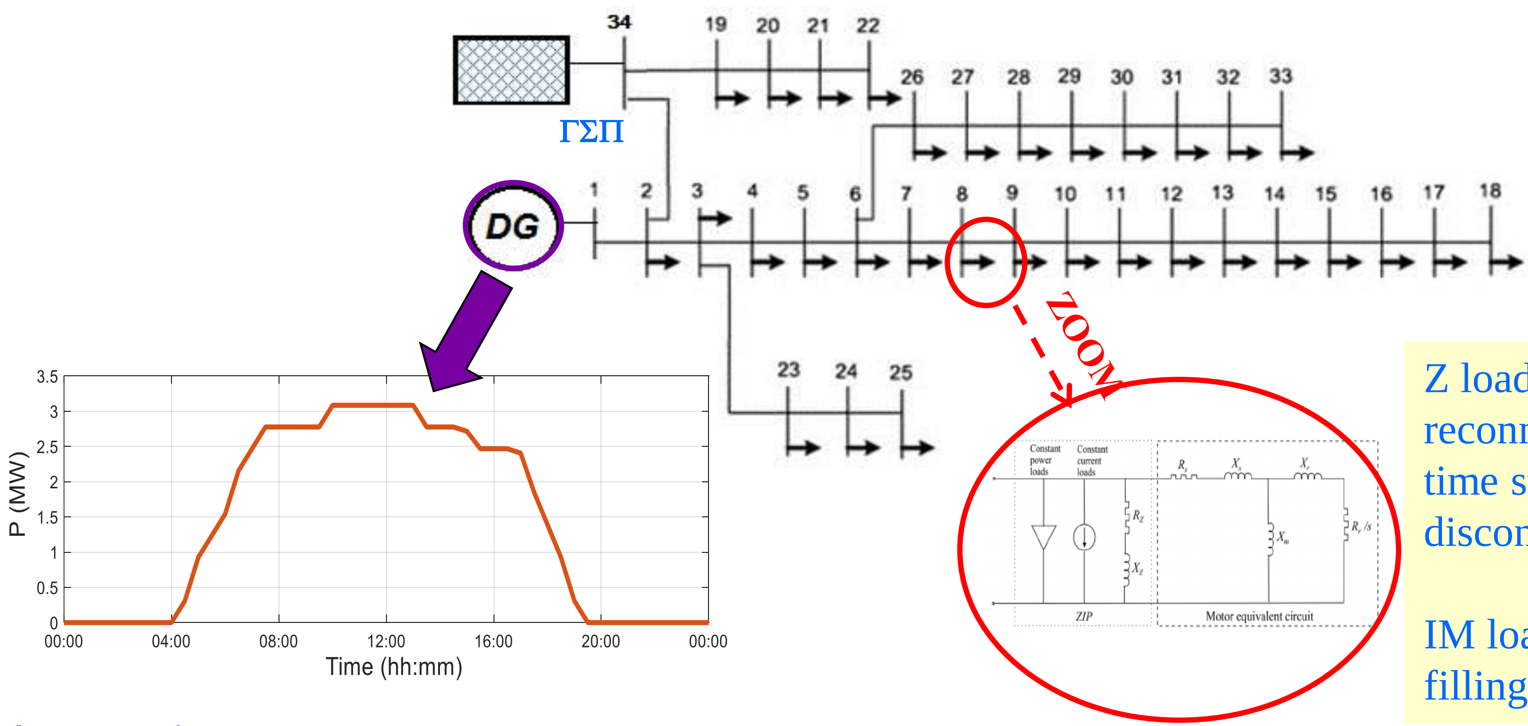



Voltage levels after shifting **domestic Z+IM** (left) and **domestic Z+IM and commercial IM** (right) load at low **time**

# Test System

## IEEE 33 bus distribution network



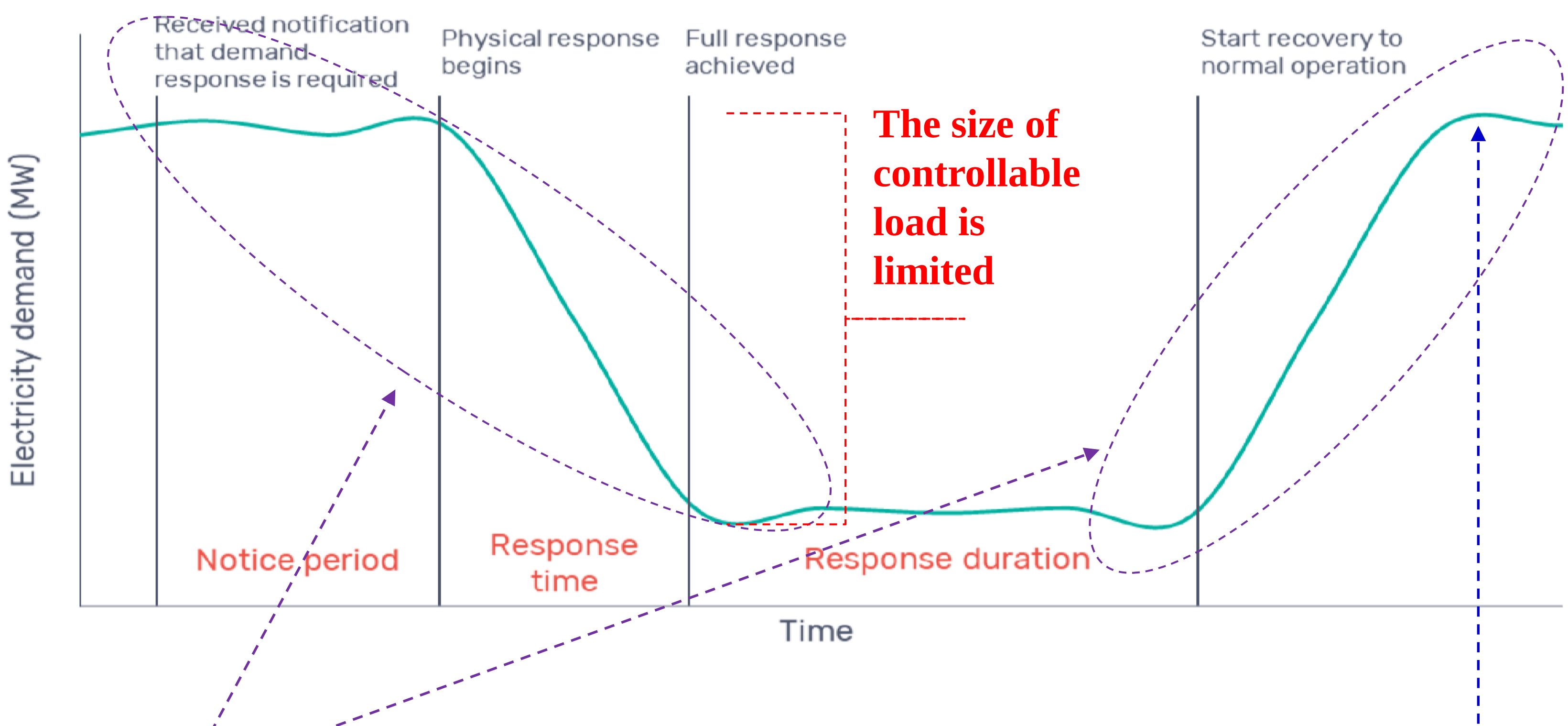

Z load payback: reconnection in 3 time steps following disconnection

IM load payback: filling load valleys

Assumptions:

- Accurate information about available renewable generation is known day-ahead
- Demand forecast and its composition are known day-ahead, based on smart meter data
- Load scheduling is performed over a 24 hour planning horizon (48 time steps of 30 min)

# Reality of demand response




**Time requirement for DSM to take effect**

**It will have to be restored at some point**

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# Case Studies

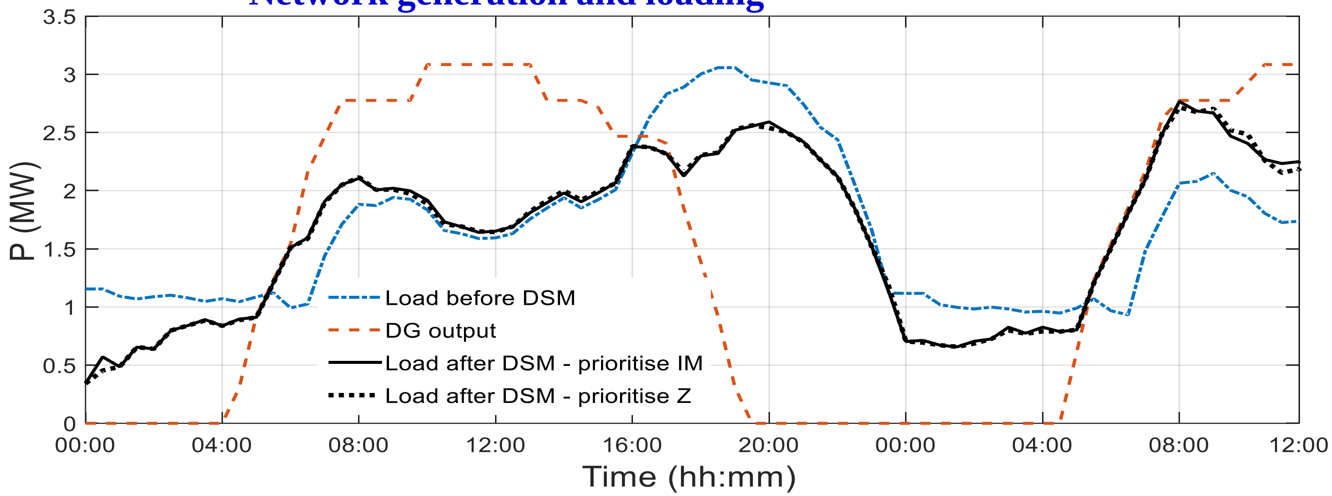
| Case Study | Subcase |
|---|---|
| 1 Base case load | A Prioritise IM in DSM |
| | B Prioritise Z in DSM |
| | C Prioritise Z in DSM with different payback load policy |
| 2 Overloaded system | Prioritise Z in DSM |
| 3 Base case load | Preserved composition |

*Jelena Ponoćko and J. V. Milanović, "Multi-objective demand side management at distribution network level in support of transmission network operation", IEEE Transactions on Power Systems, Vol. 35 , Issue 3, May 2020, pp. 1822-1833*

# Case Study 1 A&B

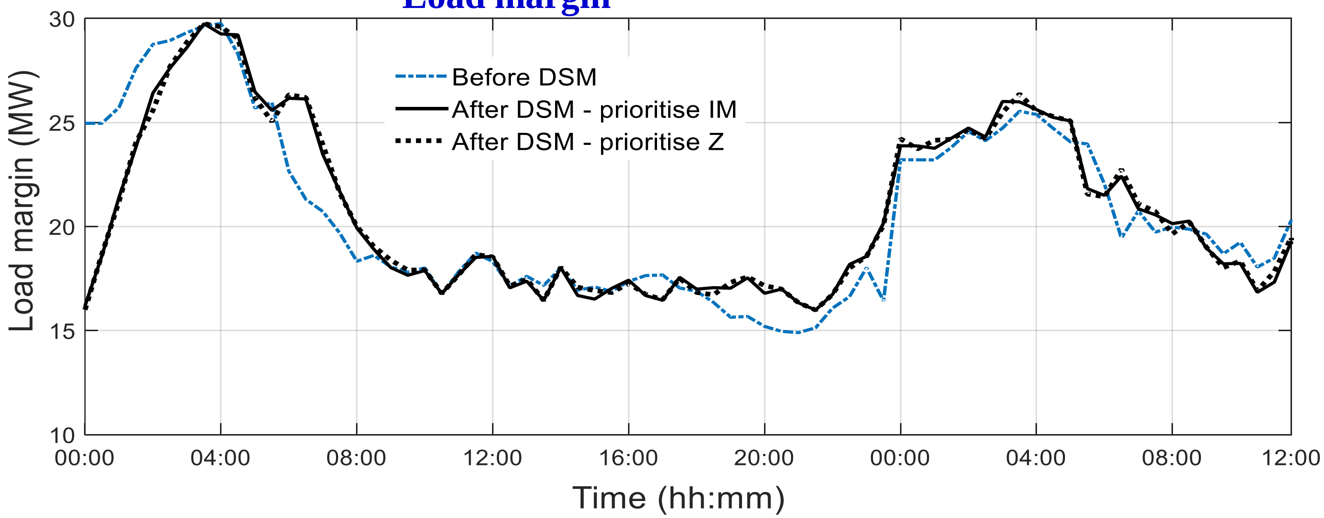
## Base case load, prioritised disconnection of IM or Z loads

### Network generation and loading




- Load-follow-generation is constrained by limited controllability and load payback.

### Load margin

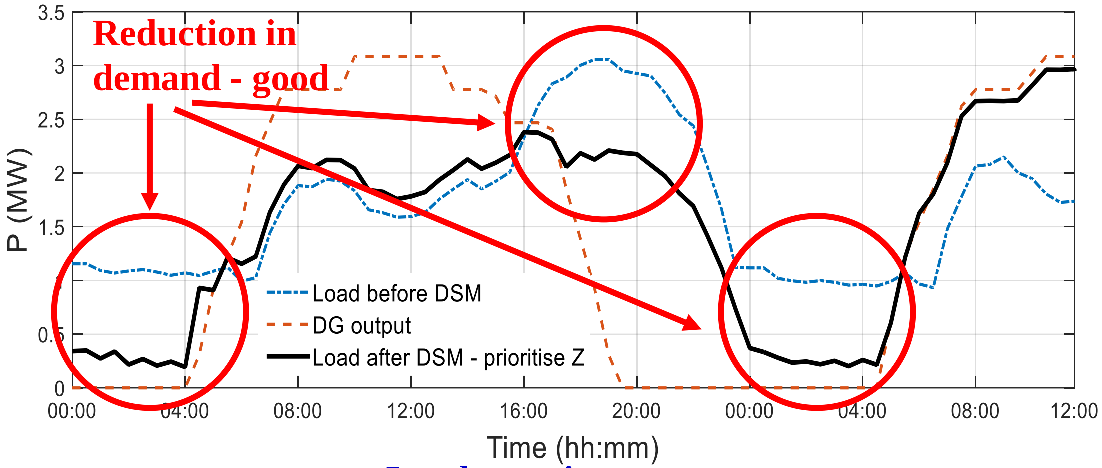



- Depending on demand composition, load margin may be deteriorated even when demand is reduced and vice versa.

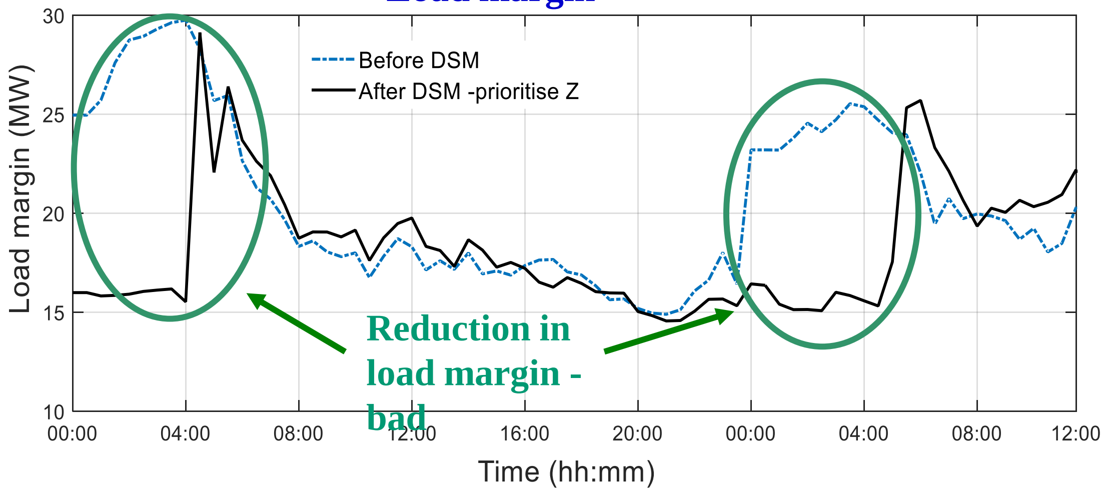
# Case Study 1 C

## Base case load, prioritised disconnection of Z loads changed load payback policy

**Network generation and loading**



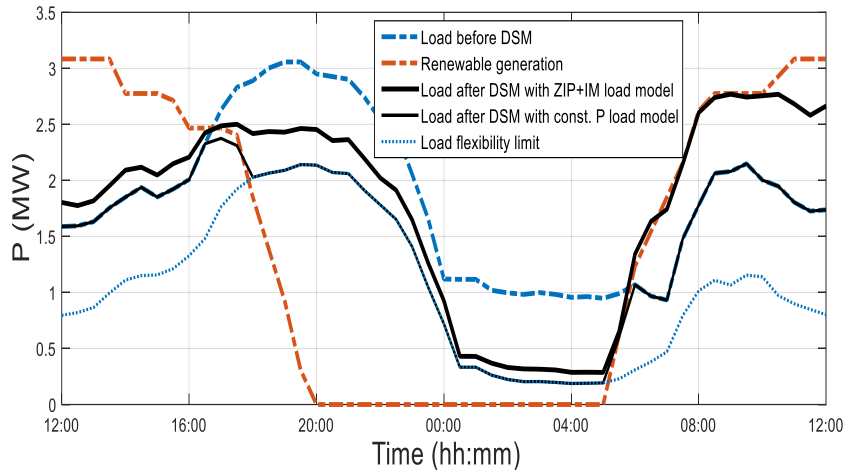

**Load margin**



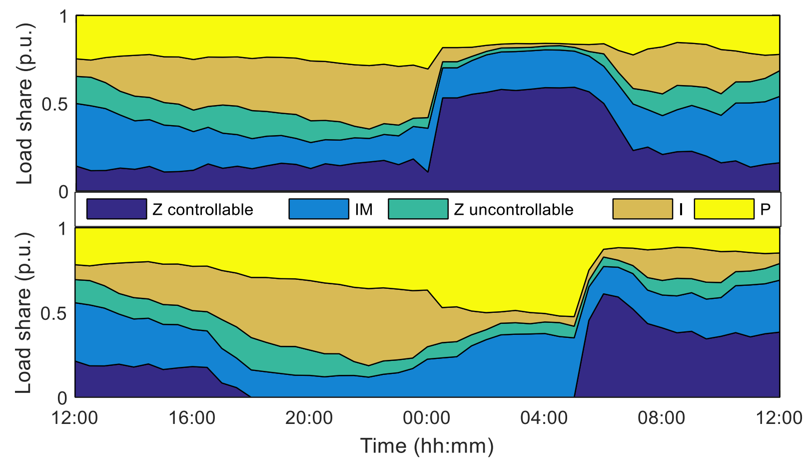

- If the Z load payback is rescheduled in the same way as the IM load, the Z load decrease is more prominent and better distributed during the day.
- This approach effectively fills the valleys of the loading curve and enables more load curtailment.
- The variation (reduction) in load margin is more pronounced, however, due to the fact that reduction in Z loads, which are beneficial for loadability, is not followed by Z load payback, so the situation is made potentially worse.

# Case Study 3

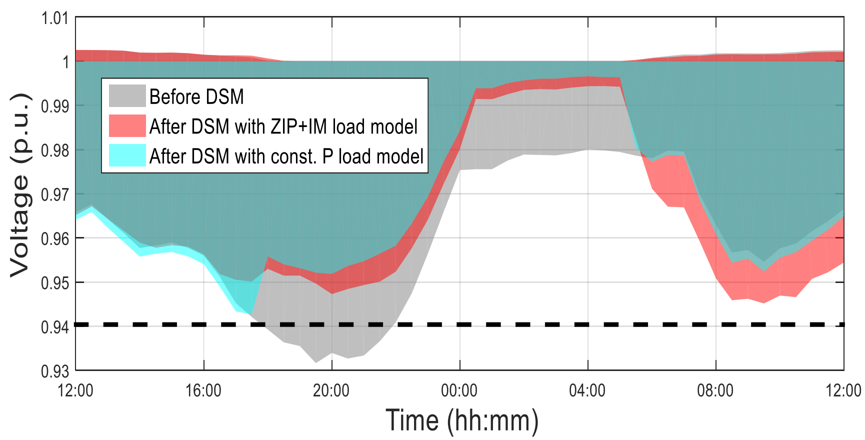
## Base case load, preserved composition



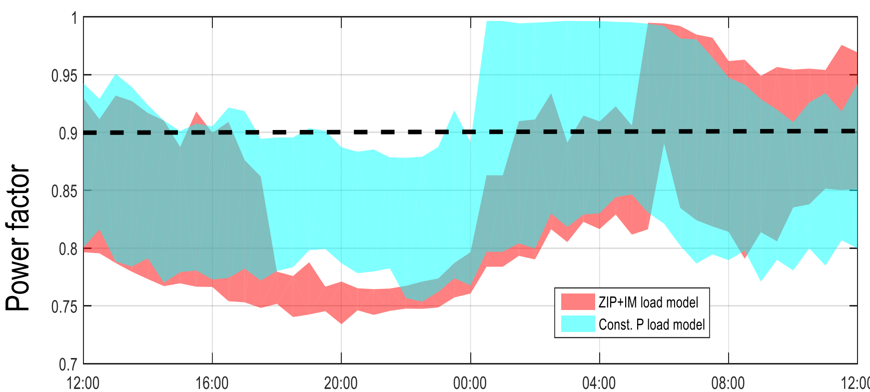

Network loading curve




Demand composition




Voltage profile in the network

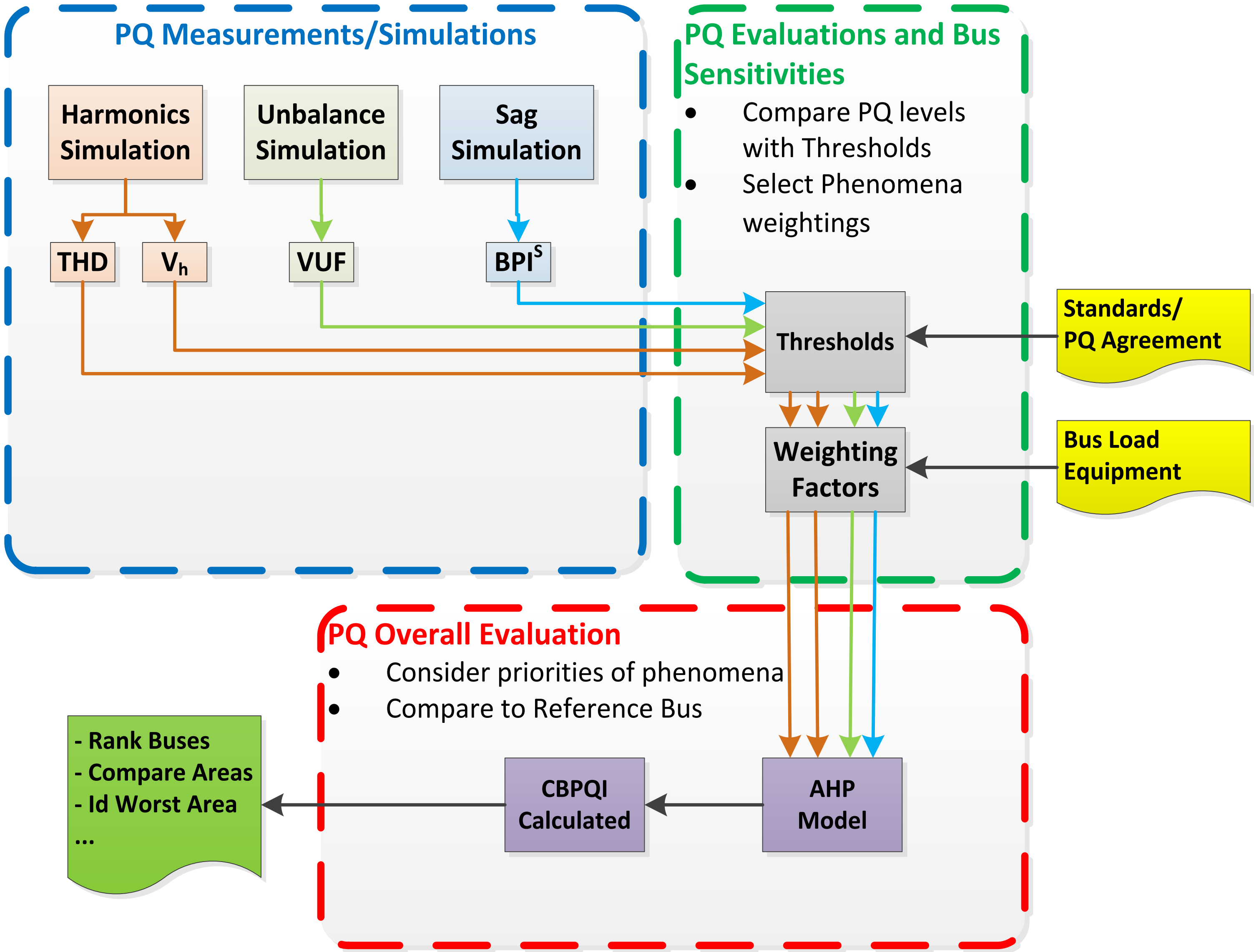



Power factors in the network

# Global monitoring and mitigation of Power Quality issues

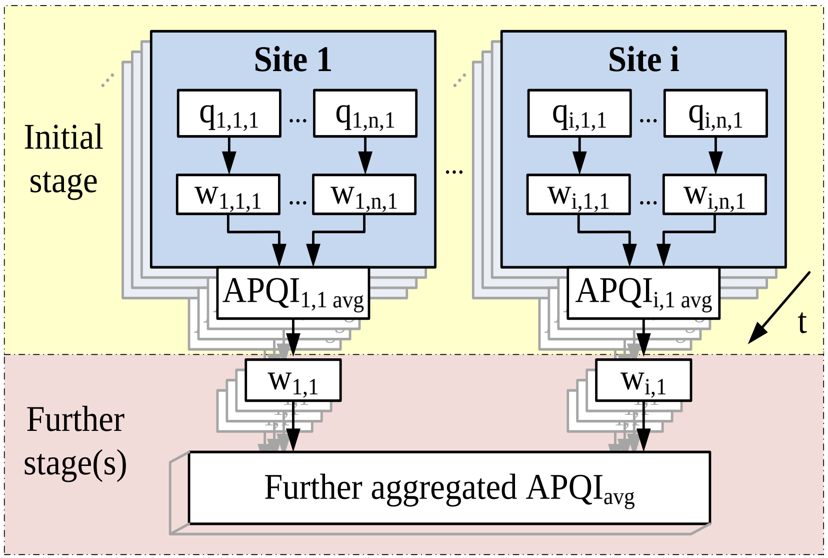
Data presentation and visualisation  for on-line tracking of system PQ performance, identification of weak areas in the netwotk,  with respect to a single or a combination of PQ parameters,  and global techno-economic mitigation of PQ isues.

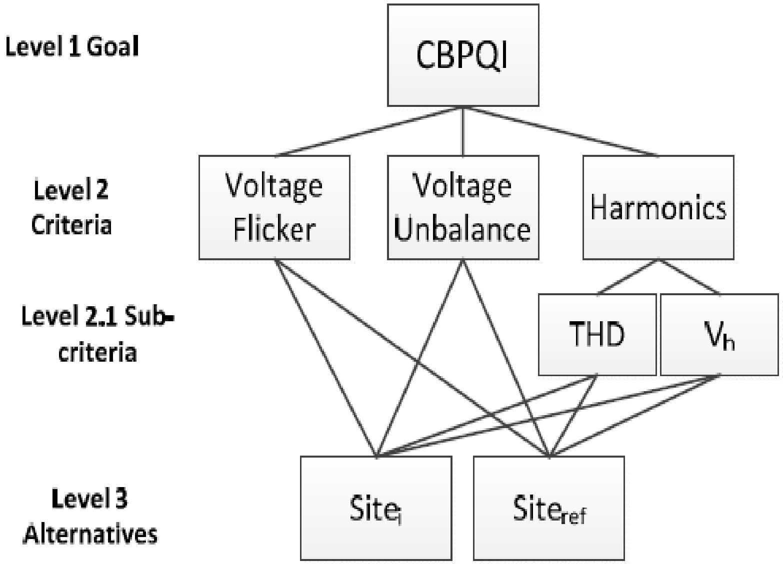
# The Framework



# Global PQ indices - 1

Both incorporate in the calculations the benchmarking levels and flexibility of considering different level of importance of PQ phenomena.




Data compression can be performed in 3d:

- Sites
- Time
- Phenomena

Different level of details and evaluating can be applied for each considered phenomenon - **Analytic Hierarchy Process (AHP)**

# Global PQ indices - 2

- Two global PQ indices, Aggregated Power Quality Index (APQI) and Compound Bus Power Quality Index (CBPQI) having different merits
- Both incorporate in the calculations the benchmarking levels and flexibility of considering different level of importance of PQ phenomena.

$$APQI_{i,t\ avg} = \frac{\sum_{n=1}^{N} [w_{i,n,t} \cdot q_{i,n,t}]}{\sum_{n=1}^{N} w_{i,n,t}}$$

$$CBPQI_i = \frac{\sum_{n=1}^{N} score_{i,n} \times p_n}{\sum_{n=1}^{N} score_{ref,n} \times p_n}$$

$$q_{i,n,t} = \left(1 - \frac{m_{i,n,t}}{g_n}\right) \cdot 100\%$$

Individual Power Quality Index

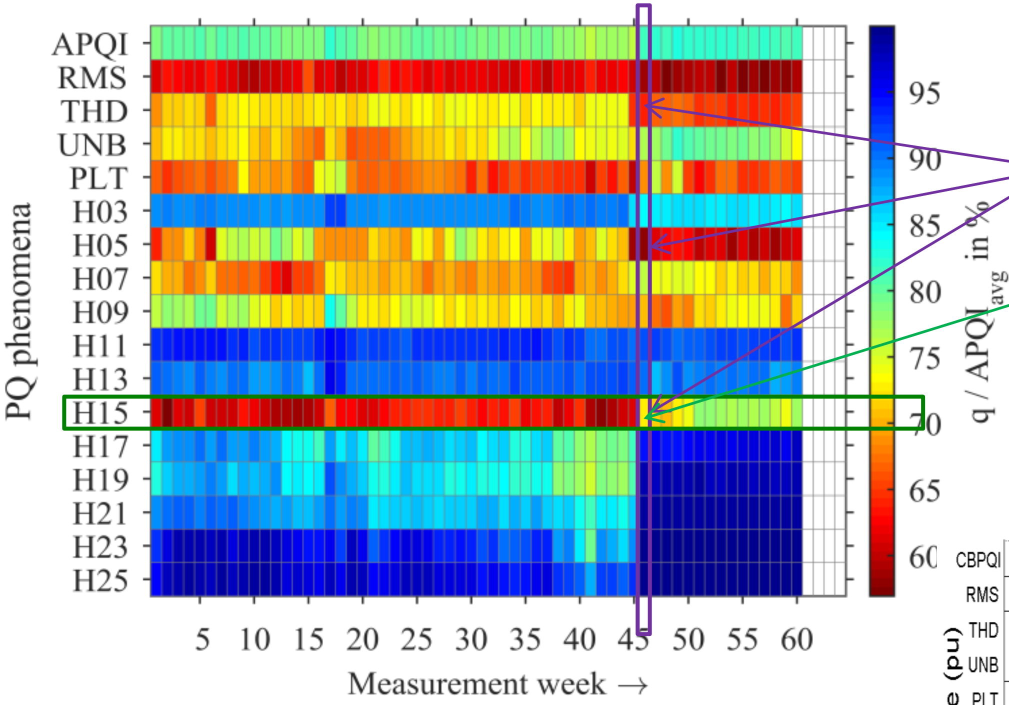
Benchmark with thresholds

Importance of phenomena

The APQI is based on the assessment of the existing reserve of an individual PQ phenomenon to a specified limit within a given time interval (e.g. according to EN 50160)

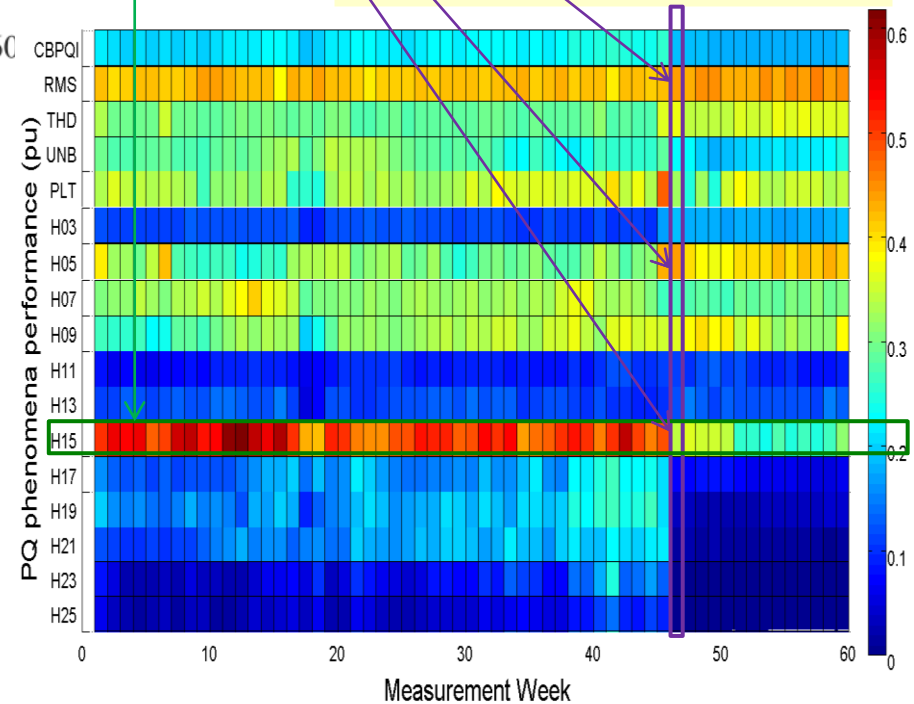
CBPQI is based on Analytic Hierarchy Process (AHP) is a "weighted" index, where all considered PQ phenomena are weighted and averaged to present the final - a ratio of the site performance and a reference performance

# Visualizing the results – single site (R1)




seasonality of performance, sudden change in PQ performance trend (e.g., week 46) and phenomenon that could be problematic (e.g., H15).

dark red - the worst site
dark blue - the best site,
black – weeks w/o data




Individual and overall average performance of PQ of one of the residential sites (global indices shown on the top row)

297 loads (industrial, commercial and domestic)

- 30 non-linear.
  - 10 at fixed locations
  - 20 change locations to reflect different contribution of customers at different times (e.g., EV)

26 distributed generators at 11 kV

- 12 photovoltaic (PV),
- 9 fuel cells
- 5 wind turbines.

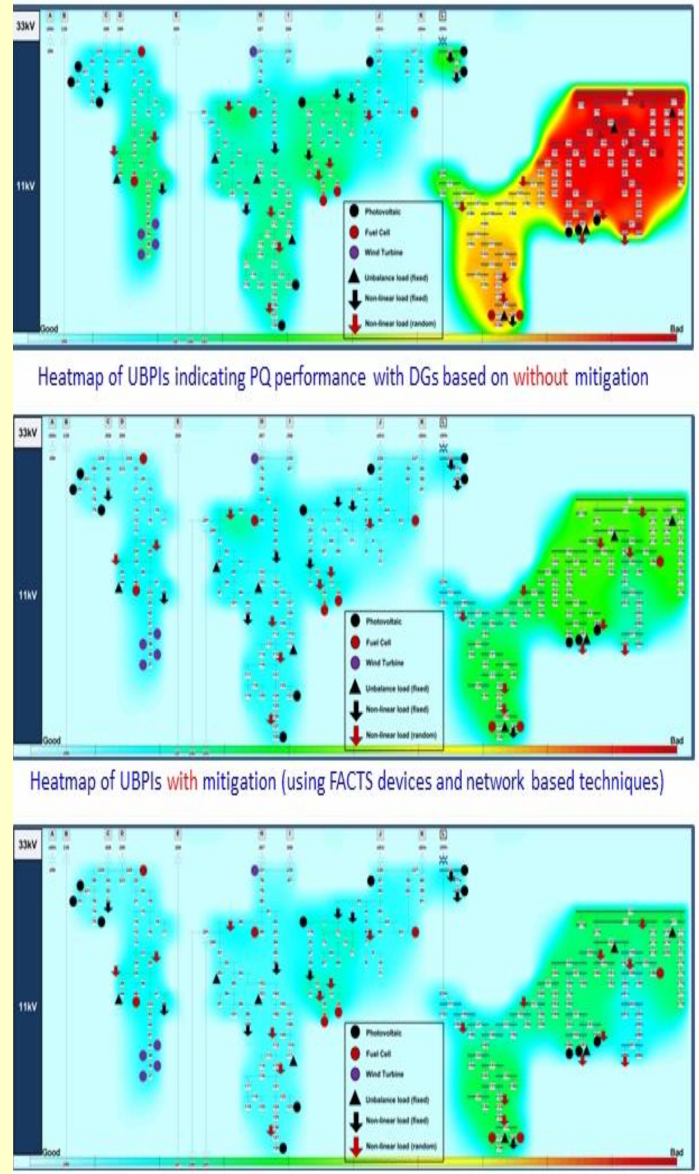
Annual hourly output curves - wind generators and PVs; the output of the fuel cells are constant.

The annual hourly loading of different types of loads.

16 representative annual operating points

- 9 based on spectral clustering of annual operating points
- 7 extreme operating points (e.g., min/max output of different DGs)

Operating Point 1




Heatmap of UBPIs indicating PQ performance with DGs based on without mitigation

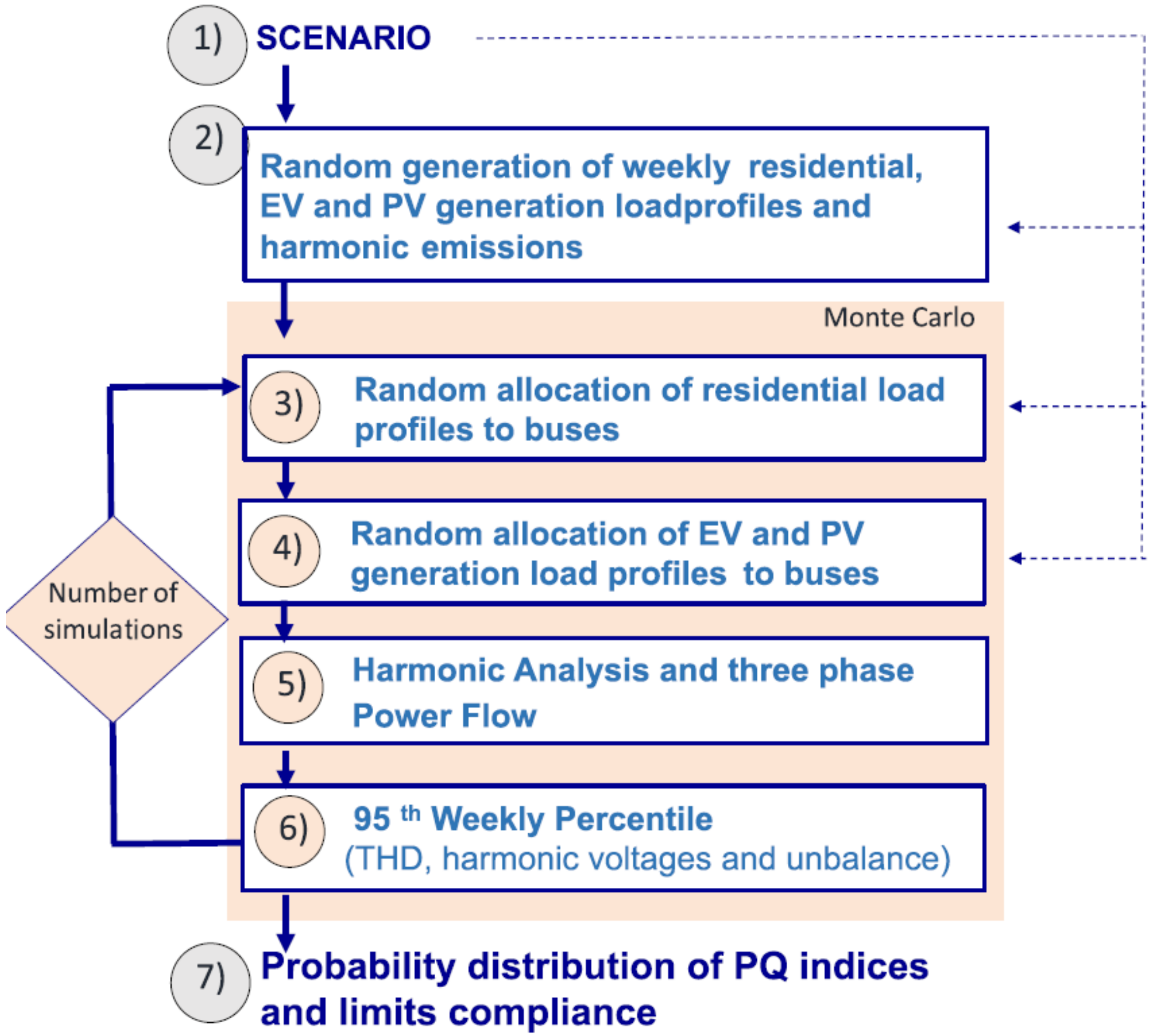
Heatmap of UBPIs with mitigation (using FACTS devices and network based techniques)

Heatmap of UBPIs with mitigation (based on economic assessment)

# The impact of EVs, nonlinear loads and PVs on power quality in residential networks

Probabilistic assessment of the combined effects of NL loads and EVs on voltage harmonic distortion and voltage unbalance in the feeders of urban residential networks with distributed photovoltaic (PV) generation considering different charging mode and different penetration level.

# Methodology

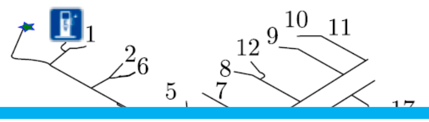


# Harmonics

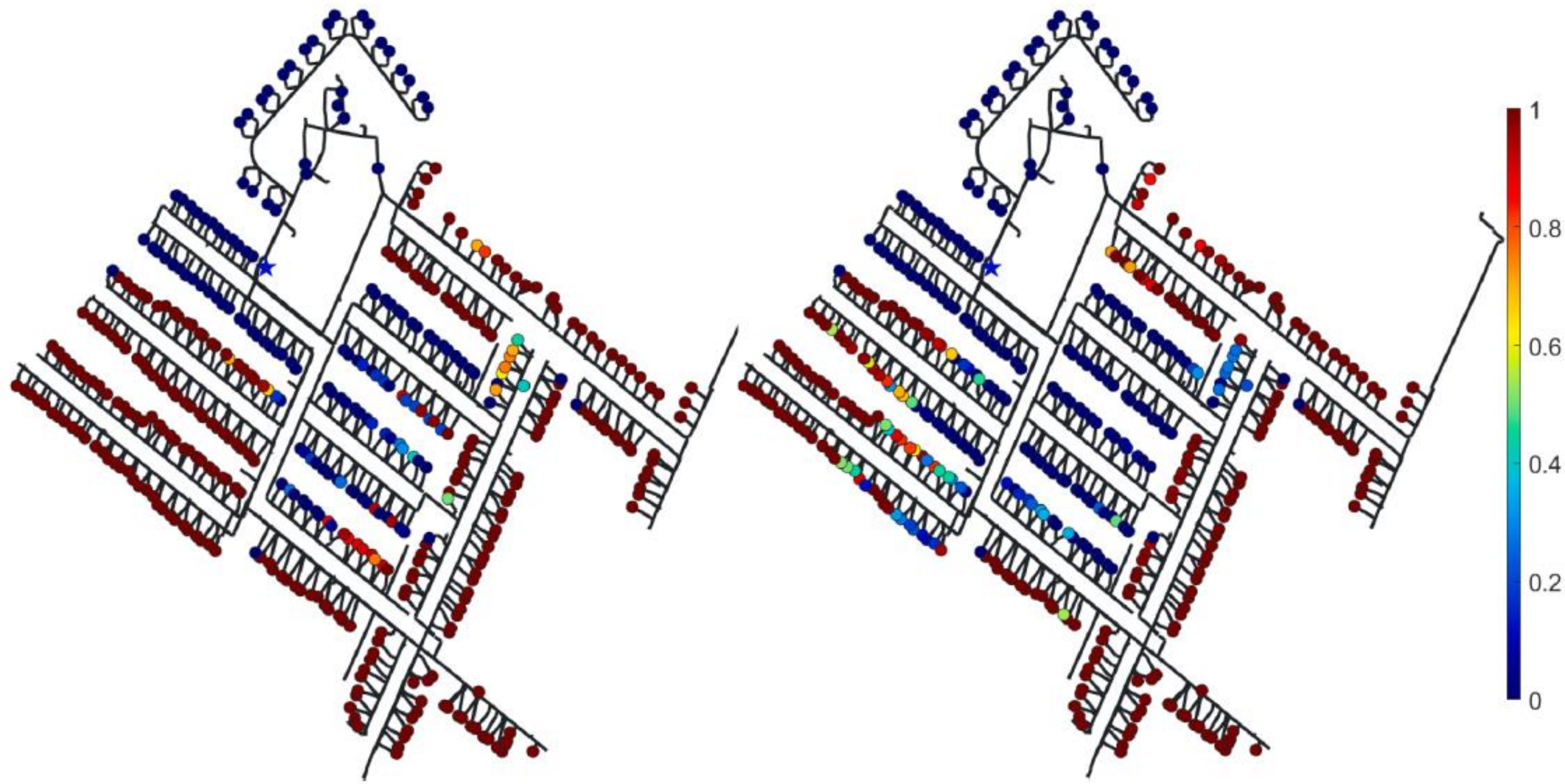
Comparison of average percentage of clients violating PQ standard with an without PV generation.

| | | THD (%) | | 3rd harmonic (%) | | Unbalance (%) | |
|---|---|---|---|---|---|---|---|
| | | No PV | With PV | No PV | With PV | No PV | With PV |
| EVs (%) | 0% | 67.78 | 63.48 | 64.24 | 62.00 | 53.33 | 51.38 |
| | 20% | 65.97 | 61.99 | 63.09 | 60.51 | 52.76 | 51.70 |
| | 40% | 65.81 | 61.99 | 63.04 | 60.72 | 53.79 | 52.23 |
| | 60% | 66.22 | 62.42 | 63.12 | 60.61 | 54.52 | 53.50 |

EV harmonic injections are randomly obtained from normal distributions of phase angle and magnitude, obtained from measurements. Measurement based charging mode - assigning stochastic charging start time and charging duration according to statistics based on real demand profile measurements




# Unbalance




(a) THD. (b) Unbalance.

The probability of exceeding THD and unbalance limits for 60% penetration of EVs in the network

Boxplot of the 95th percentile of unbalance during 160 weeksat all the buses and for different charging mode, for EVs charging at bus 53.

# Outline of presentation

- Characteristics of the evolving and future net-zero distribution power and energy networks
- Operation, modelling and control challenges of net-zero distribution networks
- Examples of the latest research results in some of the relevant areas
- Current developments in the UK related to the Electricity Distribution Price Control 2023-2028

# Developments in UK electricity distribution sector

- The new 5-year price control period, known as RIIO-ED2 starts on 1st April 2023 and lasts until 31st March 2028. (The RIIO-GD1 price control ran from April 2015- March 2023.)

(RIIO-ED2 : Revenue =Incentives + Innovation + Outputs – Electricity Distribution 2)

- Business plans for the 2023-2028 price control period for distribution networks (14 licensed DNOs owned by six different groups that cover specific geographically defined regions of Britain) submitted in December 2021
  - Electricity North West Limited
  - Northern Powergrid *(Northern Powergrid (Northeast) Limited, Northern Powergrid (Yorkshire) plc)*
  - Scottish and Southern Energy *(Scottish Hydro Electric Power Distribution plc, Southern Electric Power Distribution plc)*
  - Scottish Power Energy Networks *(SP Distribution Ltd, SP Manweb plc)*
  - UK Power Networks *(London Power Networks plc, South Eastern Power Networks plc, Eastern Power Networks plc)*
  - Western Power Distribution *(WPD (East Midlands) plc, WPD (West Midlands) plc, WPD (South West) plc, WPD (South Wales) plc)*

# Developments in UK electricity distribution sector

- The process for RIIO-ED2 started in August 2019 with an open letter published by Ofgem setting out the context and aims for the price control.

- The process involved numerous checks and balances along the way
  - The draft Business Plans submitted in **July 2021**
  - Final Business Plans on **1 December 2021**
  - Open hearings in **March 2022** – opportunity for public to comment/ask questions on BPs
  - Draft determinations on **29 June 2022** – preliminary "decisions" by Ofgem on submitted BPs
  - Final determinations on **30 November 2022** - final "decisions" by Ofgem on submitted BPs

# Developments in UK electricity distribution sector

- The main "controlling/steering entities" along the way
  - The Ofgem (the regulator) has a final say in approving proposed business plans
  - The RIIO-ED2 Challenge Group (CG)
    - established by Ofgem in September 2020 to provide effective challenge to the Business Plans (BPs) of DNOs to Ofgem, on behalf of existing and future consumers.
      - The Challenge Group is independent of Ofgem.
  - Company specific Customer Engagement Groups (CEGs)
    - established by individual companies on Ofgem request, May-September 2019 to provide effective challenge to the DNOs throughout the preparation of their Business Plans.
      - The CEGs are independent of the "host company" and the Ofgem.

- Both CG and CEGs submitted formal (public) reports to Ofgem in August 2021 and January 2022
- CEGs additionally submitted or are about to submit reports in August and December 2022.

# Developments in UK electricity distribution sector

The main sections of the BPs that these groups commented on:

- Net-zero
  - UK's commitment to achieve Net Zero by 2050 which will require the elimination of unabated fossil fuels in electricity generation, in land transport and in space heating
    - greater than usual **uncertainty** about the **load-related network investment** (it is difficult to know how much investment can be accurately forecast and firmly committed in investment plans now, and how much should be subject to uncertainty mechanisms which allow spending to be adjusted in the future in response to actual demand.)
- Distributed Energy Technology, Whole System and DSOs
  - **more actively managing networks**, including the full utilisation of **flexibility resources** and the use of **smart technology** and **data**;
  - there is a clear conflict of interest inherent in giving the task to the network owners, since **the optimum solution would almost certainly lead to a reduced requirement for network assets**

# Developments in UK electricity distribution sector

- Costs and affordability
  - **Delivering Net Zero at least cost**
  - **DNOs' expenditure plans**
    - The plans propose significant risk contingencies, allowing for some substantial (in billions) additional costs to be passed through if uncertainty mechanisms (UM) are triggered.
      - The use of UM will significantly decrease the risks that the companies face overspending their revenue allowances and should be reflected in the cost of capital allowances
- Other outputs
  - **Reliability and resilience**
  - **Environmental Action Plans**
    - setting out how it proposes to reduce its own business carbon footprint and its impact on the environment
  - **Vulnerability**
    - companies' strategies for supporting consumers in vulnerable circumstances

# Developments in UK electricity distribution sector

- Consumer Value Propositions
  - option of setting out proposals for activities which go **beyond minimum requirements** and beyond the functions typically undertaken by a DNO as business as usual and which will lead to **benefits to consumers**
    - DNOs offered a total of 24 Consumer Value Propositions (CVPs), CG rejected 20

- Finance
  - whether companies are **financeable** under Ofgem’s Working Assumptions which include a cost of equity allowance of 4.65% and a cost of debt allowance of 2.09%

**Illustrative statement at the beginning of BPs:**
**“We’ll reduce our part of bills by an average of up to £XY.PQ a year compared to the current price control, keeping costs as low as possible for customers. We’ll also deliver net social benefits of more than £A.B bn to customers …..”**

# Developments in UK electricity distribution sector

## Comparative summary of quality of ED2 Business Plans

| | | | | | | |
|---|---|---|---|---|---|---|
| Track record from RIIO-ED1 | 4 | 3 | 2 | 2 | 4 | 3 |
| Scenarios and forecasts | 3 | 4 | 4 | 2 | 3 | 4 |
| Totex: LRE, incl. anticipatory investment | 4 | 2 | 4 | 3 | 4 | 4 |
| Totex: NLRE, incl. asset health | 3 | 3 | 2 | 2 | 2 | 3 |
| Totex: Network operating costs | 4 | 4 | 3 | 2 | 5 | 5 |
| Totex: Non-operational costs | 1 | 2 | 3 | 2 | 3 | 2 |
| Totex: Ongoing efficiency and RPE | 3 | 2 | 1 | 2 | 4 | 2 |
| Totex: Uncertainty mechanisms | 2 | 3 | 2 | 2 | 4 | 4 |
| Outputs: DSO and digitalisation strategy | 4 | 2 | 3 | 3 | 5 | 2 |
| Outputs: Whole system strategy | 2 | 2 | 2 | 4 | 4 | 2 |
| Outputs: EAP | 3 | 3 | 4 | 3 | 4 | 3 |
| Outputs: Vulnerability strategy | 3 | 3 | 4 | 3 | 4 | 4 |
| Outputs: Reliability | 3 | 3 | 3 | 3 | 4 | 3 |
| Finance | 2 | 3 | 3 | 3 | 4 | 2 |

| | |
|---|---|
| 5 | High ambition, well justified |
| 4 | Some gaps in ambition and justification |
| 3 | Average ambition and justification |
| 2 | Limited ambition and justification |
| 1 | Low ambition, poorly justified |

*RIIO-2 Challenge Group independent report for Ofgem on RIIO-ED2 business plans, 8 February 2022*, *file:///C:/Users/mchssjvm/Desktop/Downloads/RIIO-ED2%20Challenge%20Group%20Report%20-%20February%208%2020221644319075724.pdf*

# Instead of conclusion

Challenges posed by forthcoming net-zero power/energy systems call for close collaboration between:

- industry,
- regulator,
- research funding agencies and
- research institutions

to develop and deliver appropriate national *training*, research, development, demonstration and deployment programme to facilitate timely, affordable and inclusive transition to sustainable future.