Model-Free DER Hosting Capacity and Operating Envelopes: Project Update

Part of the Model-Free Operating Envelopes at NMI Level Project

Thank you for joining!

This webinar will start soon.

Important Information

- We will start at 13:02 PM. ~40-min presentation followed by ~10-min Q&A session.
- Please **use the Q&A box to ask any questions** you might have.
- The **webinar will be recorded** and will be available after the event.

Model-Free DER Hosting Capacity and Operating Envelopes:

Project Update

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Webinar

15th Feb 2023

The Team
Faculty of Engineering and Information Technology

Prof Nando Ochoa

Vincenzo Bassi

Prof Tansu Alpcan

Prof Chris Leckie

Outline

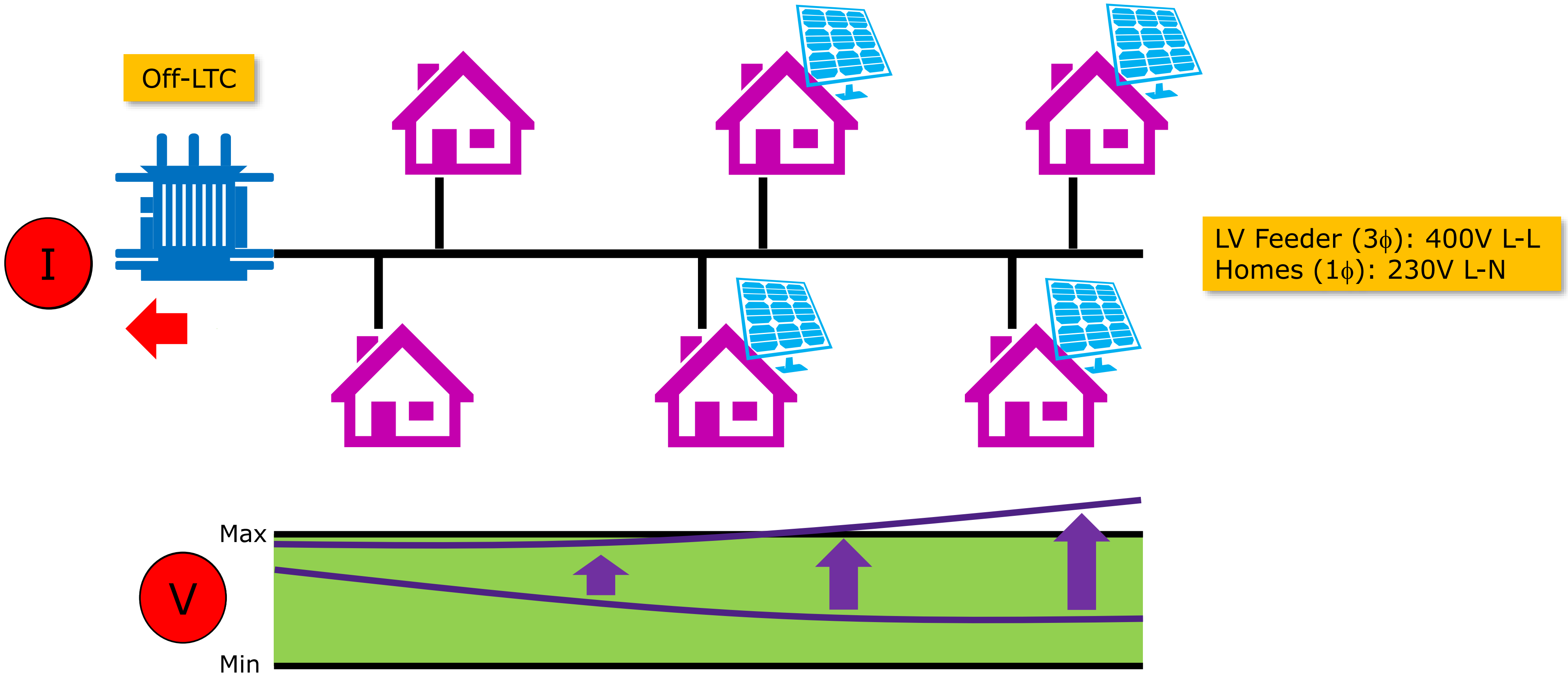
1. Voltage Calculations and DER[1]
2. Our Model-Free Approach
   Improvements: Offline Data Pipeline and NN Recipe
3. Model-Free Applications
4. Too good to be true? Model-Driven vs Model-Free
5. Partial Smart Meter Data Availability
6. Key Remarks

[1] DER = Distributed Energy Resources

1 Voltage Calculations and DER

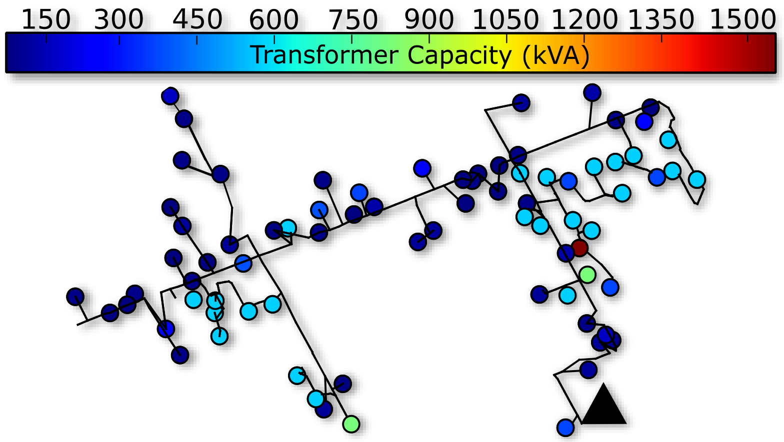
1 Voltage Calculations and DER

DER & Low Voltage (LV) Networks

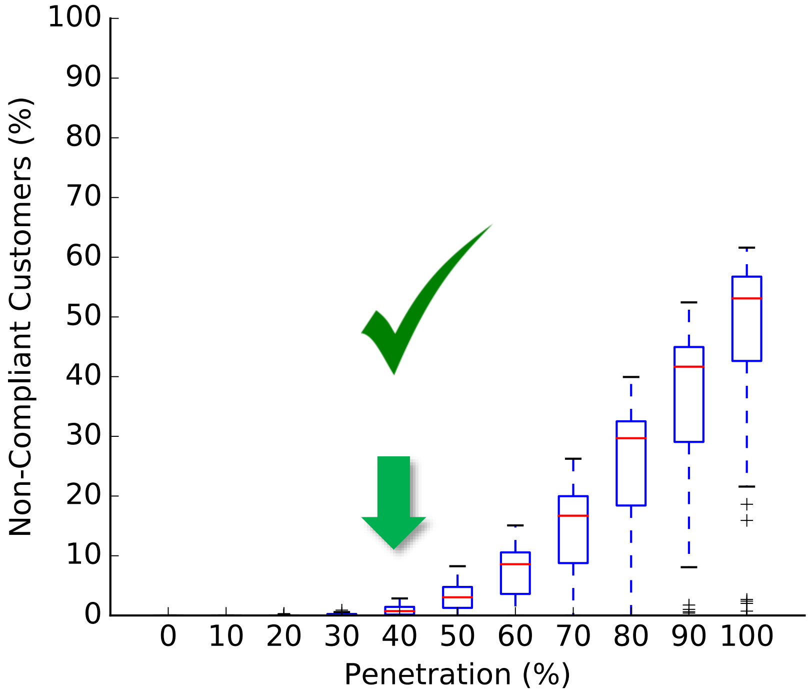


How can we determine the maximum exports (or imports) that our networks can withstand?

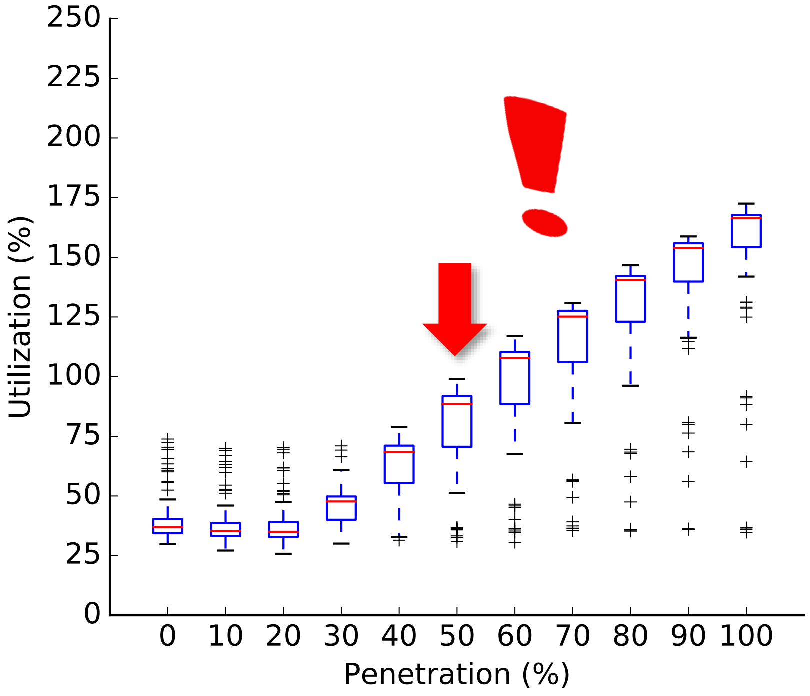
1 Voltage Calculations and DER
Hosting Capacity



LV Voltage Issues

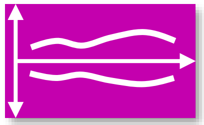


HV Conductors Congestion

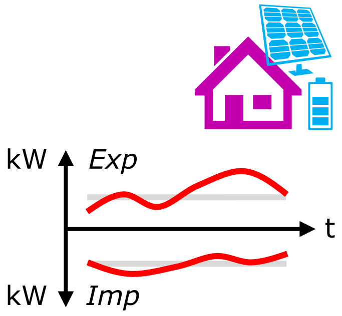


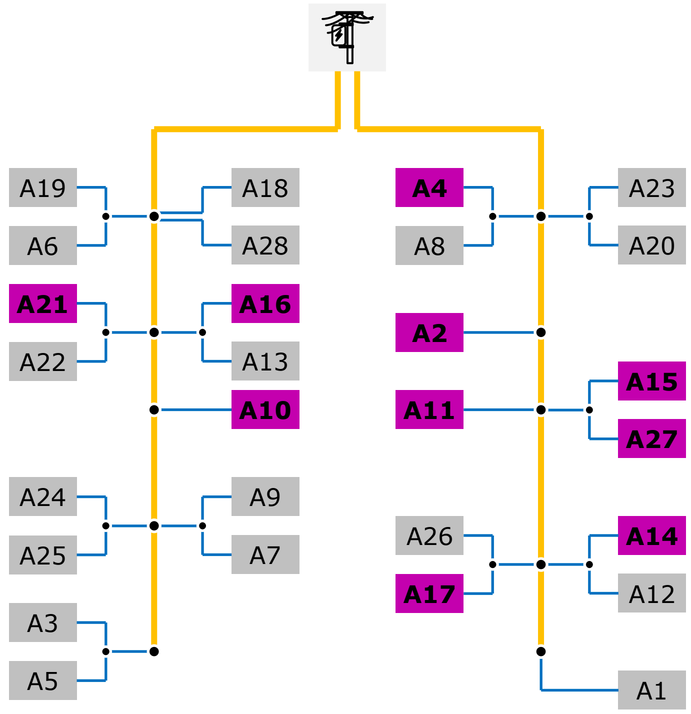
Exploration of DER scenarios → Power flows are essential

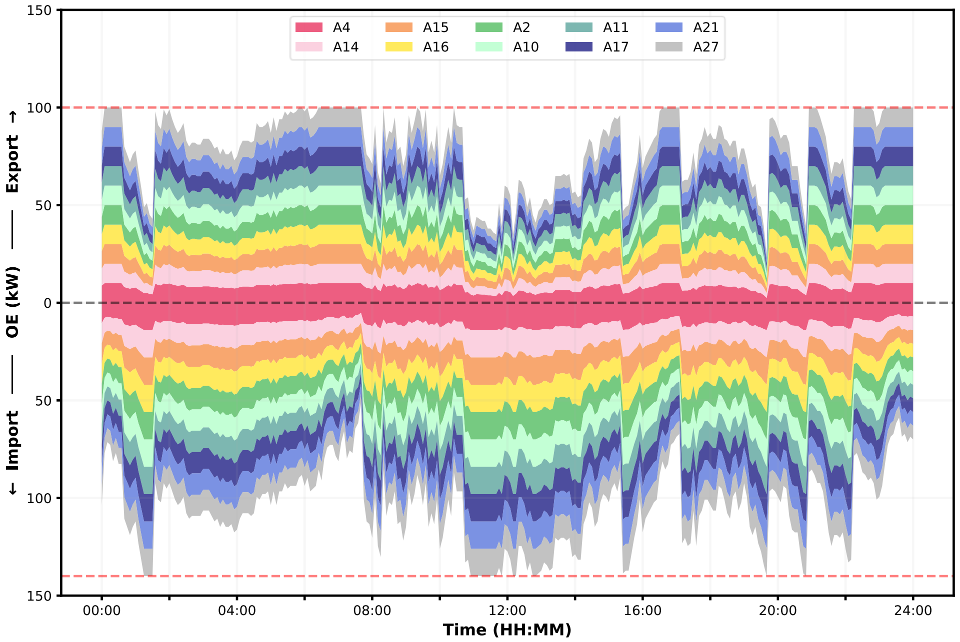
1 Voltage Calculations and DER
Operating Envelopes



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



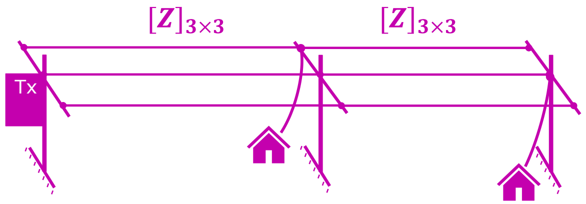




Again, exploration of DER scenarios → Power flows are essential

1 Voltage Calculations and DER
Today (Ideally)

Scenario to Check	*Electrical LV Network Model*	*3ϕ Power Flow*	*Voltages*
Min/Max Demand (P_{cust}, Q_{cust}) DER exp/imp (P_{DER}, Q_{DER}) Voltage at the ref bus	Topology Impedances ($[Z]_{3\times3}$) Phase Grouping (a, b, c)	E.g., OpenDSS ☺	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]

[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 LV Network Model

3ϕ Power Flow

What if we could calculate voltages without electrical models?

Voltages

V of customers

Voltages OK?

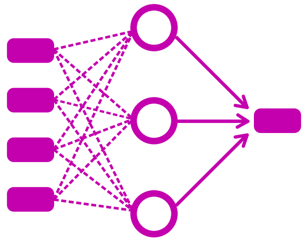
Yes → *Harder Scenario*

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]

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



2 Our Model-Free Approach

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

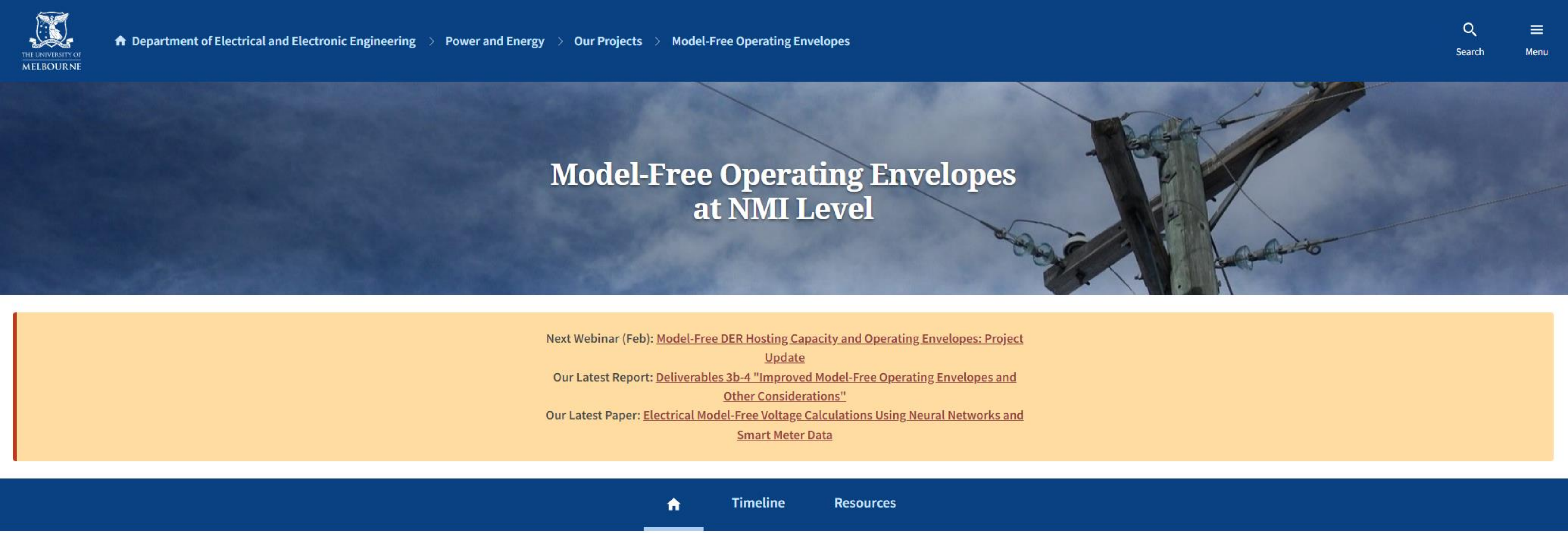
Deliverables 3b-4: *Improved Model-Free Operating Envelopes and Other Considerations*, Report, 2023 (ResearchGate)

Deliverable 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)



C4NET
Centre for New Energy Technologies

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

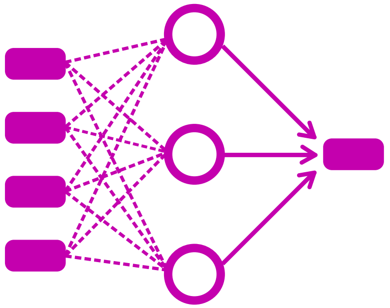
2 Our Model-Free Approach

Concept

Scenario to Check

- Min/Max Demand (P_{cust}, Q_{cust})
- DER exp/imp (P_{DER}, Q_{DER})
- ~~Voltage at the ref bus~~

Model-Free Voltage Calculations



Clever stuff to capture the physics ☺

Neural Network trained with historical Smart Meter data

Voltages

V of customers

Voltages OK?

Yes → *Harder Scenario*

No →

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

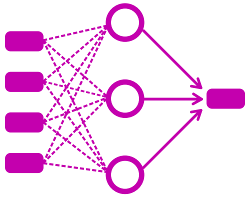
✓ **Removes time and cost** associated with the production of **LV electrical models**

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

2 Our Model-Free Approach
Development and Application

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

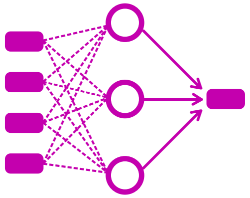
Processing of Smart Meter Data (P, Q, V)



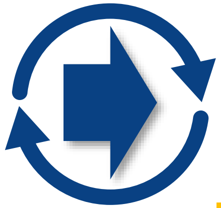
NN Training (*Recipe*) and Selection $V = f(P, Q)$

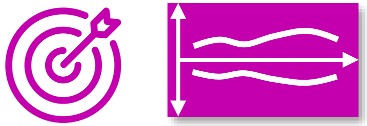
2. **Application**

DER Scenario or Forecasts (P, Q)



NN Calculates Voltages (V)





- ✓ **Hosting Capacity**
- ✓ **Connection Request**
- ✓ **Operating Envelopes**

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2 Our (Improved) Model-Free Approach
Development 1/2

Smart Meter Data: Improved Offline Data Pipeline

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

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

Step 3: Remove invalid and unfeasible instances

Step 4: Remove customers that do not show normal demand behaviours[3]

- ✓ Some customers have no consumption for most data points (e.g., construction)
- ✓ The NN will not be able to calculate voltages for P and Q very far from training

➢ **Output:** Training data set $(\boldsymbol{P}, \boldsymbol{Q}, \boldsymbol{V})$

The NN must be trained considering normal demand behaviours

[3] *Deliverables 3b-4: Improved Model-Free Operating Envelopes and Other Considerations*, Report, 2023 (ResearchGate)

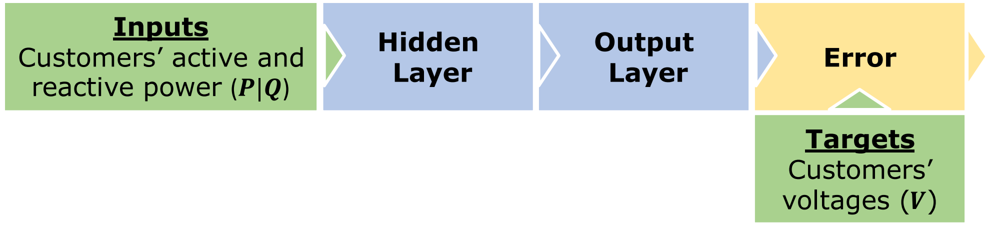
2 Our Model-Free Approach
Development 2/2

NN Training (Recipe) and Selection

Step 5: Define NN hyperparameters and settings according to NN recipe[4]

- Enhanced extrapolation capabilities and reduced production time

Hyperparameters and Settings	
Inputs	$2\|C\|$
Outputs	$\|C\|$
Output Act. Function	Linear
Error Function	MSE
Scaler	[0,1]
Optimiser	ADAM
Regularisation	L2
Number of Neurons	$5\|C\|$
Activation Function	Tanh
Learning Rate	1e-4
Regularisation Factor	1e-5
Batch Size	Eq. to 6 hours
Epochs	2,000



The NN can be produced in minutes

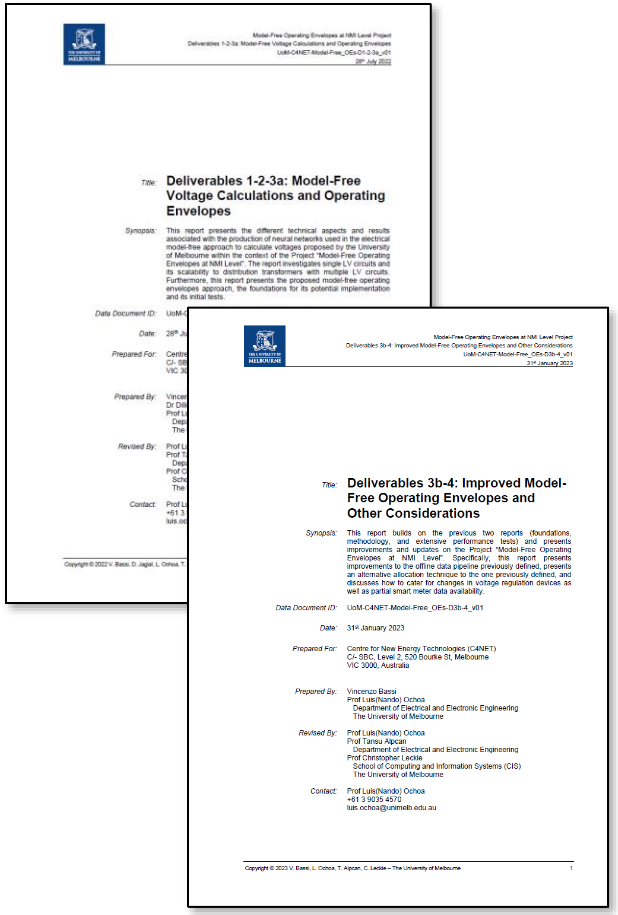
Step 6: 10 NNs based on Step 5 are trained from scratch. Select the lowest RMSE in training.

- **Output:** Final NN ready for voltage calculations $\boldsymbol{V} = \boldsymbol{f}(\boldsymbol{P}, \boldsymbol{Q})$ ☺

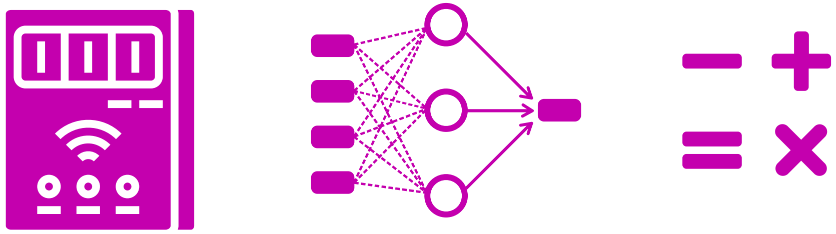
[4] *Electrical Model-Free Voltage Calculations Using Neural Networks and Smart Meter Data*, IEEE Trans. on Smart Grid (ResearchGate)

2 Our Model-Free Approach
What has been achieved so far?

- ✓ Accurate and quick multi-LV circuit voltage calculations
  - One NN per transformer (all LV circuits simultaneously captured)
- ✓ Only 3 weeks of historical data ($\boldsymbol{P}$, $\boldsymbol{Q}$, and $\boldsymbol{V}$) are required
  - Data from all customers connected to the transformer
  - No topological changes in the historical data
- ✓ NN can be used for multiple months without updates
  - If no changes in the LV network have occurred
- ✓ Several applications tested
  - Operating Envelopes, Connection Request, Hosting Capacity



✓ Removes time and cost associated with the production of **LV electrical models**
✓ Extremely quick alternative to power flow-based techniques



3 Model-Free Applications

3 Model-Free Applications
Jemena Case Study

- **Site:** 1 Distribution transformer with **4 LV circuits**
- **148 Customers**:
  - 110 single-phase
  - 38* three-phase
  - Total of **222** customers for the NN ($|C| = 110 + 2 \times 2 + 36 \times 3$)
- **Resolution:** 5 minutes ($\boldsymbol{P}, \boldsymbol{Q}, \boldsymbol{V}$)
- **NN Production:** ~3 weeks (Training data)
- **Performance Assessment:** ~Next 3 weeks (Test data)

→ **Objective 1:** Produce a single Neural Network for all 4 LV circuits

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

* 1 phase from 2 three-phase customers were removed due to unfeasible measurements

3 Model-Free Applications
NN Production using Training Data

Hyperparameters and Settings (Recipe)	
Inputs	$2|C| = 444$
Outputs	$|C| = 222$
Output Act. Function	Linear
Error Function	MSE
Scaler	[0,1]
Optimiser	ADAM
Regularisation	L2
Number of Neurons	$5|C| = 1{,}110$
Activation Function	Tanh
Learning Rate	1e-4
Regularisation Factor	1e-5
Batch Size	Eq. to 6 hours
Epochs	2,000

a 10 NNs are trained from scratch

b Final NN based on RMSE Training

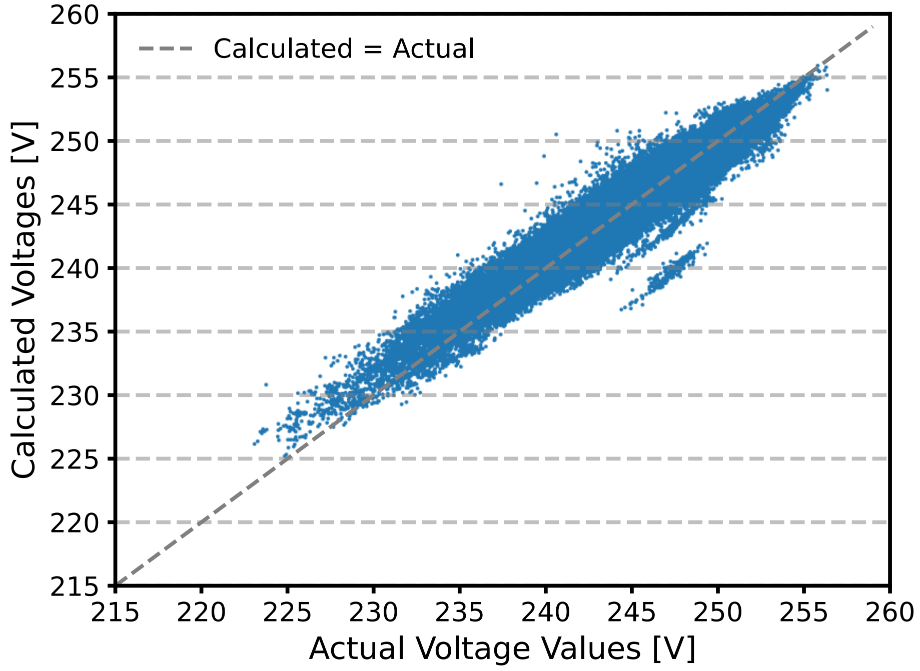
NN recipe massively reduces the computational time to produce the NN

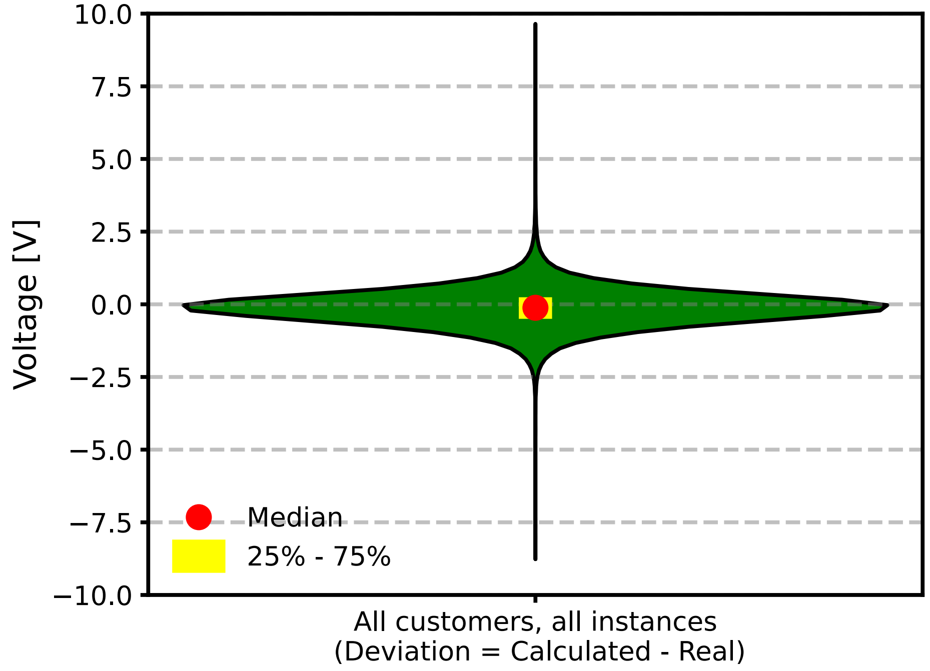
→ From weeks (hyperparameter exploration) to minutes!

3 Model-Free Applications

NN Accuracy using Test Data (all 148 Customers)

Model-Free Voltage Calculations Results	
RMSE Test [V]	0.64
Av Dev Test [V]	0.48
Max Dev Test [V]	9.86

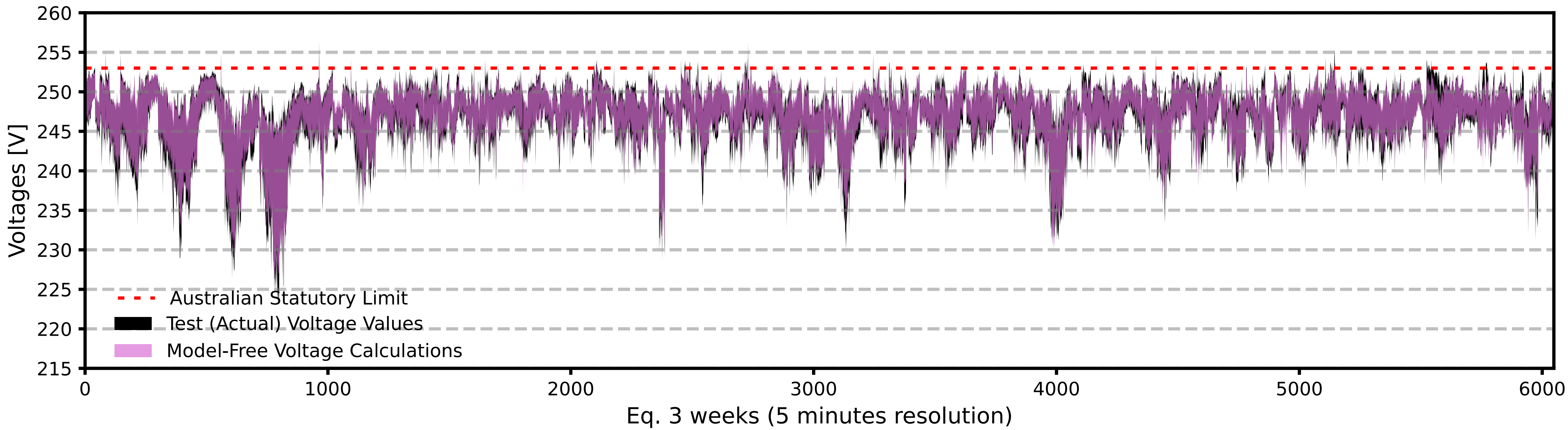




Improved results: Voltage calculations with an avg deviation of less than 0.5 V (out of around 230 V)

3 Model-Free Applications

NN Accuracy using Test Data (all 148 Customers)



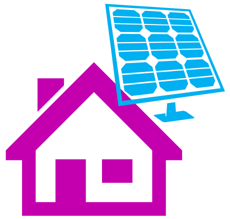
Accurate voltage calculations ☺

3 Model-Free Applications
DER Connection Request

Can a single customer install a 5 kW PV system?

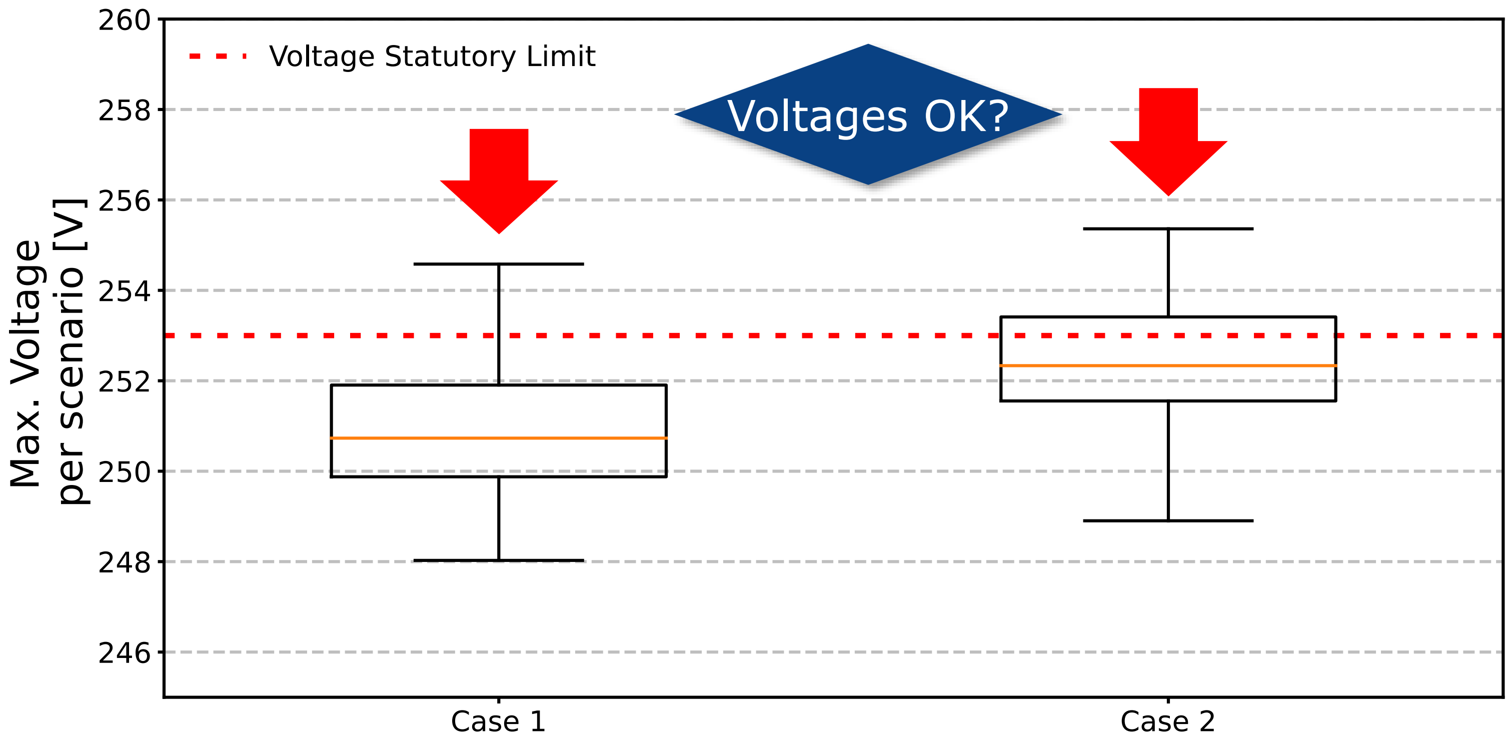
Intensive Assessment using *Monte Carlo*

- Customers with PV $\boldsymbol{P_{PV}} = -5\ kW$ (*high exports*)
- Single customer being assessed: $\boldsymbol{P_{PV}} = -5\ kW$ (*high exports*)
- 100 demand scenarios
  - $\boldsymbol{P_{Load}} = random(0,1)\ kW$ (low demand)
  - $pf\ = inductive\ random(0.90,0.99)$
- **Two cases**
  - **Case 1:** Customer with low voltages (closer to the trafo)
  - **Case 2:** Customer with high voltages (far from the trafo)
- **Check:** Compliance with voltage statutory limits (≤ 253 V)



Improvement: Active and reactive power can be specified ☺

3 Model-Free Applications
DER Connection Request - Results



Case 1	Case 2
NO *non-compliant scenarios: **11%***	**NO** *non-compliant scenarios: **34%***

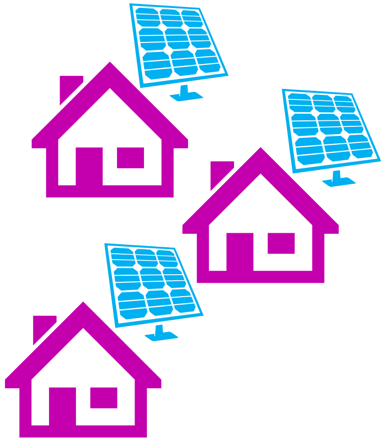
DER connection requests can be assessed extremely fast ☺
(even Monte Carlo is just few seconds)

3 Model-Free Applications
DER Hosting Capacity

How much PV systems the LV network can withstand?

Intensive Assessment using *Monte Carlo*

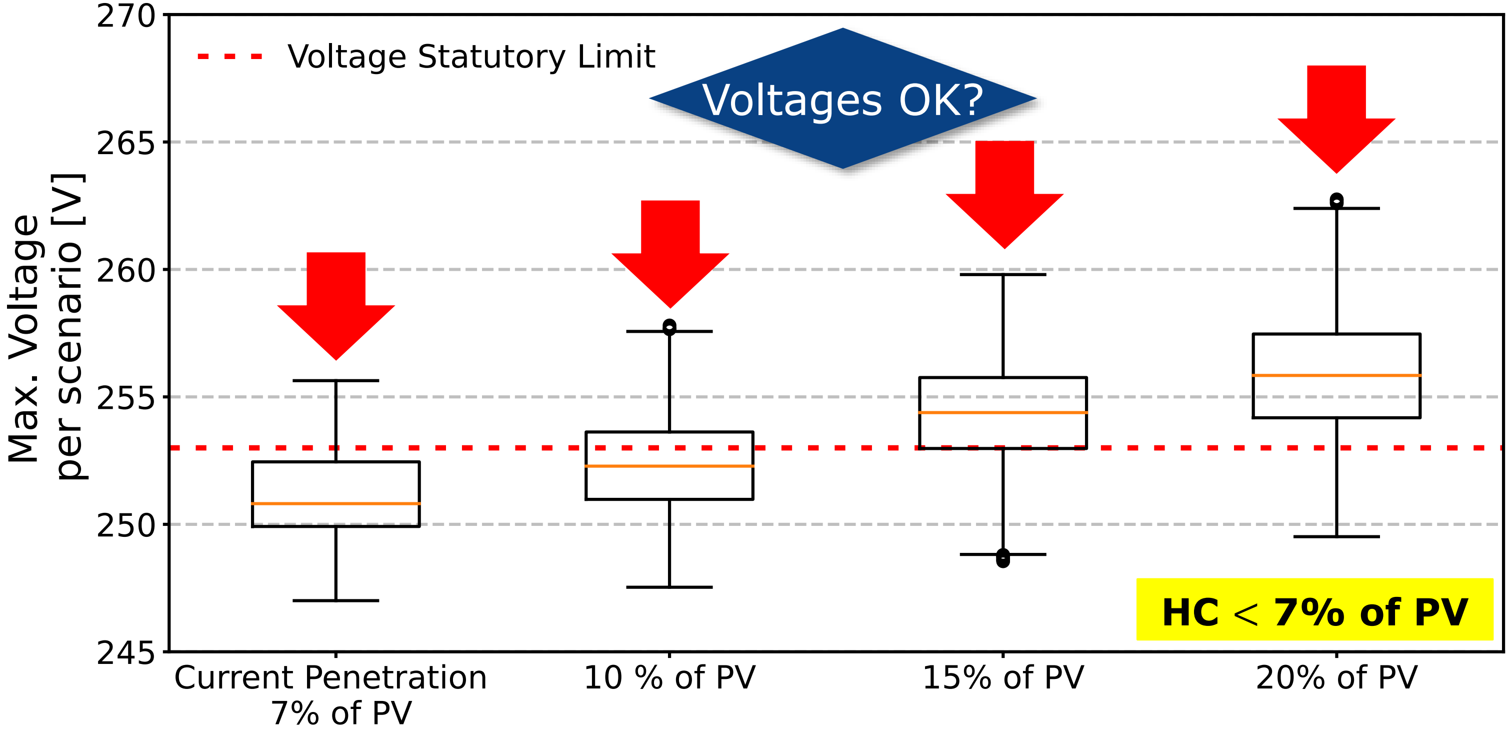
- Customers already with PV $\boldsymbol{P_{PV}} = -5\ kW$ (*high exports*)
- 100 PV allocation scenarios
  - Customers installing PV are randomly allocated $\boldsymbol{P_{PV}} = -5\ kW$ (high exports)
  - 100 Demand scenarios (low demands, same as before)
- Four progressive PV penetration scenarios
  - ~7% (*current PV*), ~10%, ~15% and ~20% of customers with PV
- **Check:** Compliance with voltage statutory limits (≤ 253 V)



Improvement: Active and reactive power can be specified ☺

3 Model-Free Applications

DER Hosting Capacity - Results



Current PV Penetration (7% of PV)

NO

non-compliant scenarios: ***18%***

Super quick DER hosting capacity assessments ☺ *(a few mins depending on penetrations)*

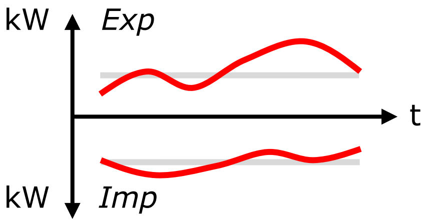
3 Model-Free Applications

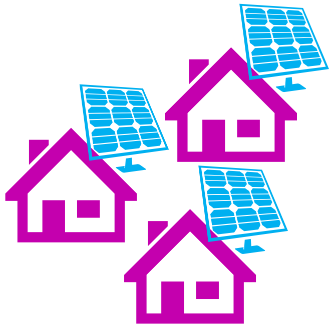
Operating Envelopes

How much exports from active customers the LV network can withstand?

Assessment

- ➢ OEs are calculated for a single instance (noon)
- ➢ Passive customers:
  - Demands ($\boldsymbol{P}$ and $\boldsymbol{Q}$) from the previous instance (5 mins ago)
- ➢ Active customers:
  - ~50% of customers with PV (12) are selected as active customers (6)
  - $\boldsymbol{P}$ → Equal opportunity OEs; Progressive assessment of exports
  - $pf = 1$
- ➢ **Check:** Compliance with voltage statutory limits (≤ 253 V)





Improvement: Active and reactive power can be specified ☺

3 Model-Free Applications

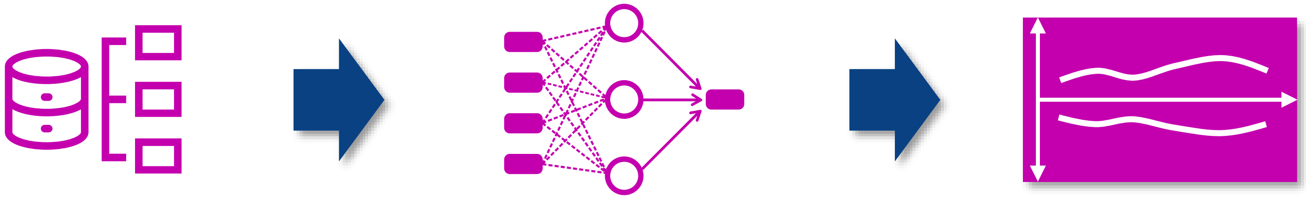
Operating Envelopes - Results

Voltages OK?

Exports	Max Voltage
0 kW	248.37 V
1 kW	248.89 V
2 kW	249.72 V
3 kW	250.11 V
4 kW	250.75 V
5 kW	251.39 V
6 kW	252.03 V
7 kW	252.66 V
8 kW	253.30 V

OE

Again, super quick OE calculations ☺



4 Model-Driven vs Model-Free

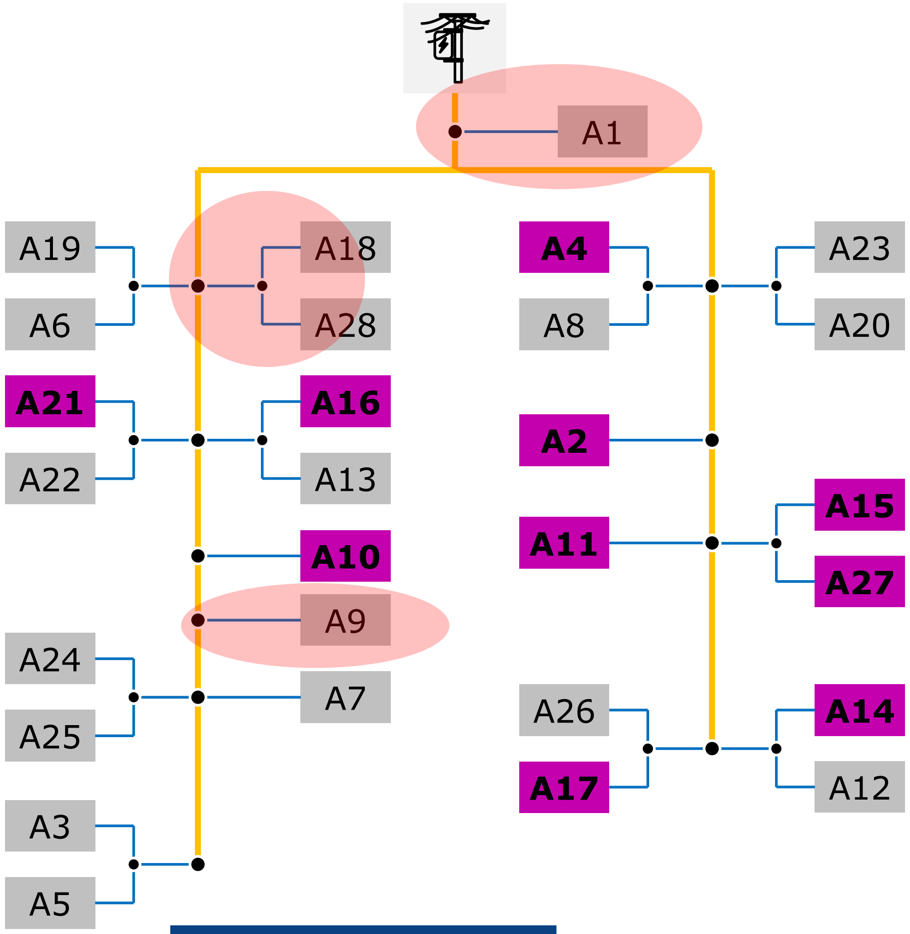
Our Latest Webinar: Reactive power and voltage regulation devices to enhance operating envelopes (Slides)
Our Latest Paper: Using OPF-Based Operating Envelopes to Facilitate Residential DER Services
Reports now available: Operating Envelopes Calculation Architecture and High-level Assessment of Objective Functions

EDGE
AusNet services
AEMO AUSTRALIAN ENERGY MARKET OPERATOR

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

4 Model-Driven vs Model-Free

Unvalidated vs Validated Electrical Model (EDGE AusNet SiteA)

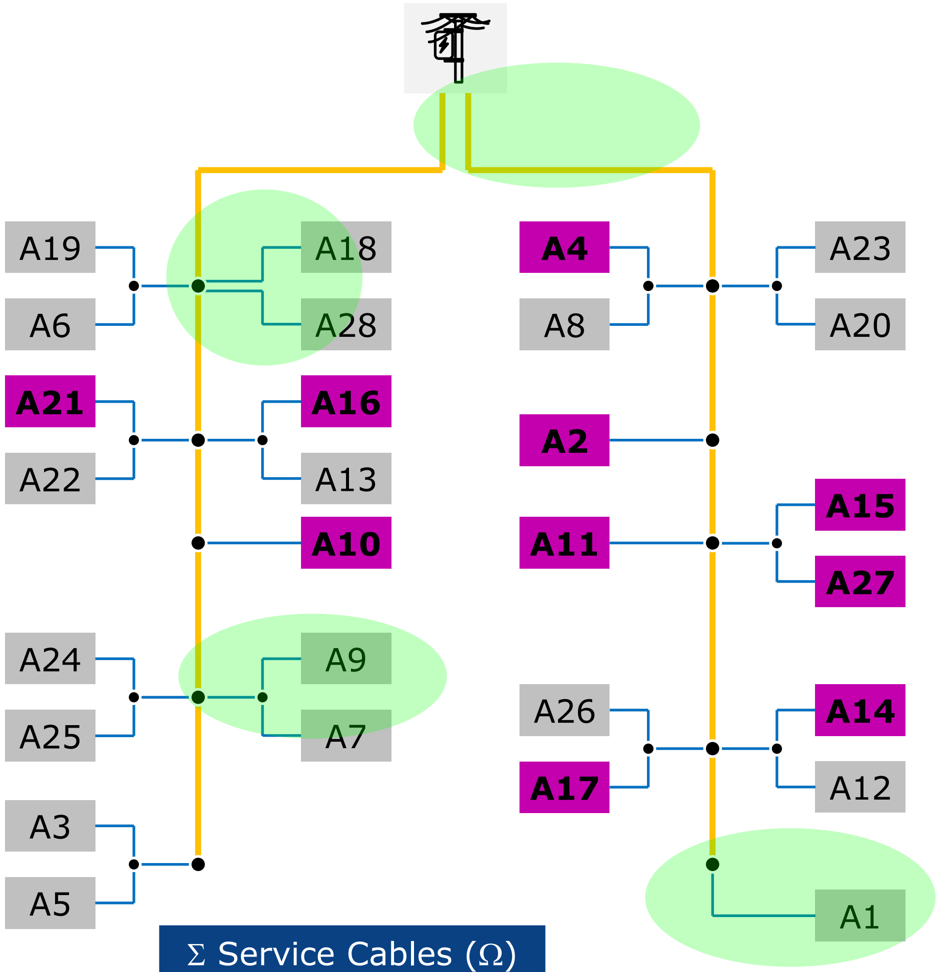


Σ Service Cables (Ω)	
Rs	1.20
Xs	0.17

Initial

- backbone
- service cable
- passive cust.
- active cust.

- ✓ Desktop analyses
- ✓ Site visits



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

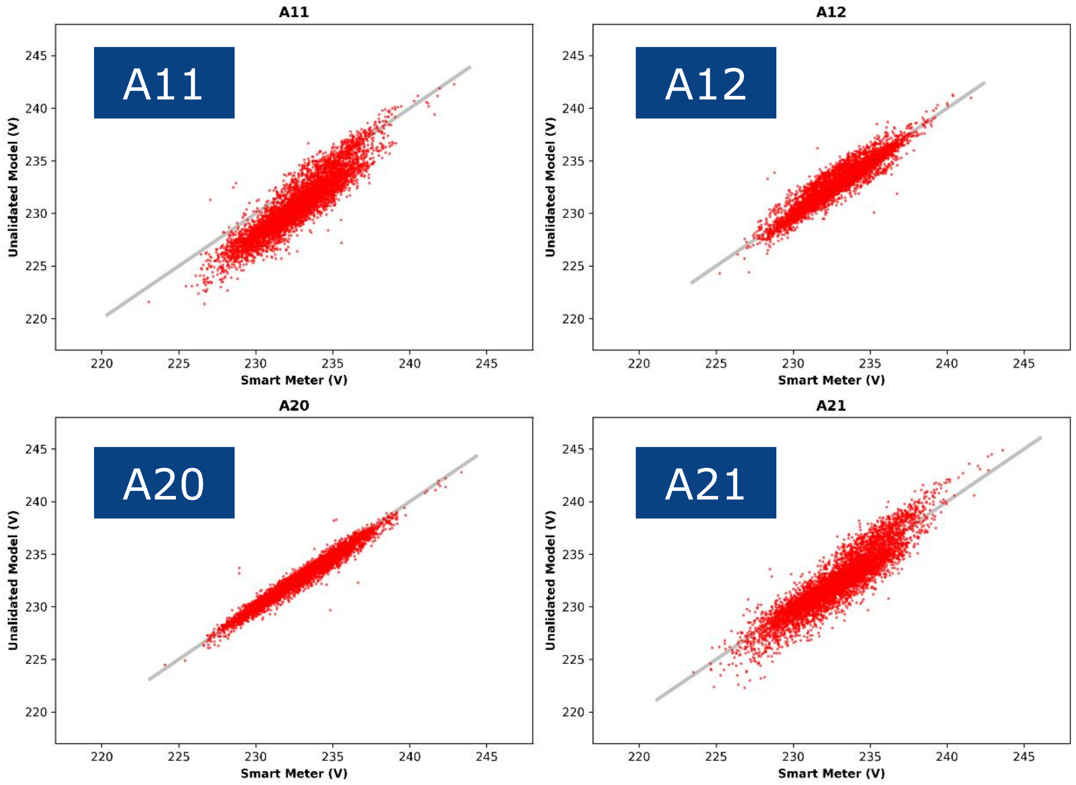
Final

This process is … **painful**

4 Model-Driven vs Model-Free

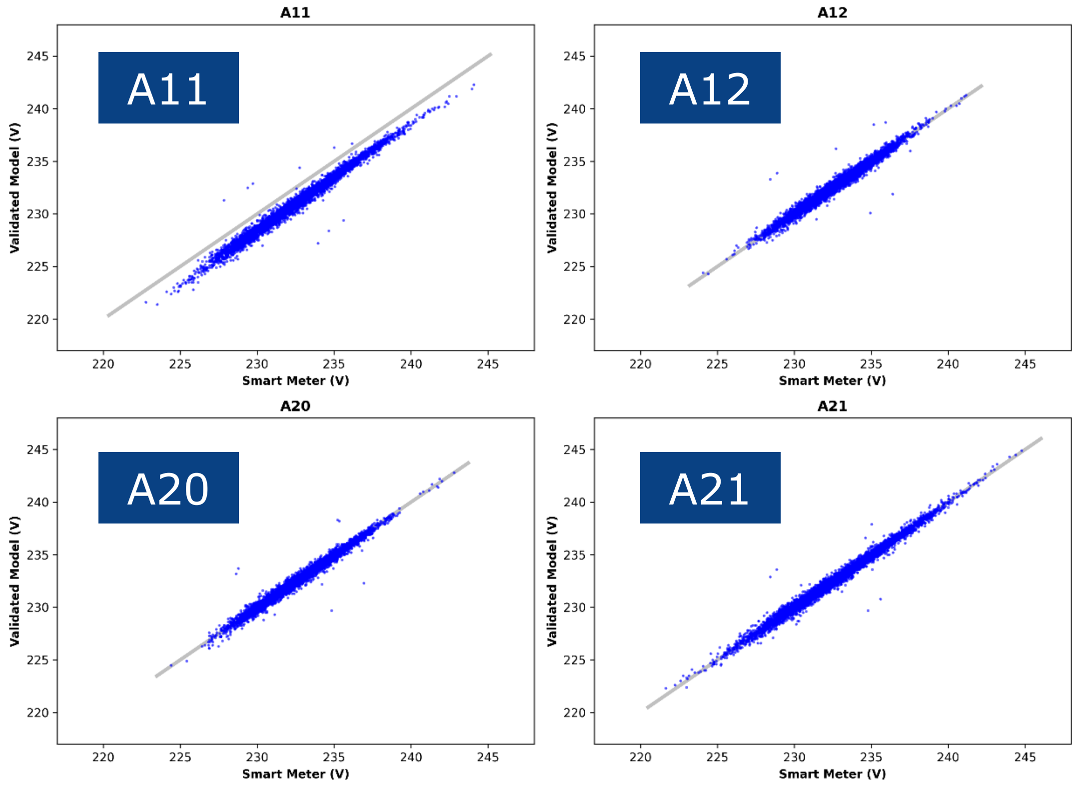
Unvalidated vs Validated Electrical Model (Voltage Calculations)

Initial



Lots of work

Final



Initial Model → Does not capture the physics

Final/Validated Model → Way better ☺

… but, can we do this in just minutes instead of weeks?

4 Model-Driven vs Model-Free
Implementing our Model-Free Approach in EDGE

NN Adaptation

- Using smart meter data + head-of-feeder voltage measurements[5]:

$$V = f_{NN}(P, Q, W) \rightarrow V = f_{NN}(P, Q, V_h, W)$$

Development → Same as before

- **Data Processing**
  - Historical smart meter data + head-of-feeder voltages (~6 weeks, 5min)
- **NN Production**
  - Use NN recipe

A very straightforward process ☺

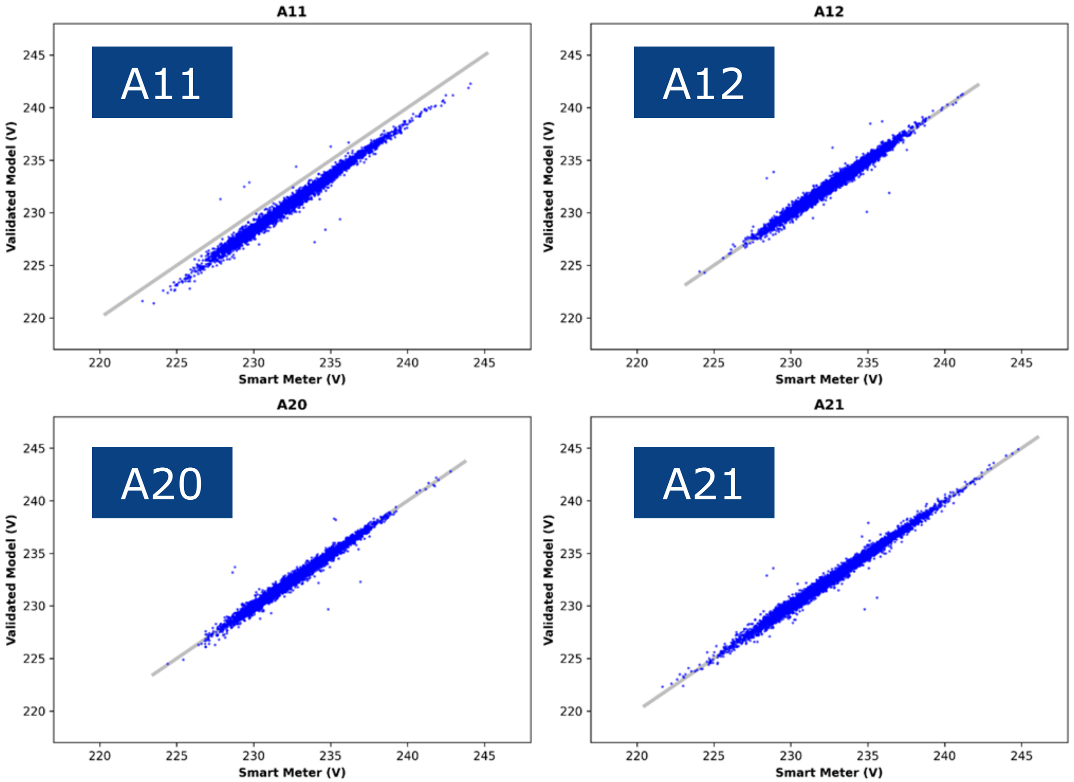
[5] *Deliverable 0: Concept, Smart Meter Data, and Initial Findings*, Report, 2022 (ResearchGate)

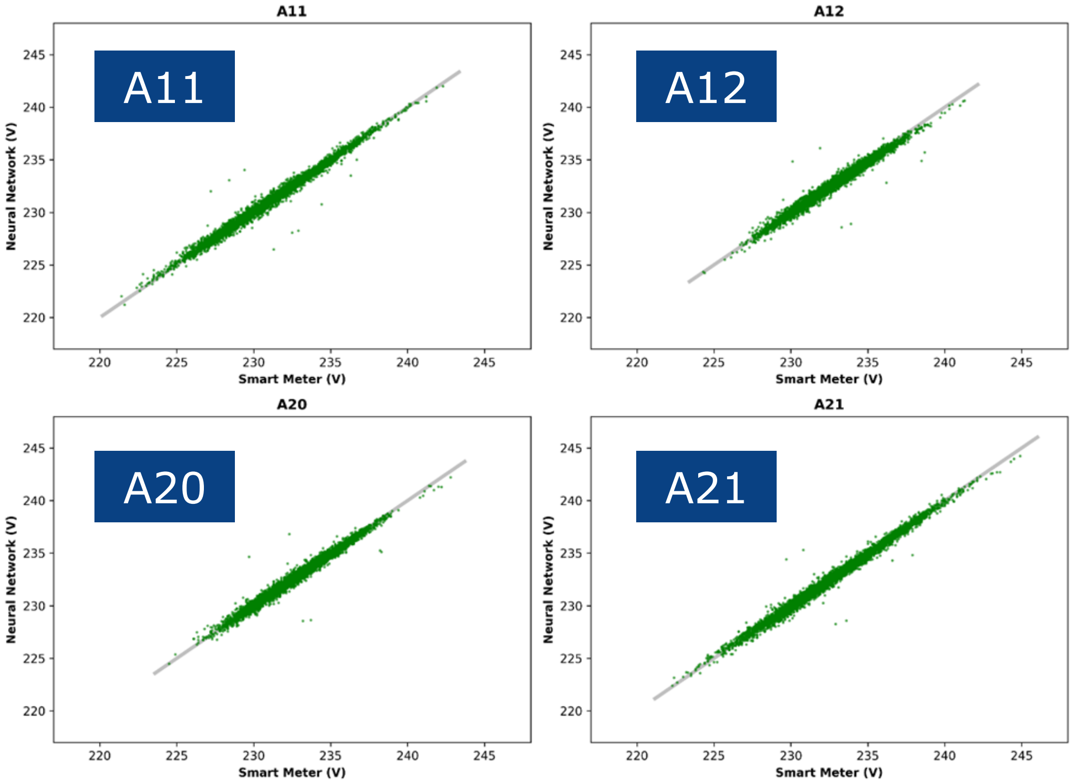
4 Model-Driven vs Model-Free

Validated Electrical Model vs NN (Voltage Calculations)

Electrical Model
Slow, expensive process

Neural Network
Fast and cheap ☺

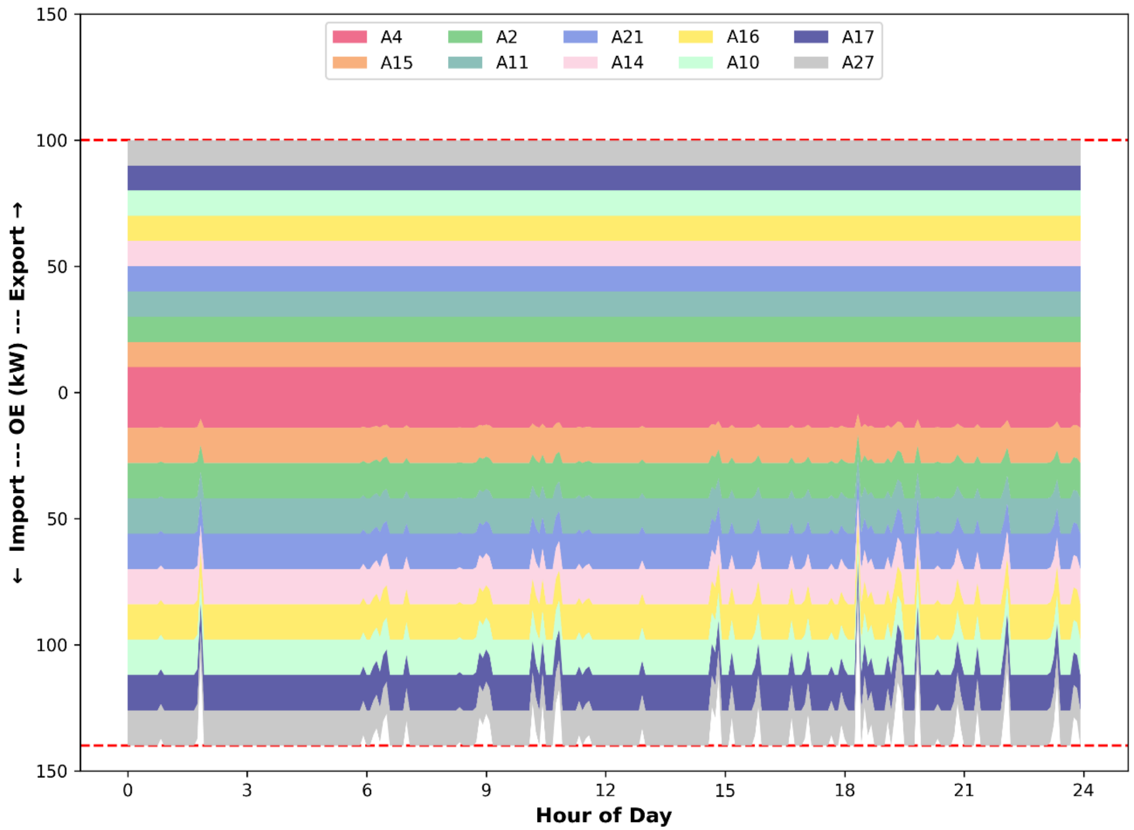


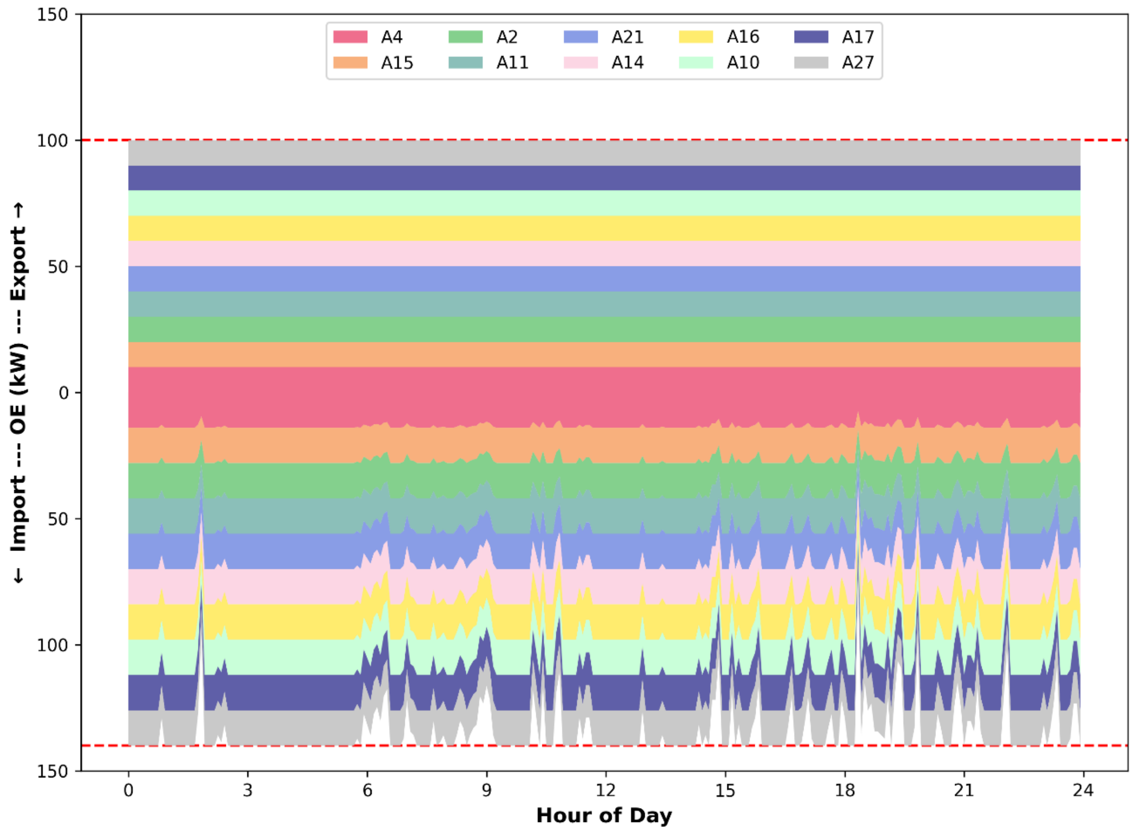


NN outperforms the electrical model!

4 Model-Driven vs Model-Free

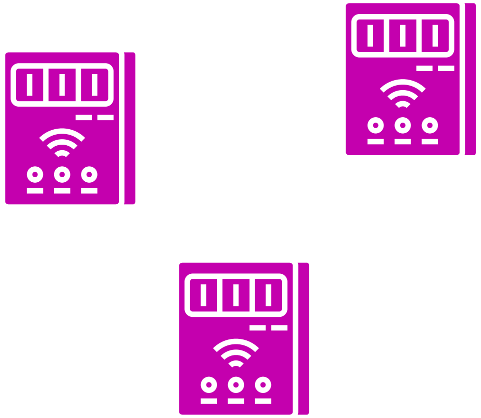
OEs for Site A[3] - *Model-Driven (Left) vs Model-Free (Right)*





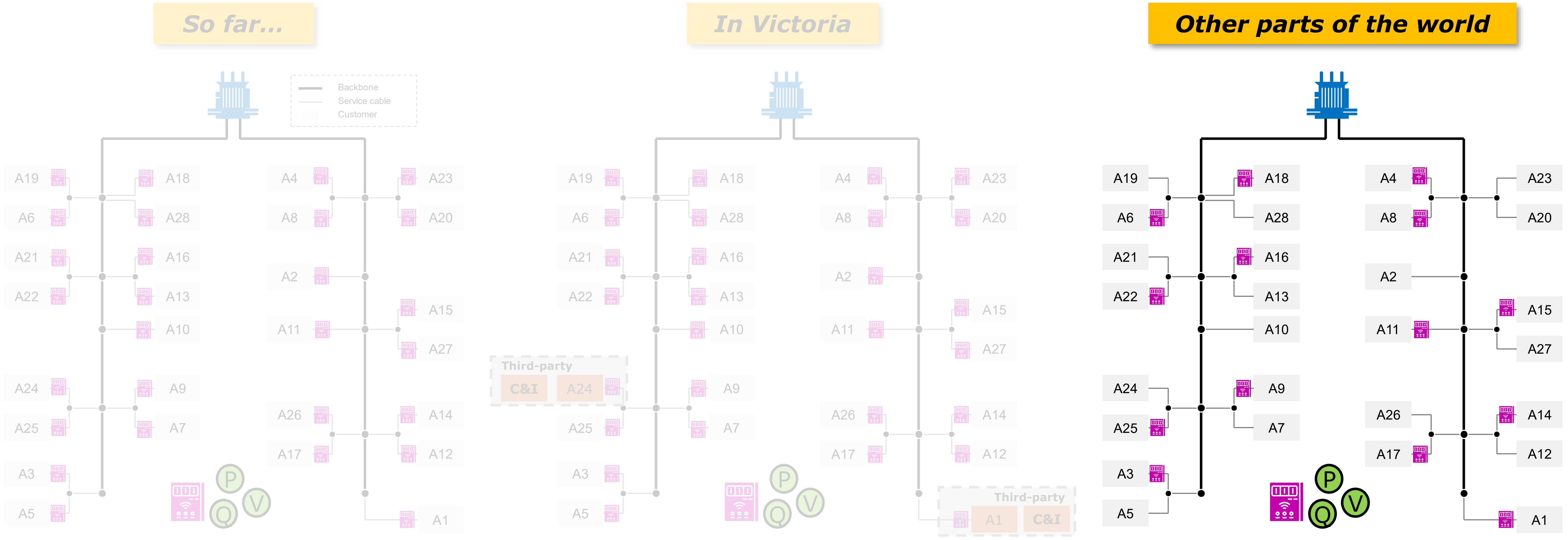
Overall, very consistent performance for both approaches ☺

[3]Equal opportunity objective function is used; historical data is used as forecasts



5 Partial Smart Meter Data Availability

5 Partial Smart Meter Data Availability
Context



<u>Key Question:</u> Can we use our method when data from all customers is not available?

5 Partial Smart Meter Data Availability

Preliminary Analyses – Overview and Assumptions

Partial vs Full Observability

- Partial: Data from all 3Φ customers is *assumed* unavailable
  - Data is **not used** **to produce the NN or to assess its performance**
- Full: Data from all customers is available
  - All data is used

Jemena Case Study

- **Site:** 1 Distribution transformer with **4 LV circuits**
- **148 customers:** 110 1Φ and 38* 3Φ
- **NN Production: Resolution:** 5 minutes ($\boldsymbol{P}, \boldsymbol{Q}, \boldsymbol{V}$)
- **NN Production:** ~3 weeks (Training data)
- **Performance Assessment:** ~Next 3 weeks (Test data)

* 1 phase from 2 three-phase customers were removed due to unfeasible measurements

5 Partial Smart Meter Data Availability
Preliminary Analyses – Results

Scenario	Inputs (Ps and Qs)	Outputs (Vs)	Training data points
Full Observability	2*(110 + 2*2 + 36*3) = **444**	110 + 2*2 + 36*3 = **222**	**4,027,968**
Partial Observability	110*2 = **220**	**110**	**1,995,840**

Almost 50% of the data is not available!

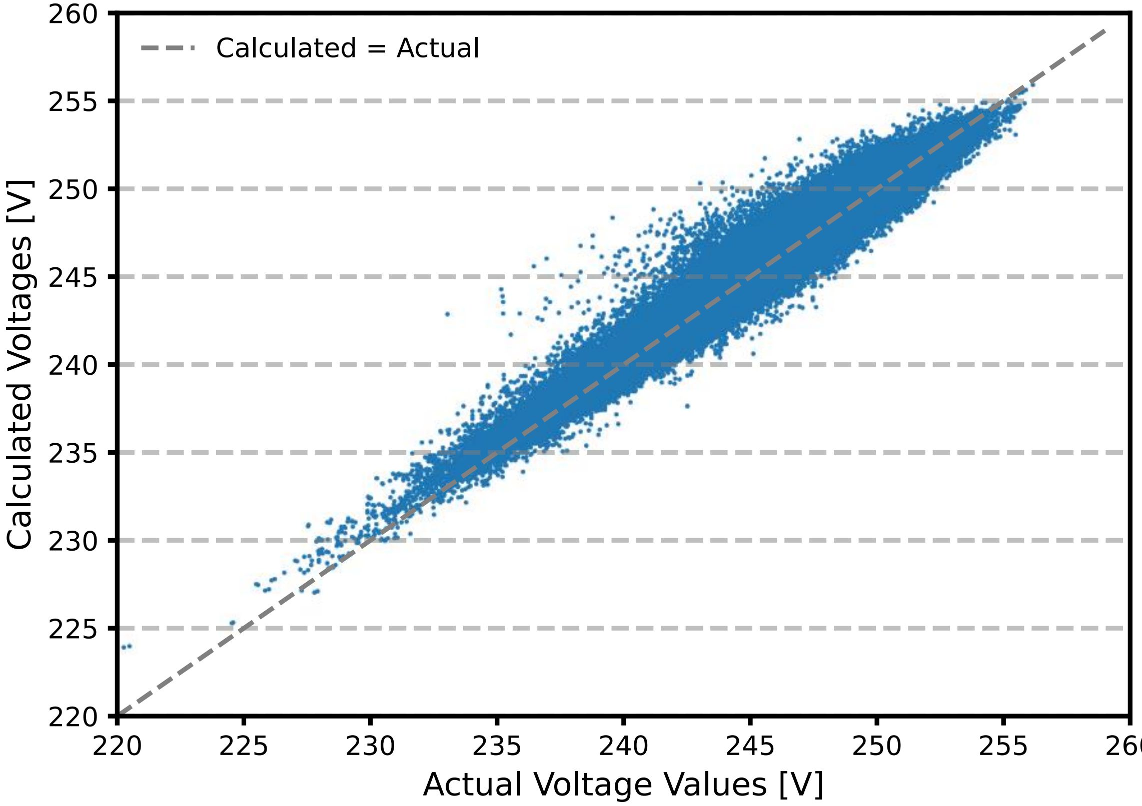
Scenario	RMSE Test [V]	Av Dev Test [V]	Max Dev Test [V]
Full Observability	0.55	0.43	9.70
Partial Observability	0.97	0.76	9.88

Despite the accuracy decrease in the case of partial observability, accurate voltage calculations are obtained in both scenarios ☺

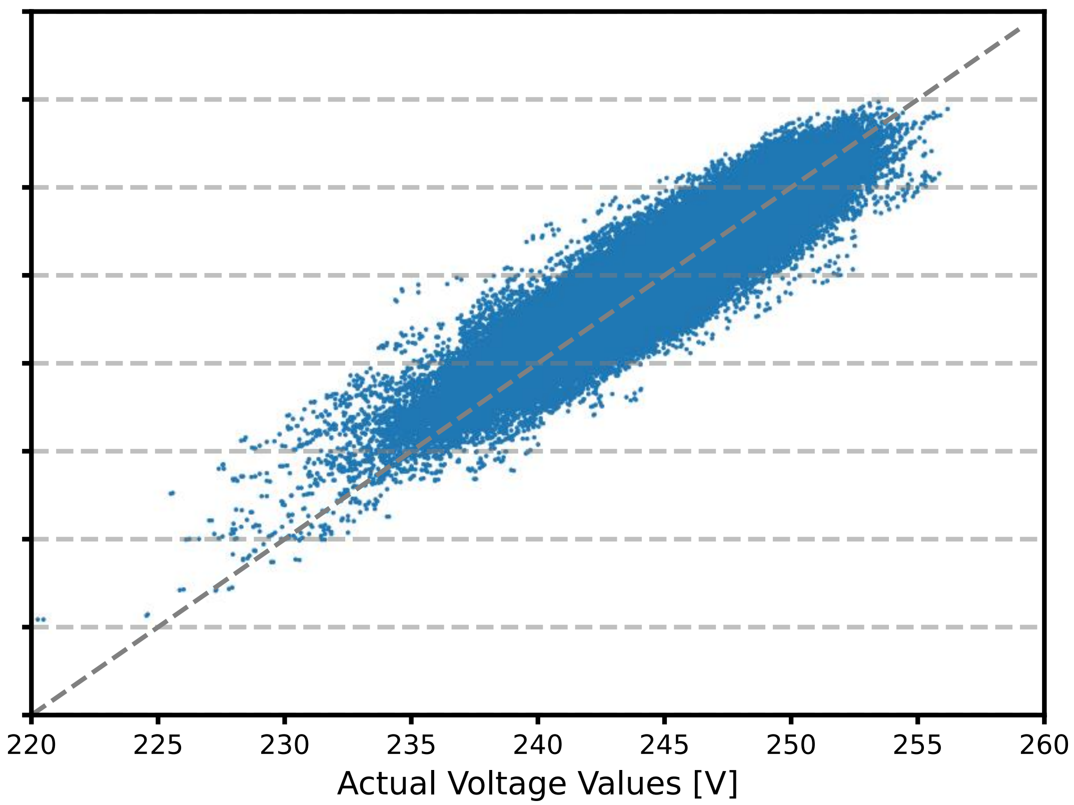
5 Partial Smart Meter Data Availability

Preliminary Analyses – Results

Full Observability



Partial Observability *(~50%)*



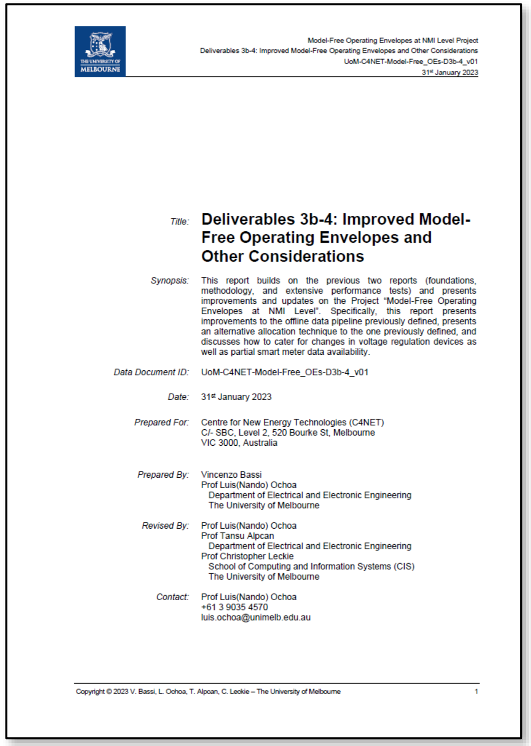
Accuracy decrease with partial availability (*as expected*).
But we can still produce accurate voltage calculations ☺

5 Partial Smart Meter Data Availability

Further Details

- **What about the calculation of OEs?**
  - ➢ You can find this in our latest report available at ResearchGate
  - ➢ Spoiler Alert: **Consistent OEs are obtained ☺**

- **Deliverables 3b-4:** Improved Model-Free Operating Envelopes and Other Considerations
  - ✓ Offline Data Pipeline Improvements
  - ✓ Operating Envelopes Allocation Technique: Maximise Exports
  - ✓ Voltage Regulation Devices
  - ✓ Partial Smart Meter Data Availability



Model-Free Operating Envelopes at NMI Level Project
Deliverables 3b-4: Improved Model-Free Operating Envelopes and Other Considerations
UoM-C4NET-Model-Free_OEs-D3b-4_v01
31st January 2023

Title: **Deliverables 3b-4: Improved Model-Free Operating Envelopes and Other Considerations**

Synopsis: This report builds on the previous two reports (foundations, methodology, and extensive performance tests) and presents improvements and updates on the Project "Model-Free Operating Envelopes at NMI Level". Specifically, this report presents improvements to the offline data pipeline previously defined, presents an alternative allocation technique to the one previously defined, and discusses how to cater for changes in voltage regulation devices as well as partial smart meter data availability.

Data Document ID: UoM-C4NET-Model-Free_OEs-D3b-4_v01

Date: 31st January 2023

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6 Key Remarks

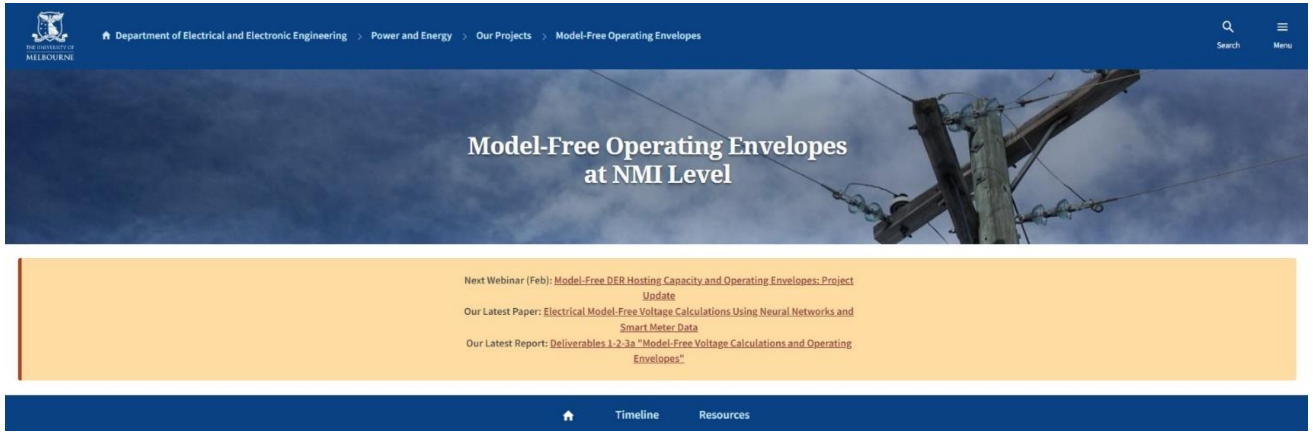
6 Key Remarks

- ***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** (many times faster than power flows) to assess DER connection request DER Hosting Capacity, Operating Envelopes, etc.
  - NN can even **outperform** good electrical models
  - **Minimum data needed?** 3 weeks (5-min res) and (potentially) ~50% of data/customers

- *Some Challenges Remain*
  - **Reactive power** still bring some headaches
  - **Topological changes?** → NN needs updating (same for any electrical model)
    - But a NN could flag this change
  - **SWER networks?** → Tricky but not impossible

Further Reading

- **Our Project**



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

- **Latest Publications**

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

Deliverable 3b-4: Improved Model-Free Operating Envelopes and Other Considerations, Report, 2023 (ResearchGate)

Deliverable 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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