IEEE PES ISGT Asia 2022

The Future of DER Hosting Capacity and Operating Envelopes

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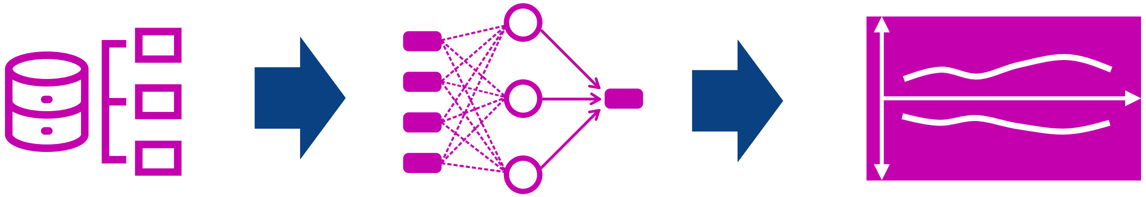
Keynote Speaker

Outline

1. Voltage Calculations and DER[1]
2. Our Model-Free Approach
3. Smart Meter Data
4. Model-Free Calculations
5. Model-Driven vs Model-Free
6. Key Remarks



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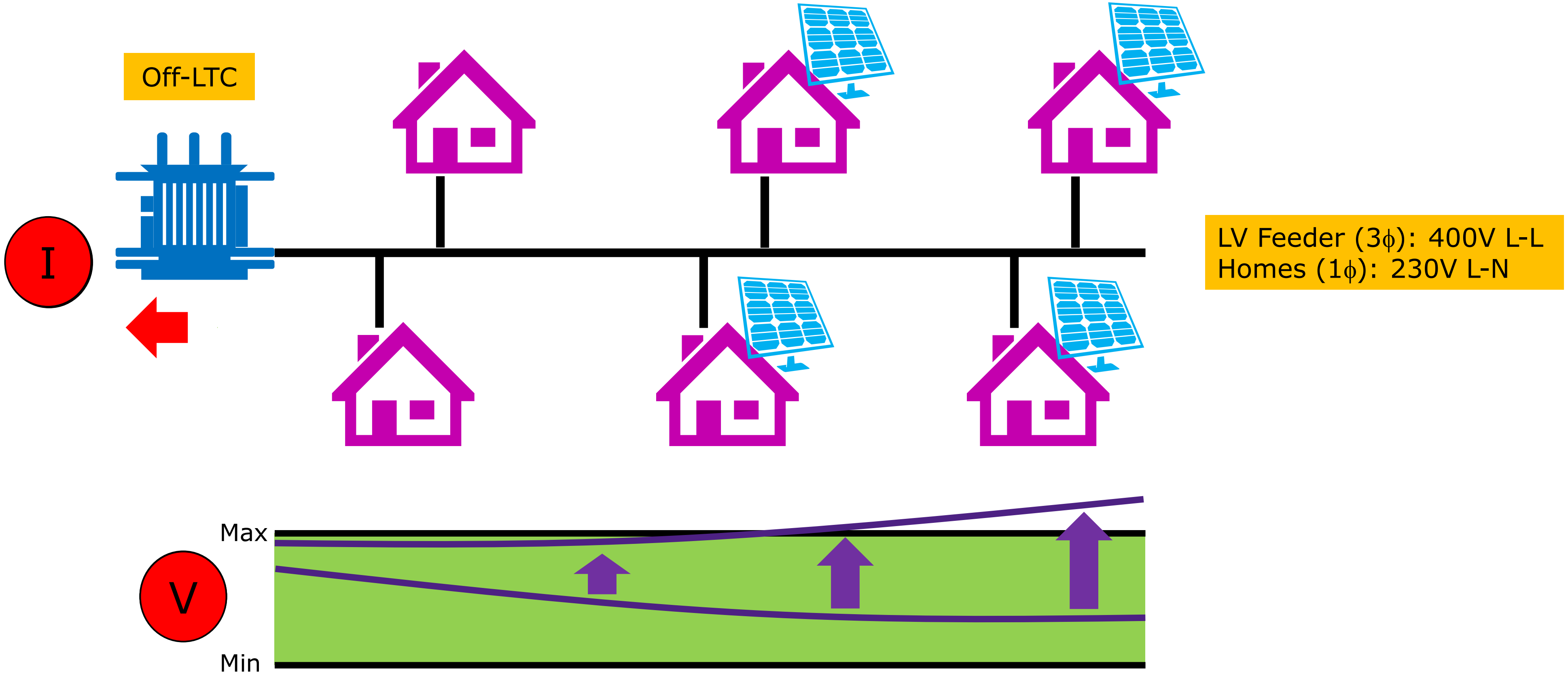
[1] DER = Distributed Energy Resources

1 Voltage Calculations and DER

1 Voltage Calculations and DER

DER & Low Voltage (LV) Networks

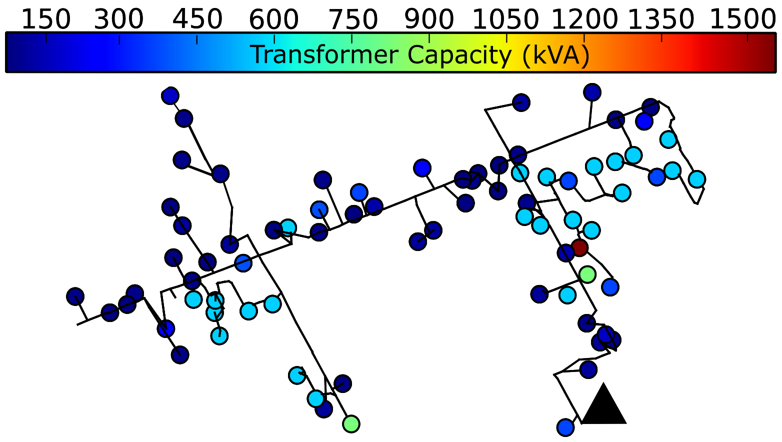


LV Feeder (3ϕ): 400V L-L
Homes (1ϕ): 230V L-N

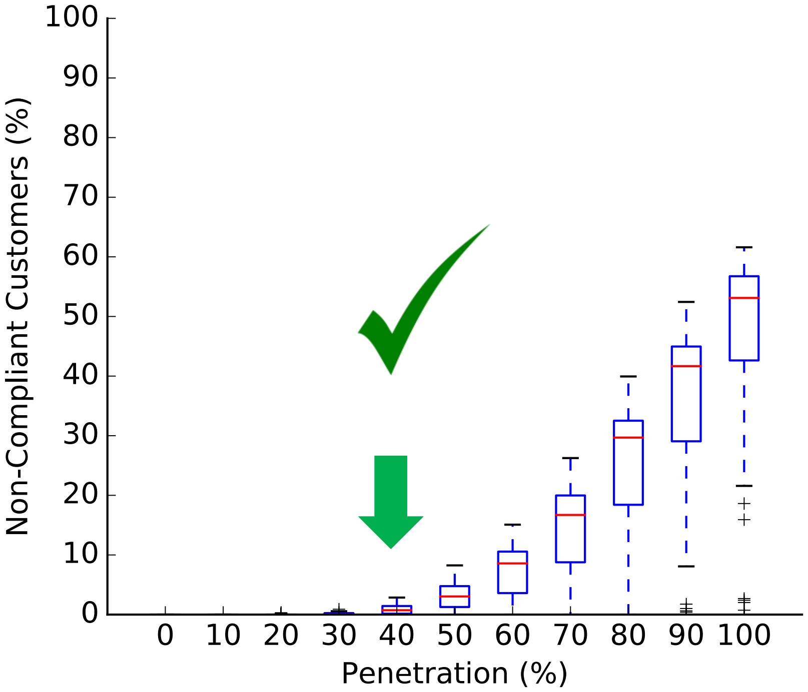
How can we determine the maximum exports (or imports) that our networks can withstand?

1 Voltage Calculations and DER

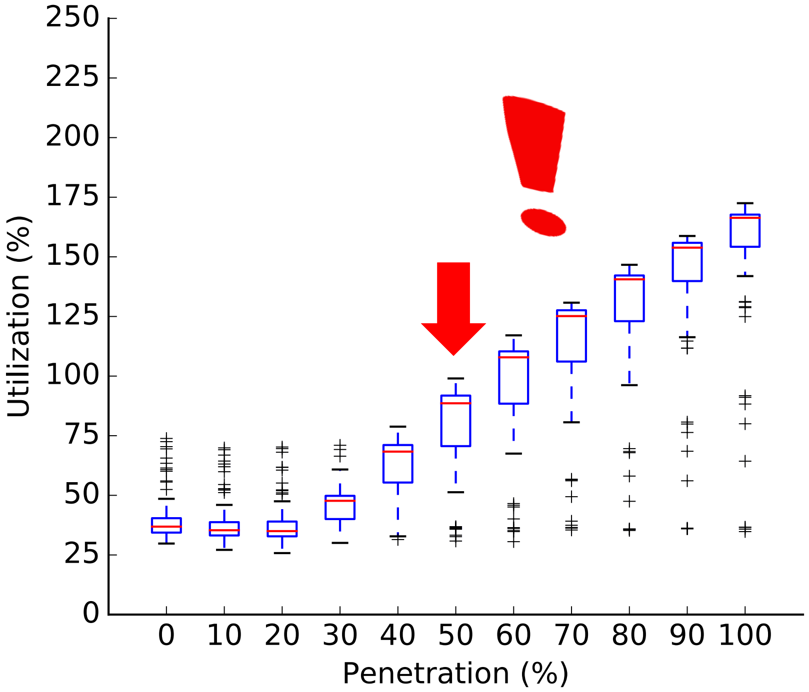
Hosting Capacity



LV Voltage Issues



HV Conductors Congestion

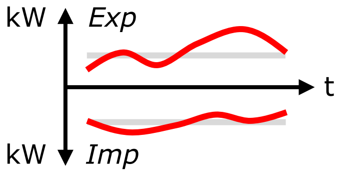


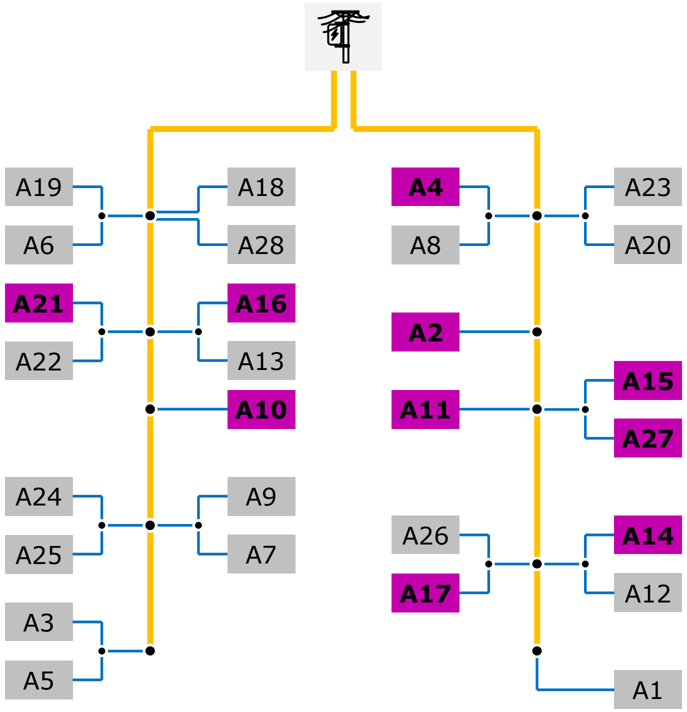
Exploration of DER scenarios → Power flows are essential

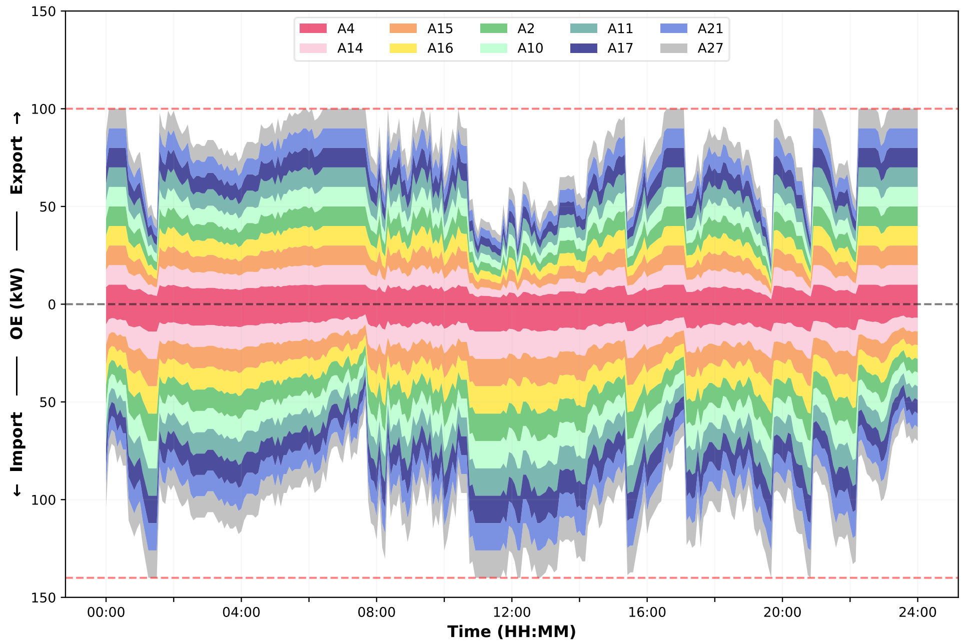
1 Voltage Calculations and DER

Operating Envelopes

- Time-varying maximum power imports/exports at the meter
- Calculated to ensure network integrity. Values may depend on location.







Again, exploration of DER scenarios → Power flows are essential

1 Voltage Calculations and DER

Today (Ideally)

Scenario to Check

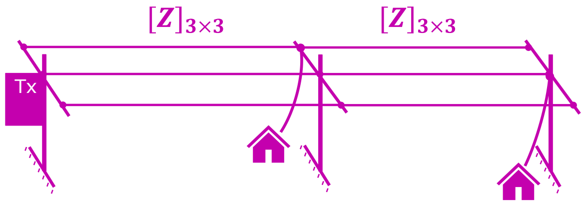
Min/Max Demand
(P_{cust}, Q_{cust})

DER exp/imp
(P_{DER}, Q_{DER})

Voltage at the ref bus

Electrical LV Network Model

Topology
Impedances ($[Z]_{3\times3}$)
Phase Grouping (a, b, c)



3ϕ Power Flow

E.g., OpenDSS ☺

Voltages

V of customers

Voltages OK?

Yes → *Harder Scenario*

No →

- ✓ Hosting Capacity (Planning)
- ✓ Operating Envelopes (Operation)
- ✓ Etc.

To achieve this, distribution companies are producing LV network models
→ **Can be time-consuming, expensive and not 100% accurate**[2]

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[2] Errors in topology, phase grouping, impedances, neutral, grounding, etc.

1 Voltage Calculations and DER

Today (Ideally)

Scenario to Check

Min/Max Demand
(P_{cust}, Q_{cust})

DER exp/imp
(P_{DER}, Q_{DER})

Voltage at the ref bus

Electrical Network Model

3ϕ Power Flow

What if we could calculate voltages without electrical models?

Voltages

V of customers

Voltages OK?

Yes

Harder Scenario

No

- ✓ Hosting Capacity (Planning)
- ✓ Operating Envelopes (Operation)
- ✓ Etc.

To achieve this, distribution companies are producing LV network models
→ **Can be time-consuming, expensive and not 100% accurate**[2]

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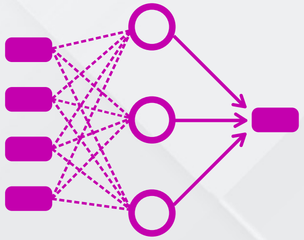
[2] Topology, phase grouping, impedances, neutral, grounding

2 Our Model-Free Approach



Electrical Model-Free Voltage Calculations Using Neural Networks and Smart Meter Data, IEEE Trans. on Smart Grid (*Under Review*)

Deliverables 1-2-3a Model-Free Voltage Calculations and Operating Envelopes, Report, 2022 (ResearchGate)

Deliverable 0: Concept, Smart Meter Data, and Initial Findings, Report, 2022 (ResearchGate)

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Calculating Voltages Without Electrical Models: Smart Meter Data and Neural Networks, CIRED 2021 (ResearchGate)

2 Our Model-Free Approach

Scenario to Check

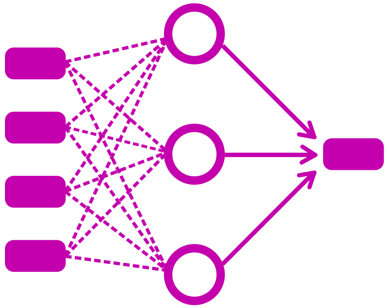
Model-Free Voltage Calculations

Voltages

Min/Max Demand
(P_{cust}, Q_{cust})

DER exp/imp
(P_{DER}, Q_{DER})

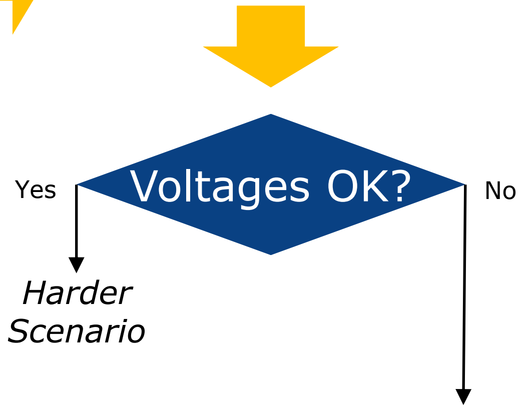
~~Voltage at the ref bus~~



Clever stuff to capture the physics ☺

Neural Network trained with historical Smart Meter data

V of customers



Voltages OK?

Yes

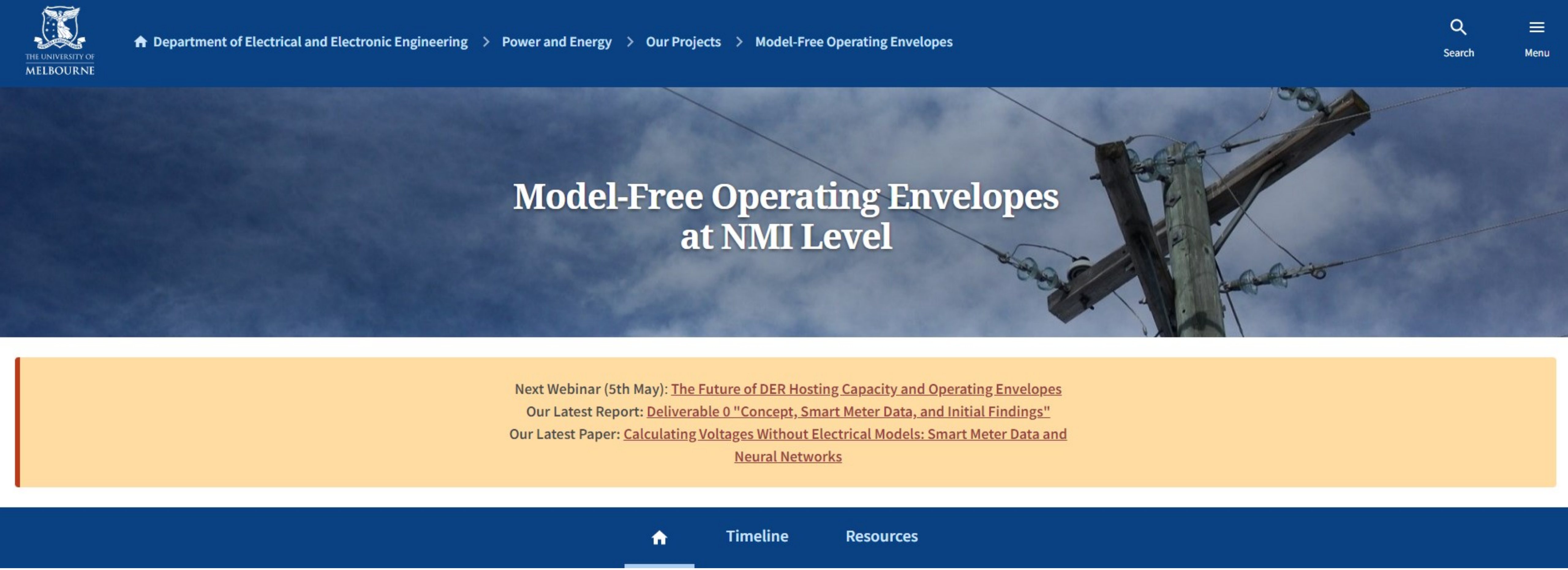
Harder Scenario

No

- ✓ Hosting Capacity (Planning)
- ✓ Operating Envelopes (Operation)
- ✓ Etc.

✓ **Removes time and cost** associated with the production of **LV electrical models**

✓ **Extremely quick alternative** to power flow-based techniques



Model-Free Operating Envelopes at NMI Level

Next Webinar (5th May): The Future of DER Hosting Capacity and Operating Envelopes
Our Latest Report: Deliverable 0 "Concept, Smart Meter Data, and Initial Findings"
Our Latest Paper: Calculating Voltages Without Electrical Models: Smart Meter Data and Neural Networks

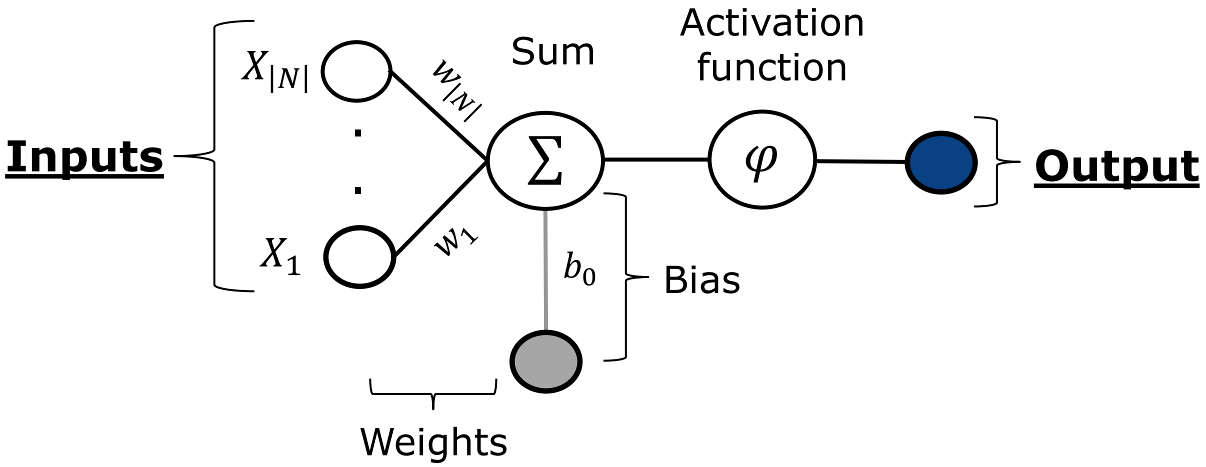
C4NET
Centre for New Energy Technologies

https://electrical.eng.unimelb.edu.au/power-energy/projects/model-free-operating-envelopes

2 Our Model-Free Approach

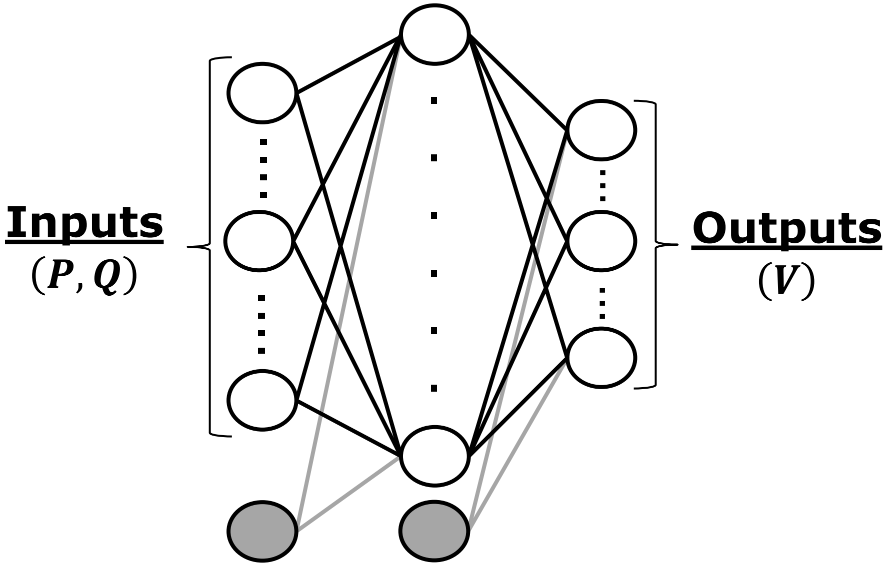
Neural Networks to Capture the Physics

Single Neuron



$$Y(\boldsymbol{X},\boldsymbol{W}) = \varphi\left(\sum_{n \in N} w_n X_n + b_0\right)$$

Neural Network (NN)



$$\boldsymbol{V} = \boldsymbol{f}_{NN}(\boldsymbol{P},\boldsymbol{Q},\boldsymbol{W})$$

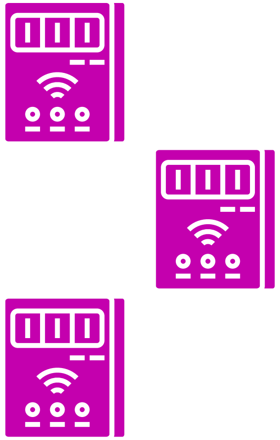
Captures the non-linearities

Training: Using historical data, we produce a NN that links inputs (P,Q) and outputs (V).
Once trained: We can calculate V based on a set of P,Q. ☺

2 Our Model-Free Approach

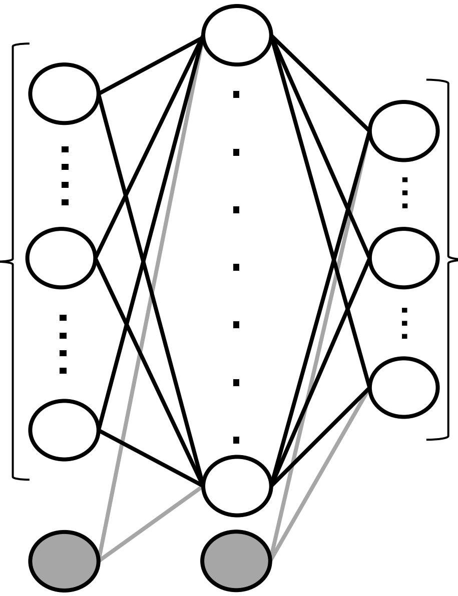
Methodology 1/4

I



Smart meter data (P, Q, V)

II

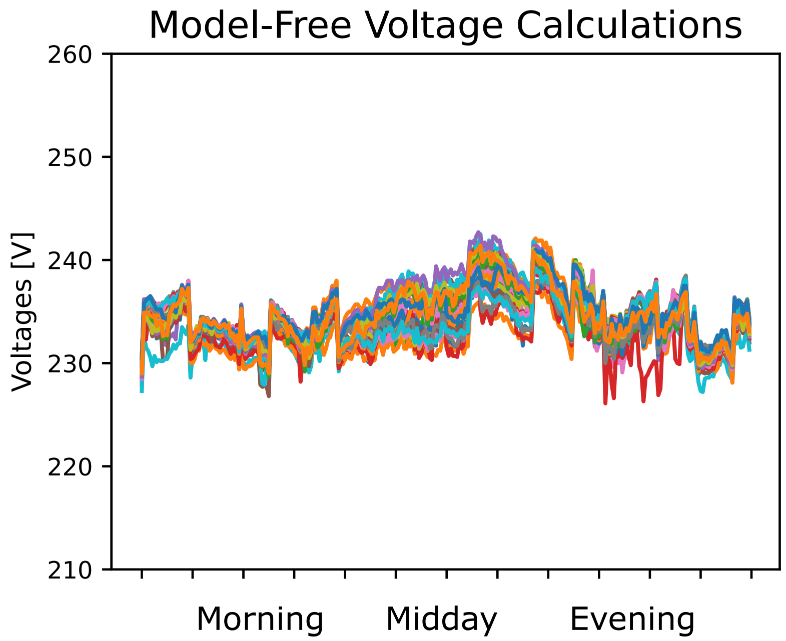


Inputs
(P, Q)

Outputs
(V)

Neural Network Production

III



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2 Our Model-Free Approach

Methodology 2/4

I. Smart Meter Data

Step 1: Collect the historical per-phase smart meter data

Step 2: Pre-process the historical smart meter data to obtain P and Q values

Step 3: Build training data set (set of instances of P, Q, and V)

II. Neural Network Selection

Step 4: Define hyperparameters and NN characteristics (using our *recipe*)

- Input layer dimension (twice the number of customers, $2|C|$)
- Output layer dimension (number of customers, $|C|$)
- Output layer activation function (Linear)
- Loss function (MSE)
- Scaler ([0,1])
- Optimiser (ADAM)

2 Our Model-Free Approach

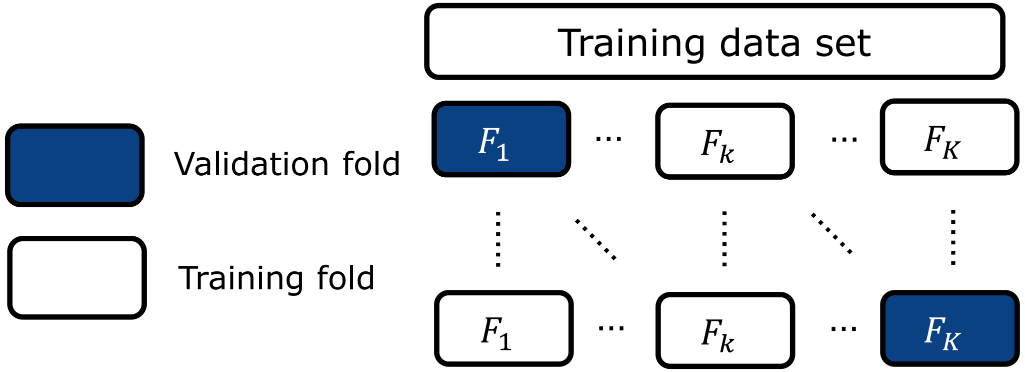
Methodology 3/4

Step 5: Define search spaces for the remaining hyperparameters (using our *recipe*)

- 1 hidden layer (part of our *recipe*)
- Neurons and activation functions in each hidden layer
- Learning rate, batch size, epochs

Step 6: K-fold cross validation considering combinations of hyperparameters defined in Step 5

- Select hyperparameter combination with the **lowest** $\boldsymbol{RMSE_{Kfold}}$



$$RMSE_{Kfold} = \frac{1}{K}\left(\sum_{k=1}^{K} RMSE_{val_k}\right)$$

2 Our Model-Free Approach

Methodology 4/4

Step 7: 10 NNs are trained from scratch with the hyperparameters defined in Step 6

- **NN with the lowest $RMSE$→ Final NN ready for voltage calculations ☺**

III. Model-Free Voltage Calculations

Step 8: Voltages can be calculated by specifying P and Q of customers ☺

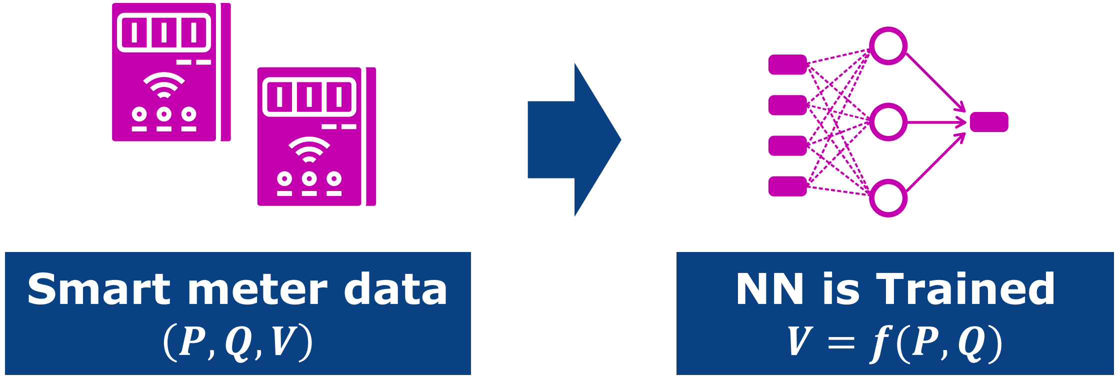
Implementation: Open-Source Software

K python™ TensorFlow

2 Our Model-Free Approach

Summary

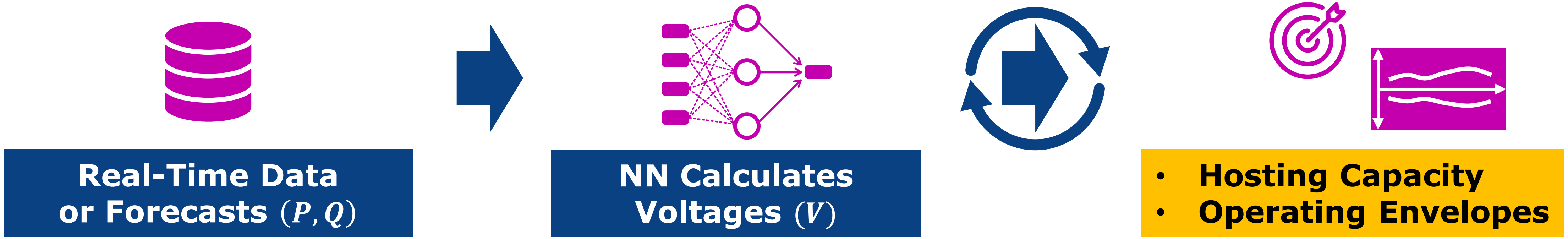
1. **Development**: Production of the Neural Network (NN) using our *recipe*



Smart meter data (P, Q, V)

NN is Trained $V = f(P, Q)$

2. **Application**: Calculation of Hosting Capacity, Operating Envelopes, etc.



Real-Time Data or Forecasts (P, Q)

NN Calculates Voltages (V)

- **Hosting Capacity**
- **Operating Envelopes**

2 Our Model-Free Approach

Data Requirements (Prod of NN)

- Smart Meter Data from all customers fed by the same transformer
  - We can still produce good results with missing data (e.g., C&I customers)
- Smart Meter Data needs to be good
  - No topological changes in the historical data (otherwise the physics change)
  - All data points need to be valid and make sense → Pre-processing/filtering
- Smart Meter Data for at least 3 weeks
  - Minimum period considering 5-min data (the filtering might reduce the dataset by 20-50%)

Challenging for most distribution companies in the world**...**
but little by little **smart meters are becoming a reality** ☺

3 Smart Meter Data

3 Smart Meter Data

Overview

	Jemena	United Energy	AusNet
Distribution Transformers	3	3	2
LV Circuits	9	7	2
Single-Phase Customers	394	176	35
Three-Phase Customers	67	23	7
Date Range	01 Sep 2020 to 30 Sep 2021 (~56 weeks)	01 Aug 2020 to 31 Aug 2021 (~56 weeks)	19 Jan 2021 to 23 Aug 2021* (~30 weeks)
Voltage magnitude, V [V]	✓	✓	✓
Current magnitude, I [A]	✓	✓	✓
Power factor (-1) to (1), PF	✓	✓	-
Imaginary current, I^{imag} [A]	-	-	✓
Real current, I^{real} [A]	✓	-	✓

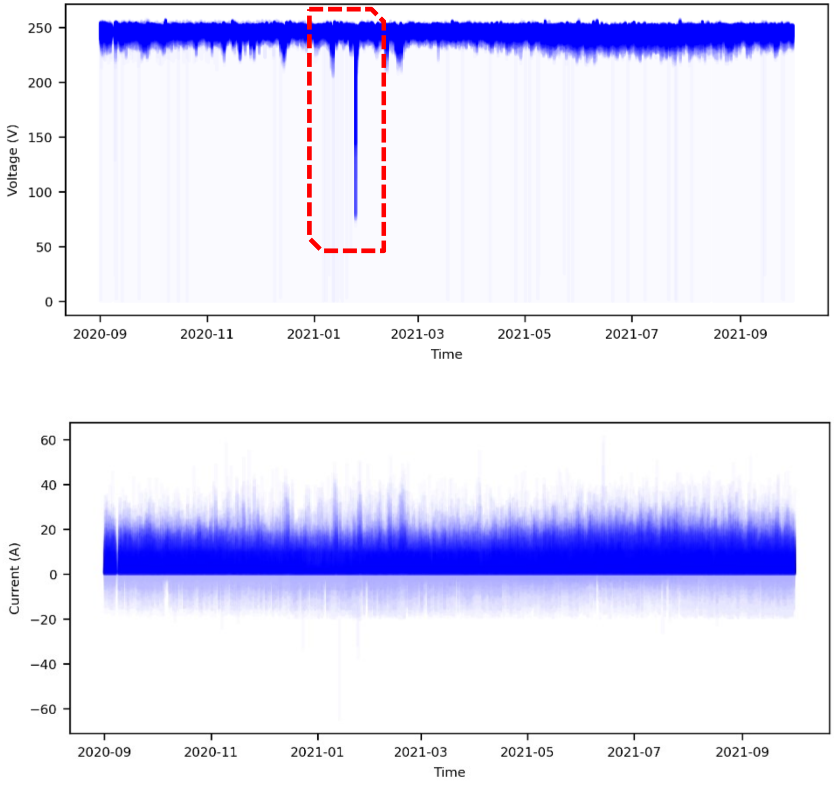
Data needs to be pre-processed (P, Q) **and filtered** (to remove noise)

* The data rage indicated is not continuous i.e., there exist a gap in the data

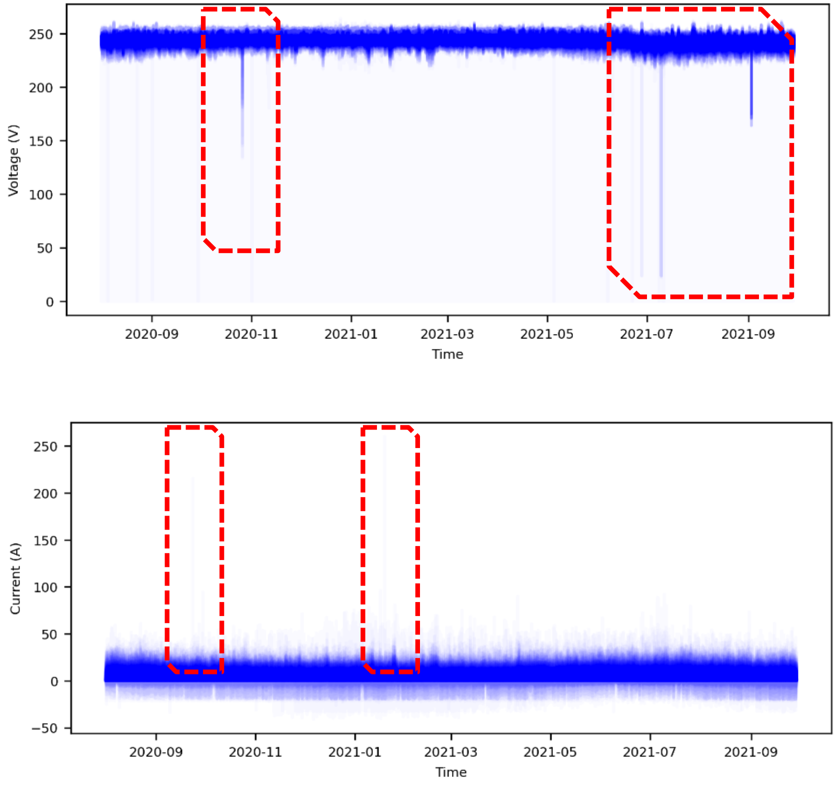
3 Smart Meter Data

Unfiltered Data: Voltage and Currents

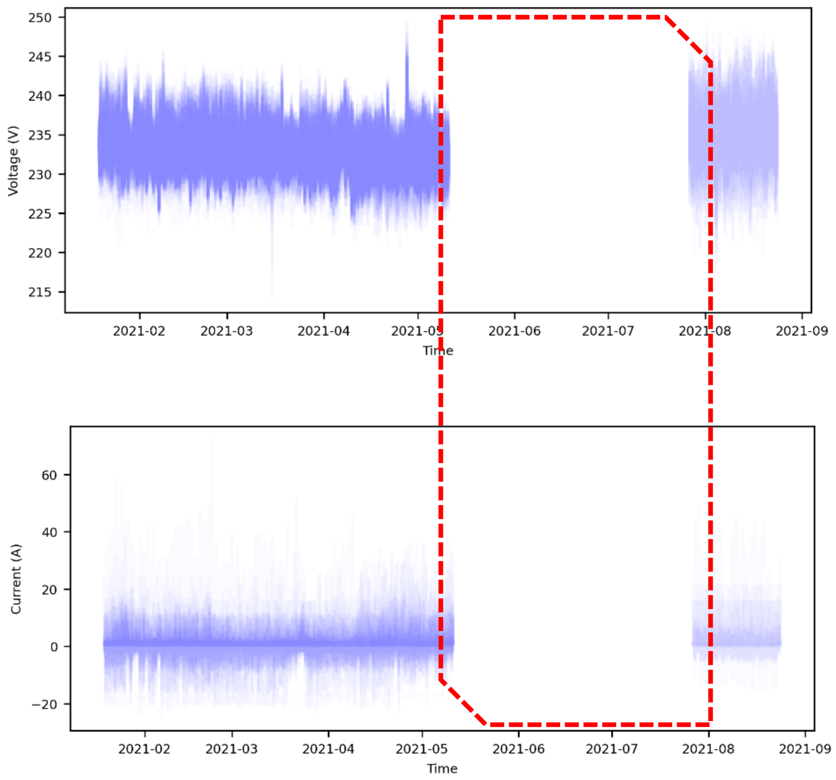
Jemena



United Energy



AusNet



Real data challenges: Abnormal voltages and currents (e.g., faults), missing data, etc.

3 Smart Meter Data

Filtering

- Filtering process to extract valid instances
  - Remove instances with zero values on voltages
  - Remove incomplete instances (i.e., no measurements for all customers)

	Jemena			United Energy			AusNet	
	SubA	**SubB**	**SubC**	**SubA**	**SubB**	**SubC**	**Site A**	**Site B**
Total instances	113,760	113,760	113,760	122,111	122,111	122,111	32,256	8,064
Valid instances	88,755	59,979	80,724	117,475	111,235	72,463	29,441	5,676
Valid instances (%)	78.02	52.72	70.96	96.20	91.09	59.34	91.27	70.39

- Final filter due to small changes in the number of customers (Jemena)

	Jemena			United Energy			AusNet	
	SubA	**SubB**	**SubC**	**SubA**	**SubB**	**SubC**	**Site A**	**Site B**
Final Valid Instances	80,763	44,926	42,490	117,475	111,235	72,463	29,441	5,676
Equivalent Weeks	40.06	22.28	21.08	58.27	55.18	35.94	14.60	2.81

Final valid instances (a few weeks only) → **NN training and testing**

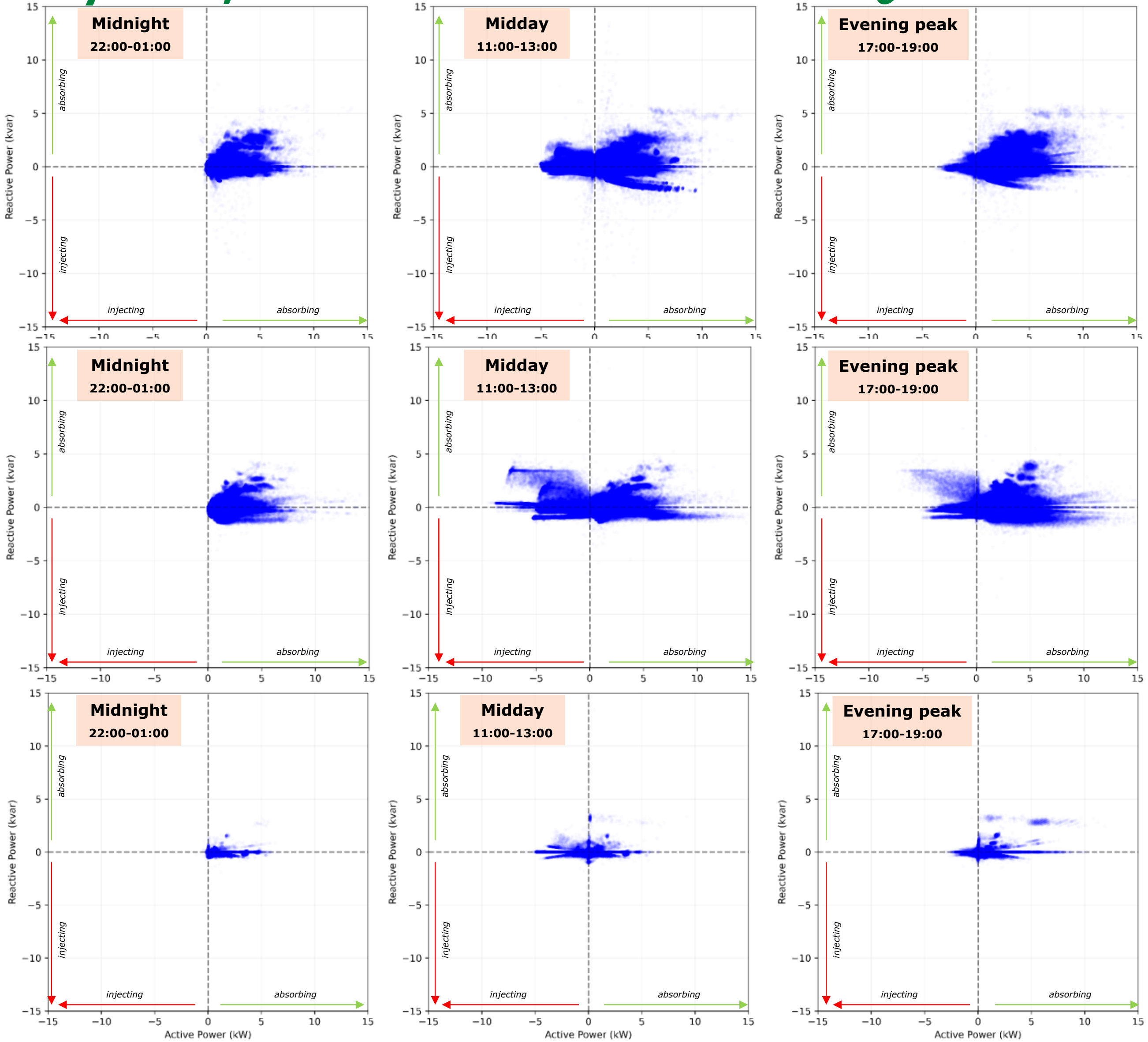
3 Smart Meter Data

Time Analysis, All Customers: Q vs P

Jemena

United Energy

AusNet



Useful to do a 'sense' check (e.g., no generation at night)

Q can be capacitive or inductive throughout the day

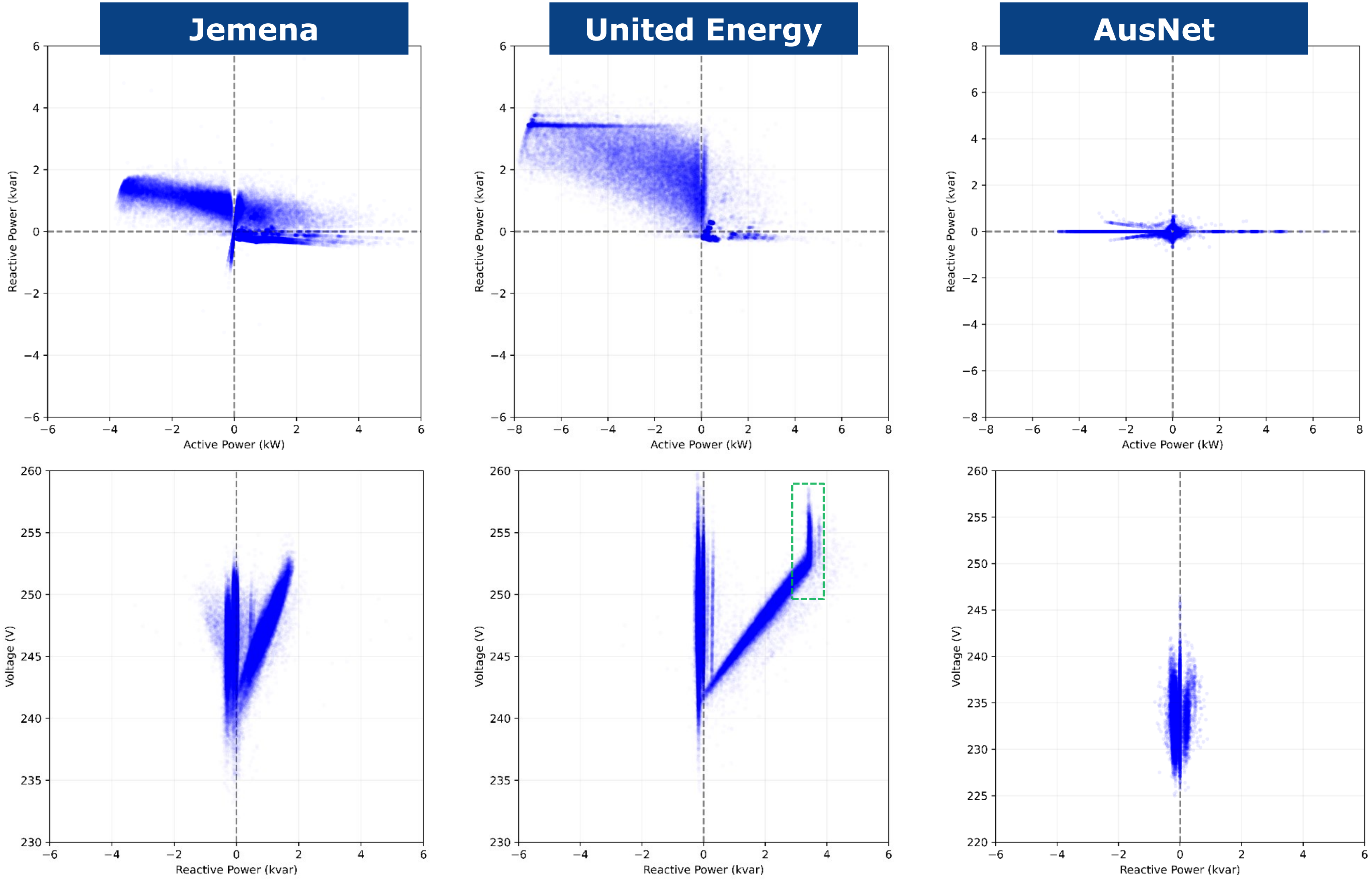
+ve → absorbing
-ve → injecting

3 Smart Meter Data

Single Customer: Q vs P and V vs Q

Q vs P

+ve → absorbing
-ve → injecting



V vs Q

+ve → absorbing
-ve → injecting

Volt-var response becomes evident

4 Model-Free Calculations

4 Model-Free Calculations

Jemena Case Study

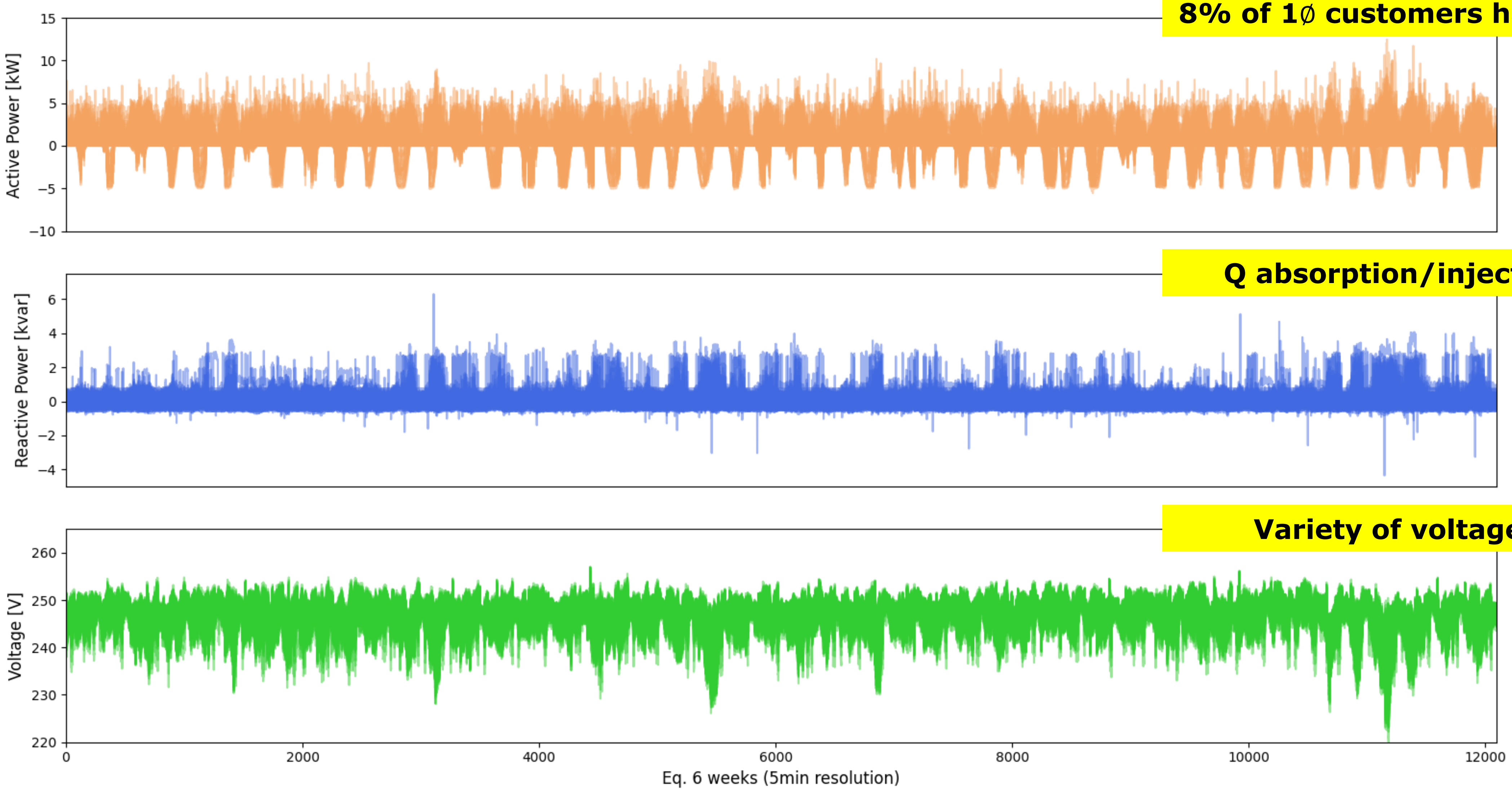
- **Site:** 1 Distribution transformer with **3 LV circuits**
- **Customers**:
  - 156 single-phase (13 with PV systems)
  - 14 three-phase
  - Total of **198** customers for the NN ($|C| = 156 + 14 \times 3 = 198$)
- **Resolution:** 5 minutes ($\boldsymbol{P}, \boldsymbol{Q}, \boldsymbol{V}$)
- **Training data:** ~6 weeks
- **Test data:** ~3 weeks

→ **Objective 1:** Produce a single Neural Network for all 3 LV circuits

→ **Objective 2**: DER Connection Request, DER Hosting Capacity and Operating Envelopes

4 Model-Free Calculations

Training Data Set



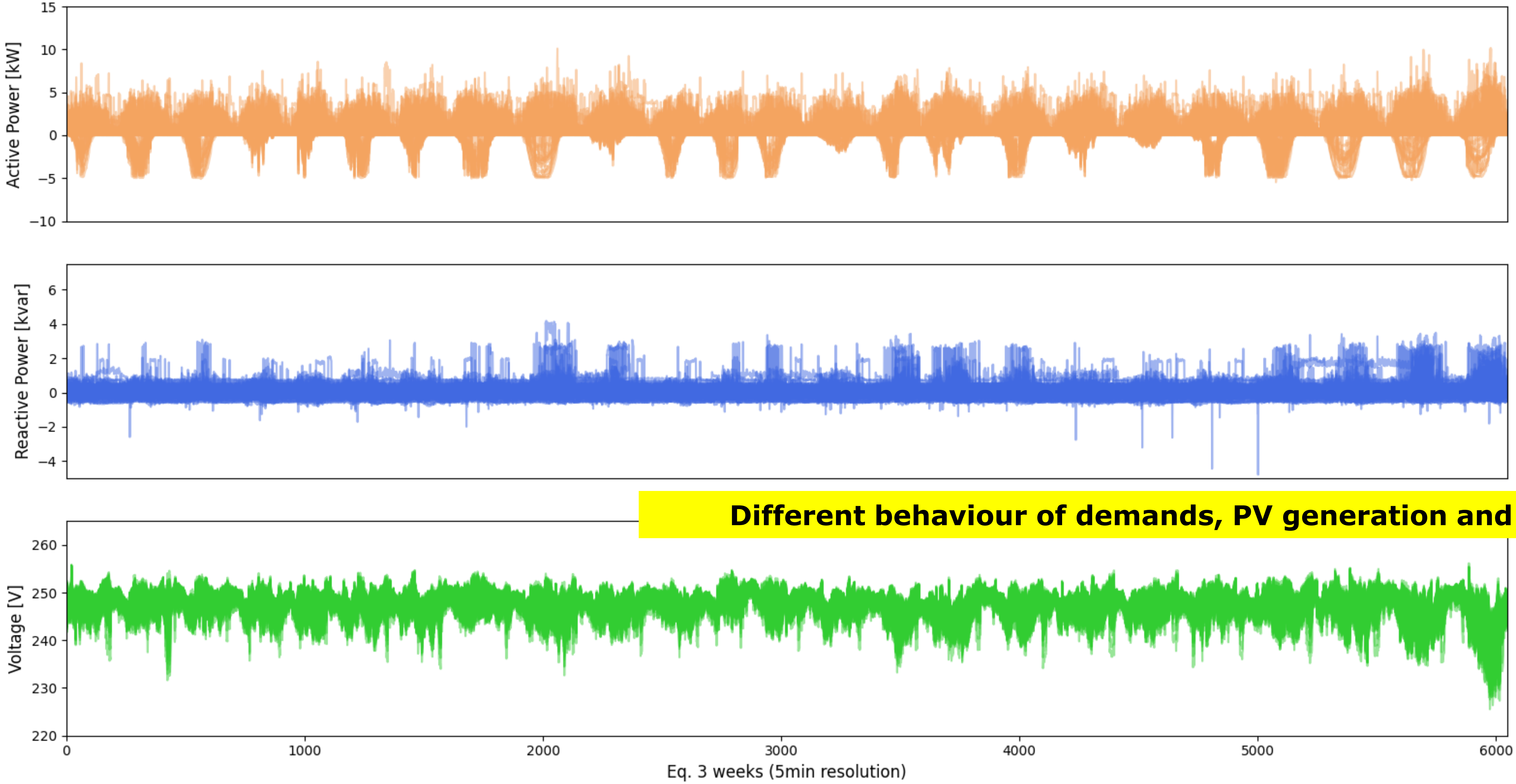
8% of 1ø customers have PV

Q absorption/injection

Variety of voltages

4 Model-Free Calculations

Test Data Set



Different behaviour of demands, PV generation and Q

4 Model-Free Calculations

Neural Network Selection

Problem Characteristics	
Input Layer dimension	$2 \times (156 + 3 \times 14)$ $(396 = 2|C|)$
Output Layer dimension	$156 + 3 \times 14$ $(198 = |C|)$
Output Activation Function	Linear
Loss Function	MSE
Optimiser	ADAM

K Fold Cross Validation	
K Fold	6 (1 week length each)
N° of hidden layers	1
N° of Neurons	$[0.5, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10] \times |C|$
Activation Function	Tanh, Swish, ReLu
Learning rate	$1 \times 10^{-2}, 1 \times 10^{-3}, 1 \times 10^{-4}, 1 \times 10^{-5}$
Batch size	$72, 144, 288$
Epochs	$500, 1{,}000, 2{,}000$
Total	**1,188 (6 runs each)**

a Best hyperparameter combination

b 10 NNs are trained from scratch

c Final NN based on RMSE Training

Final NN

(~15 min)

$10 \times |C|$

Tanh

1×10^{-5}

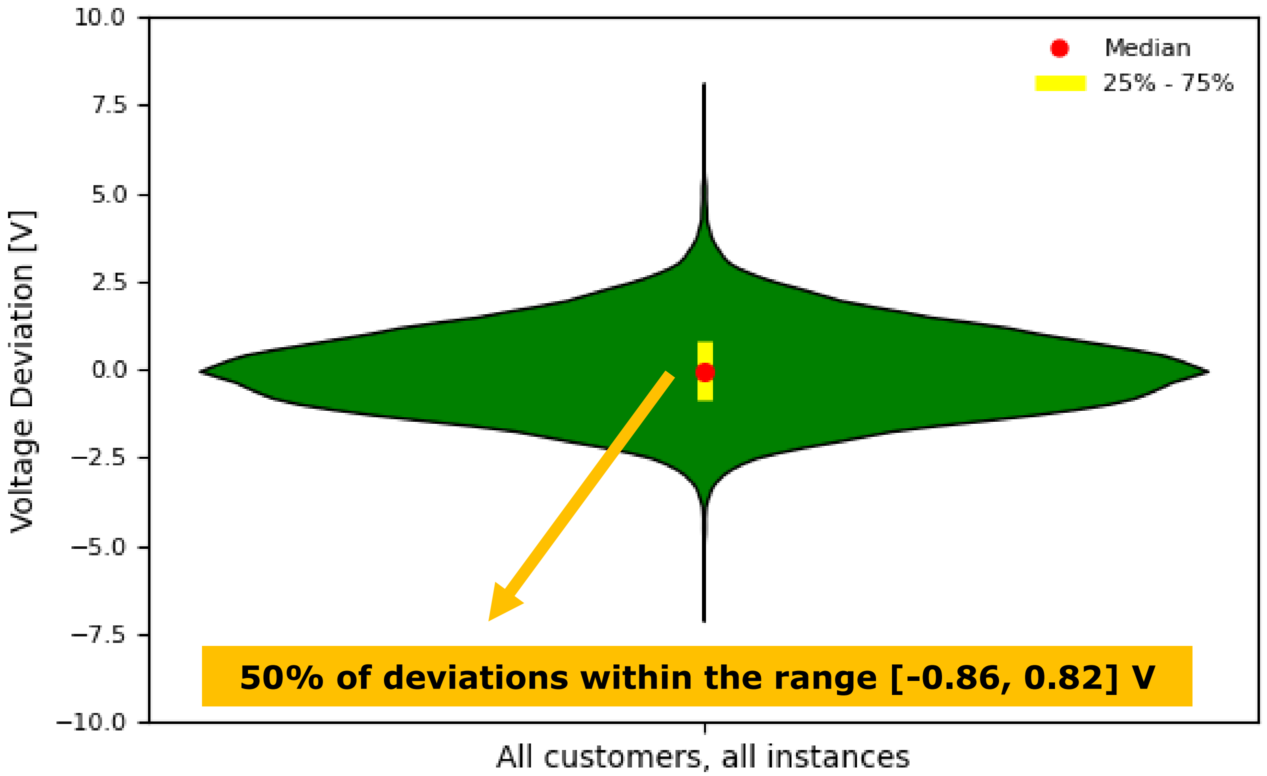
72

$2{,}000$

4 Model-Free Calculations

Final Neural Network

Model-Free Voltage Calculations Results	
RMSE Test [V]	1.25
Av Dev Test [V]	0.99
Max Dev Test [V]	8.12



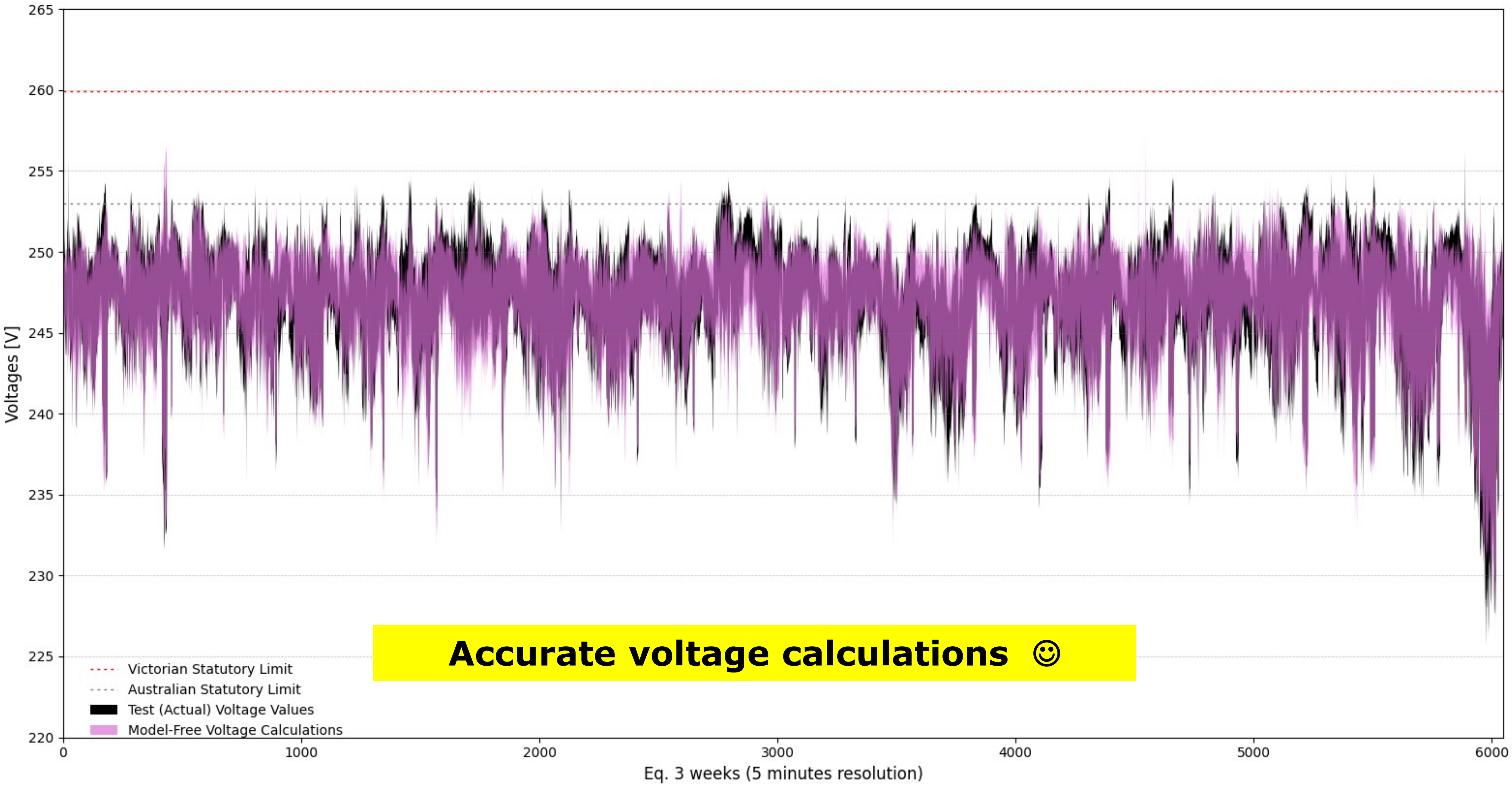
50% of deviations within the range [-0.86, 0.82] V

Voltage Deviation = Calculated Voltage − Actual Voltage

Accurate voltage calculations achieving an average deviation of less than 1 V
(out of around 230 V)

4 Model-Free Calculations

Results – All 170 Customers

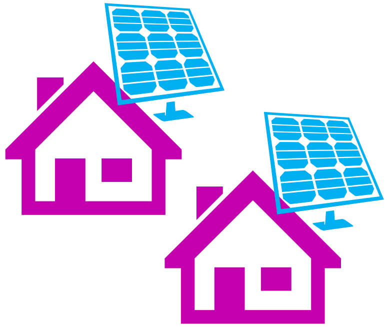


Accurate voltage calculations ☺

4 Model-Free Calculations

Application – DER Hosting Capacity

Assessment of PV Hosting Capacity



- Same considerations as before
- Four scenarios: ~10, ~20, ~30 and ~40% of customers with PV
- **Check**: Max voltage of all customers ≤ 260V (new VIC limit)

Voltages OK?

PV Penetration	Max Voltage
Base case (8%)	**YES (252.16 V)**
Scenario 1 (10%)	**YES (253.59 V)**
Scenario 2 (20%)	**YES (254.84 V)**
Scenario 3 (30%)	**YES (259.69 V)**
Scenario 4 (40%)	**NO (263.17 V)**

Hosting Capacity

Super quick DER hosting capacity assessments ☺

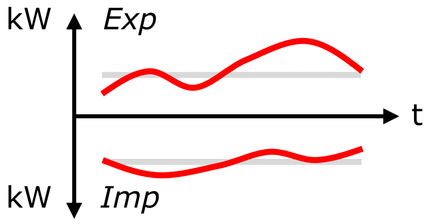
(a few secs depending on penetrations, etc.)

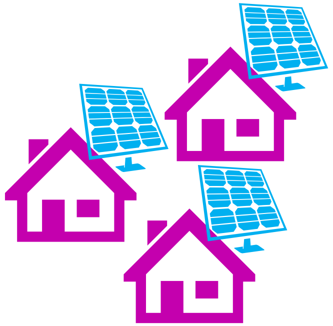
4 Model-Free Calculations

Application – Operating Envelopes

Calculation of OEs (Exports)

- Same considerations as before (for passive customers)
- 30 active customers: Equal Opportunity (same OEs to all)
- Progressive assessment: 1, 2, … 10kW of exports
- **Check**: Max voltage of all customers ≤ 260V (just an example)





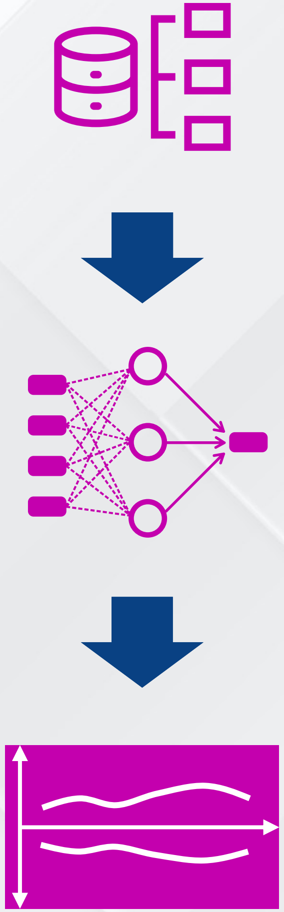
Voltages OK?

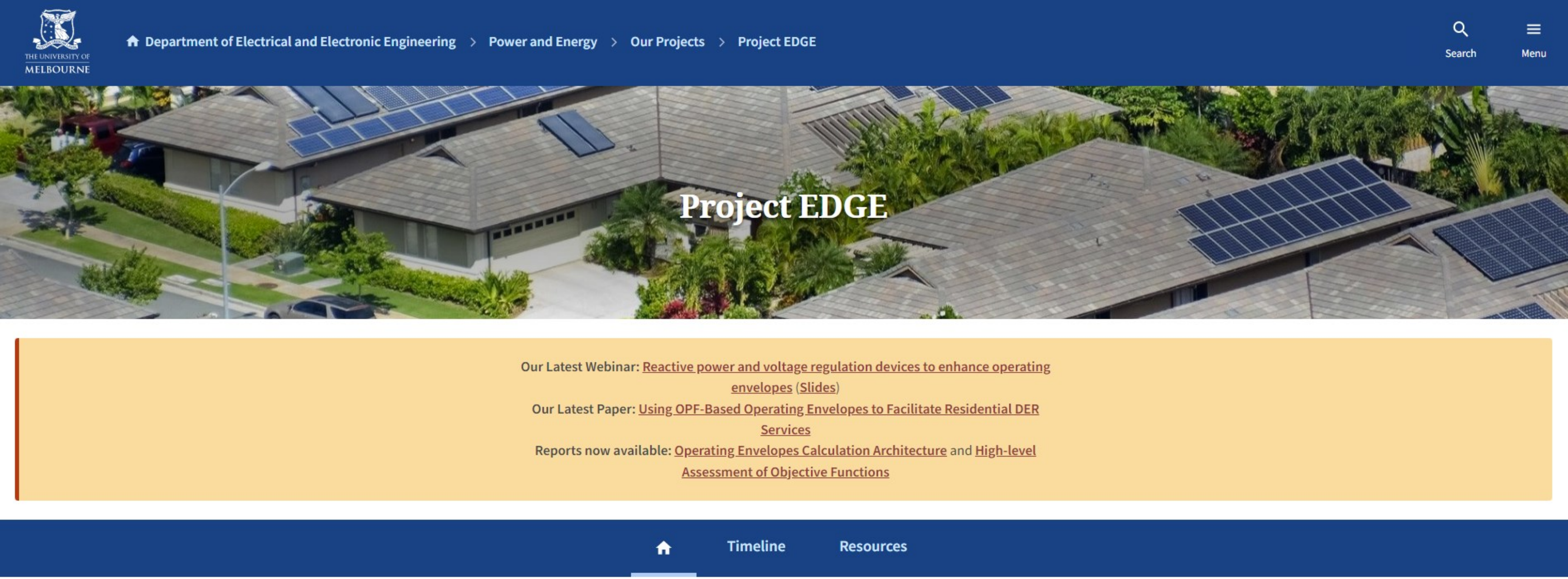
Exports	Max Voltage
0 kW	YES (252.61 V)
1 kW	YES (253.22 V)
2 kW	YES (253.76 V)
3 kW	YES (254.71 V)
4 kW	YES (257.12 V)
5 kW	YES (259.40 V)
6 kW	NO (261.53 V)

OE

Again, super quick OE calculations ☺

5 Model-Driven vs Model-Free





Project EDGE

Our Latest Webinar: Reactive power and voltage regulation devices to enhance operating envelopes (Slides)

Our Latest Paper: Using OPF-Based Operating Envelopes to Facilitate Residential DER Services

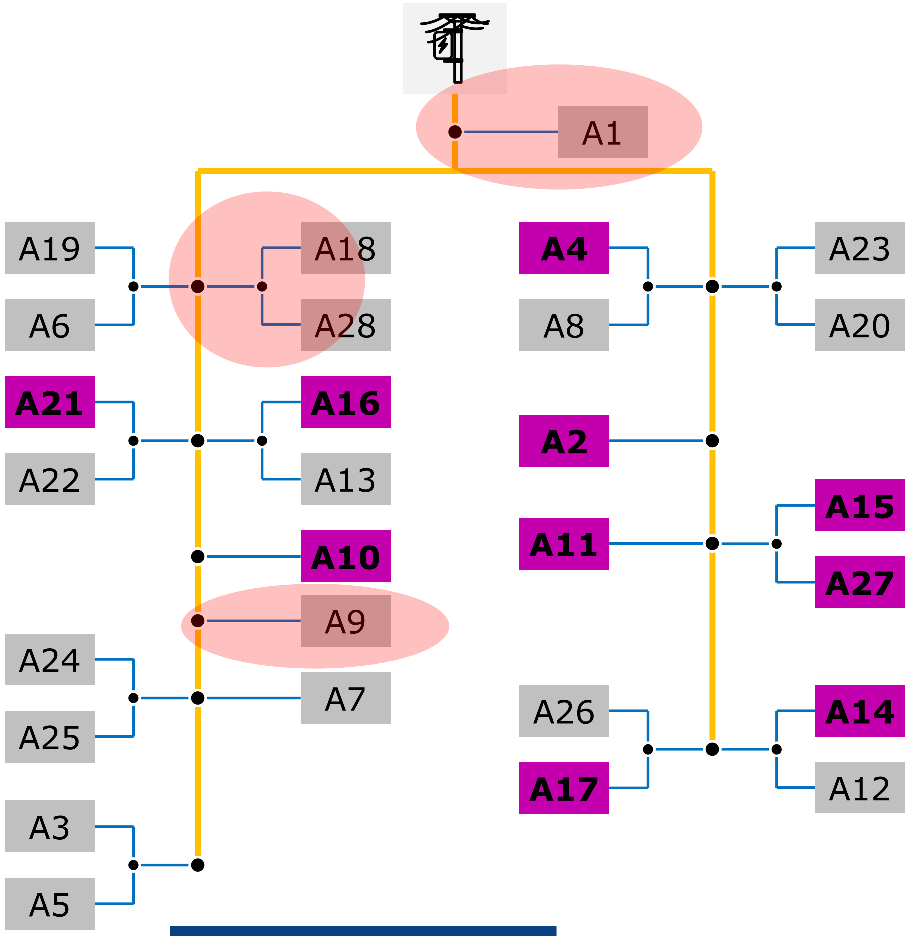
Reports now available: Operating Envelopes Calculation Architecture and High-level Assessment of Objective Functions

EDGE AusNet services AEMO AUSTRALIAN ENERGY MARKET OPERATOR

https://electrical.eng.unimelb.edu.au/power-energy/projects/project-edge

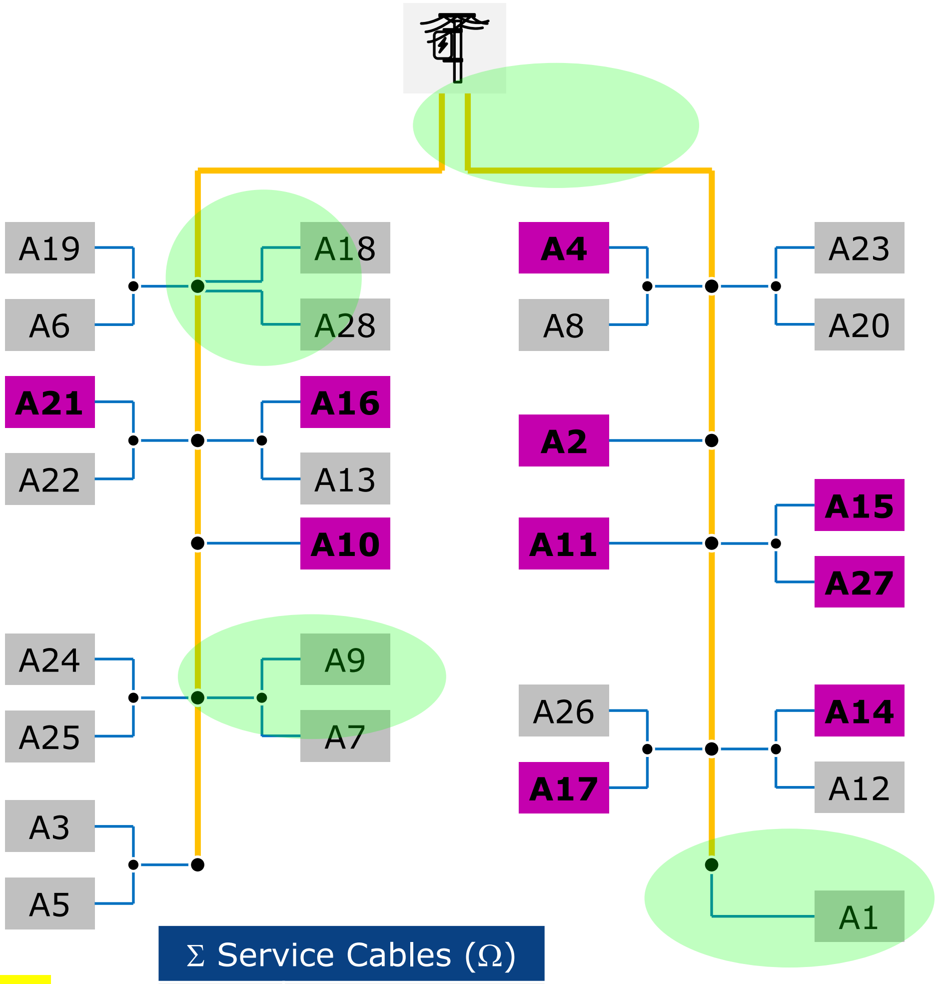
5 Model Validation for Site A (Project EDGE)

Unvalidated vs Validated



▬ backbone
— service cable
⬜ passive cust.
🟪 active cust.

- ✓ Desktop analyses
- ✓ Site visits



Σ Service Cables (Ω)	
Rs	1.20
Xs	0.17

Initial

This process is …
painful.

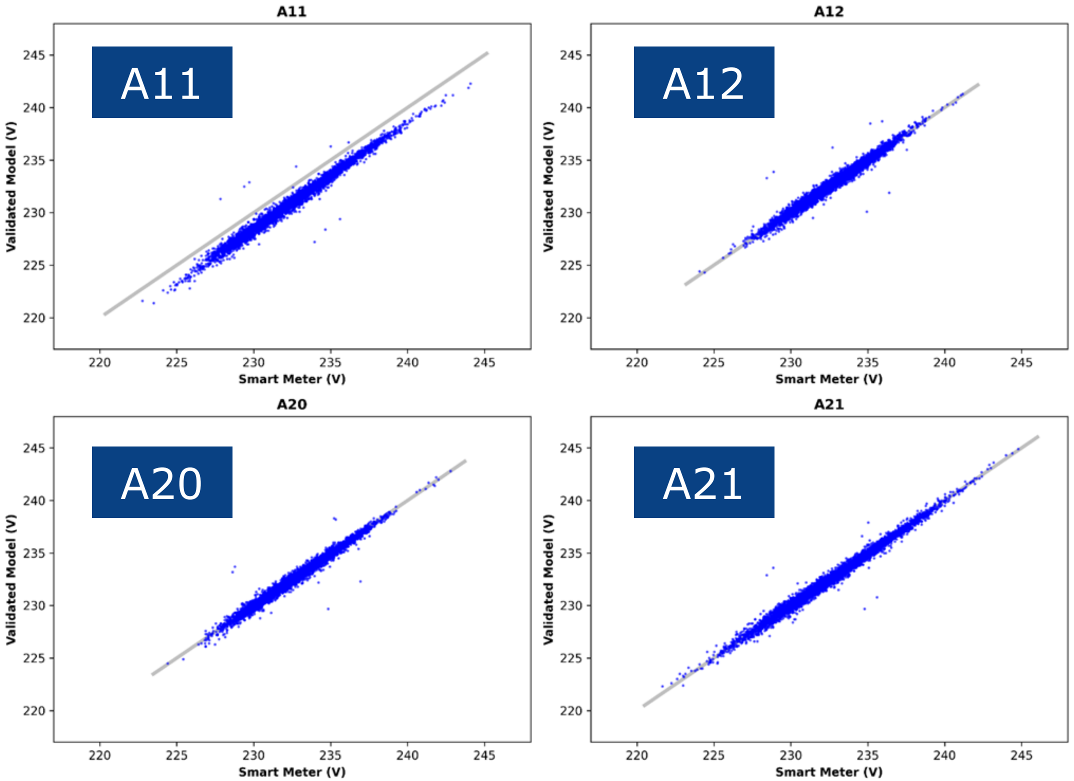
Σ Service Cables (Ω)	
Rs	2.03 (~1.7x)
Xs	0.74 (~4.4x)

Final

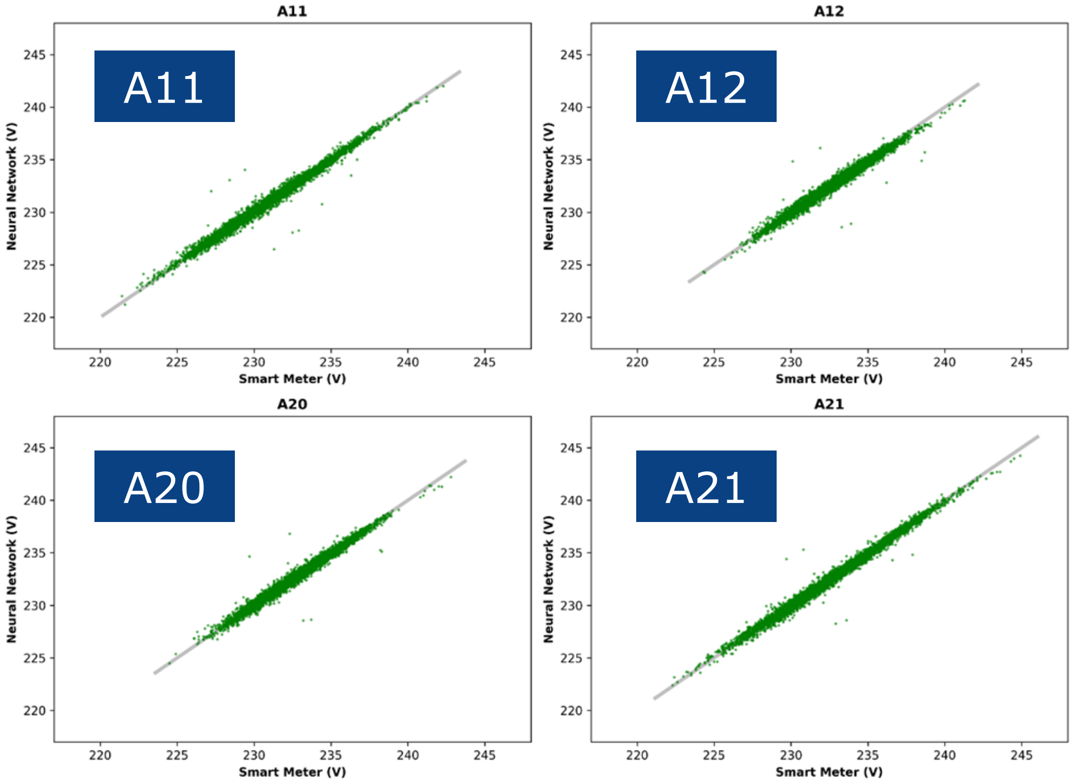
5 Electrical Model vs Neural Networks

(NN with 6 weeks of 5-min smart meter data)

Electrical Model
Slow, expensive process



Neural Network
Fast and cheap ☺



NN (with V at the Tx) outperforms the electrical model!

6 Key Remarks

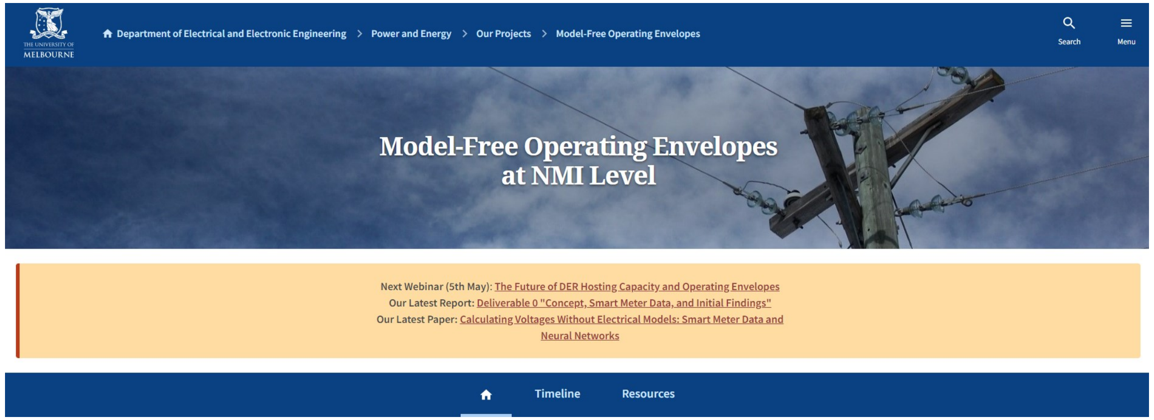
6 Key Remarks

- *Initial Findings*
  - **A model-free future is possible ☺**
  - **NNs can capture the physics** of LV networks
  - Once the NN is ready, it becomes an **alternative to calculate voltages**
    - **Extremely quick** (faster than power flows) to assess DER connection requests, DER hosting capacity, operating envelopes, etc.
  - **Minimum (valid) data needed? →** Latest findings: 3 weeks (5-min res)

- *Some Other Challenges*
  - **Topological changes? →** NN needs updating (same for any electrical model)
    - But a NN could flag this change
  - **Extrapolation has limitations** (you can have non-sensical results) → Ongoing research
  - **SWER networks? →** Tricky but not impossible ☺

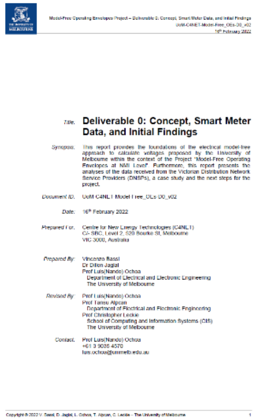
Further Reading

- Our Project



Model-Free Operating Envelopes at NMI Level

Next Webinar (5th May): The Future of DER Hosting Capacity and Operating Envelopes
Our Latest Report: Deliverable 0 "Concept, Smart Meter Data, and Initial Findings"
Our Latest Paper: Calculating Voltages Without Electrical Models: Smart Meter Data and Neural Networks



Model-Free Operating Envelopes Project – Deliverable 0: Concept, Smart Meter Data, and Initial Findings
UoM-C4NET-Model-Free_OEs-D0_v02
16th February 2022

Title: **Deliverable 0: Concept, Smart Meter Data, and Initial Findings**

Synopsis: This report provides the foundations of the electrical model-free approach to calculate voltages proposed by the University of Melbourne within the context of the Project "Model-Free Operating Envelopes at NMI Level". Furthermore, this report presents the analyses of the data received from the Victorian Distribution Network Service Providers (DNSPs), a case study and the next steps for the project.

Document ID: UoM-C4NET-Model-Free_OEs-D0_v02

Date: 16th February 2022

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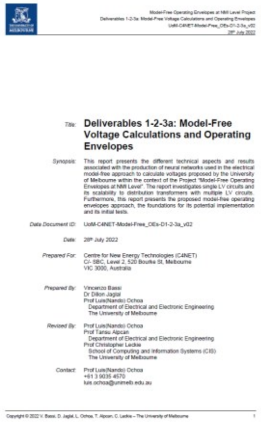

Model-Free Operating Envelopes at NMI Level Project
Deliverables 1-2-3a: Model-Free Voltage Calculations and Operating Envelopes
UoM-C4NET-Model-Free_OEs-D1-2-3a_v02
28th July 2022

Title: **Deliverables 1-2-3a: Model-Free Voltage Calculations and Operating Envelopes**

Synopsis: This report presents the different technical aspects and results associated with the production of neural networks used in the electrical model-free approach to calculate voltages proposed by the University of Melbourne within the context of the Project "Model-Free Operating Envelopes at NMI Level". The report investigates single LV circuits and its scalability to distribution transformers with multiple LV circuits. Furthermore, this report presents the proposed model-free operating envelopes approach, the foundations for its potential implementation and its initial tests.

Data Document ID: UoM-C4NET-Model-Free_OEs-D1-2-3a_v02

Date: 28th July 2022

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https://electrical.eng.unimelb.edu.au/power-energy/projects/model-free-operating-envelopes

- Recent Publications

Electrical Model-Free Voltage Calculations Using Neural Networks and Smart Meter Data, IEEE Trans. on Smart Grid (*Under Review*)

Deliverables 1-2-3a Model-Free Voltage Calculations and Operating Envelopes, Report, 2022 (ResearchGate)

Deliverable 0: Concept, Smart Meter Data, and Initial Findings, Report, 2022 (ResearchGate)

Model-Free Voltage Calculations for PV-Rich LV Networks: Smart Meter Data and Deep Neural Networks, IEEE PES PowerTech 2021 (ResearchGate)

Calculating Voltages Without Electrical Models: Smart Meter Data and Neural Networks, CIRED 2021 (ResearchGate)

Thanks!
Questions?

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