THE UNIVERSITY OF MELBOURNE

Title: **WP 1.5 Integrated MV-LV Network Studies to Assess Electrification Impacts**
Milestone 1: Literature Review on Electrification Impacts

Document ID: UoM-C4NET-ESP-WP15-M1_LitRev_Report_v01

Date: 14th May 2024

Prepared For: Centre for New Energy Technologies (C4NET)

Authors: Jing Zhu, Dr Arthur Gonçalves Givisiez, Prof Nando Ochoa
Department of Electrical and Electronic Engineering
The University of Melbourne

Contact: Prof Nando Ochoa
luis.ochoa@unimelb.edu.au

Jing Zhu
jing.zhu@unimelb.edu.au

Executive Summary

This report corresponds to "*Milestone 1: Literature Review on Electrification Impacts*" of Work Package 1.5 (WP1.5) *"Integrated MV-LV Network Studies to Assess Electrification Impacts"*. WP1.5 will ultimately provide recommendations to Victorian distribution companies about network planning beyond 2030 as part of the Centre for New Energy Technologies (C4NET)'s Enhanced System Planning (ESP) project. This report presents the Victorian context in terms of Distributed Energy Resources (DERs), a literature review on existing electrification impact studies around the world (and the corresponding research gaps), and an overview of state-of-the-art DER studies that will inform the approaches to be adopted by WP1.5.

The key findings and recommendations are outlined below:

Victorian DER Uptake and Challenges

- The adoption of DERs is on the rise in Victoria, with many households embracing new technologies such as rooftop solar photovoltaics (PVs), electric vehicles (EVs), residential batteries as well as gas electrification (e.g., heat pumps).
- While this surge in DER adoption aligns with the Victorian Government's renewable energy targets, it poses technical challenges (such as voltage issues and/or asset congestion) to the distribution networks (the 'poles and wires') as they have not been designed to host excessive generation from solar PVs and new demand from EVs/gas electrification.

Research Gaps

- Many studies focus on asset congestion issues based on net demand forecasts which neglects potential customer voltage issues. Studies that cater for both thermal and voltage issues carry out power flow simulations. However, those studies often do not consider the interactions between the Medium Voltage (MV, e.g., 22kV line-to-line) and Low Voltage (LV, e.g., 400V line-to-line) parts of distribution networks. Instead, such studies are done for either the MV or LV part. This leads to an incomplete assessment that can under or overestimate the impacts from DERs as well as the benefits from potential solutions.
- Most studies around the world focus on one or two DER technologies according to their regions (e.g., residential solar PV and batteries in Australia, EVs and heat pumps in the USA and Europe). The quantification of impacts from a mix of DER technologies has not been adequately covered and this can mask the actual scale of the challenges. Similarly, potential solutions must consider a mix of DERs to truly capture their effectiveness.

Recommendations on Electrification Impact Assessment

- An advanced and realistic model-based approach is recommended to assess the electrification impacts in integrated MV-LV distribution networks. This requires detailed network electrical models for power flow simulations, which will be produced by WP1.3. It is critical for this approach to consider the unbalanced nature of distribution networks by running three-phase power flows, as well as the time-varying nature of demand and generation by considering adequate time-series simulations (e.g., 30-min intervals).
- The realistic modelling of DERs (i.e., time-series profiles and technical behaviour of solar PVs, EVs, batteries and gas electrification) is also recommended for the impact assessment. Furthermore, realistic DER management strategies can also be assessed. For Australia, in particular, this includes the use of flexible export limits, smart EV charging, and similar. The value brought by such strategies can then be compared with conventional options used by distribution companies (e.g., network augmentation).

Table of Contents

Executive Summary **2**

Table of Contents **3**

Abbreviations and Acronyms **4**

1 Introduction **5**

1.1 The Victorian Context 5

1.2 Overview of WP1.5 6

1.2.1 Aims and Objectives 6

1.2.2 Key Milestones 6

2 Literature Review **8**

3 State-of-the-Art Australian DER Studies **12**

3.1 DER modelling 12

3.1.1 Rooftop solar PV 12

3.1.2 Light-duty EV 12

3.1.3 Residential battery 12

3.1.4 Gas electrification 12

3.2 Network Impact Assessment 13

3.2.1 Model-based approach 13

3.2.2 Model-free approach 13

3.3 DER Management Strategies 14

3.3.1 Flexible export limits 14

3.3.2 Tailored PV inverter settings 14

3.3.3 EV charging management and TOU tariffs 14

4 Conclusions and Recommendations **15**

References **16**

Abbreviations and Acronyms

ADMD	After Diversity Maximum Demand
AEMO	Australian Energy Market Operator
ARENA	Australian Renewable Energy Agency
C4NET	Centre for New Energy Technologies
DER	Distributed Energy Resource
ENA	Energy Networks Australia
ESP	Enhanced System Planning
EV	Electric Vehicle
LV	Low Voltage
MV	Medium Voltage
NMI	National Metering Identifier
NYSERDA	New York State Energy Research and Development Authority
OE	Operating Envelope
PV	Photovoltaics
TOU	Time-of-Use

1 Introduction

This section presents the Victorian context in terms of the uptake of Distributed Energy Resources (DERs), along with an overview of Work Package 1.5 (WP1.5), including the key milestones, their timeline, and the corresponding linkages.

1.1 The Victorian Context

Hundreds of thousands of Australians (including Victorians) are embracing the use of DERs – seizing the opportunity to generate, store, manage or sell their own energy. These DERs include rooftop solar photovoltaics (PVs), electric vehicles (EVs), residential batteries as well as gas electrification (e.g., heat pumps). As shown in Fig. 1 [1], which is based on AEMO's forecast of DER installed capacity by 2050 [2], solar PVs will continue to be the prominent DER technology adopted in Australia. The uptake of batteries will also increase steadily, though not as significantly as solar PVs. However, EVs will emerge as a huge DER in the next few years.

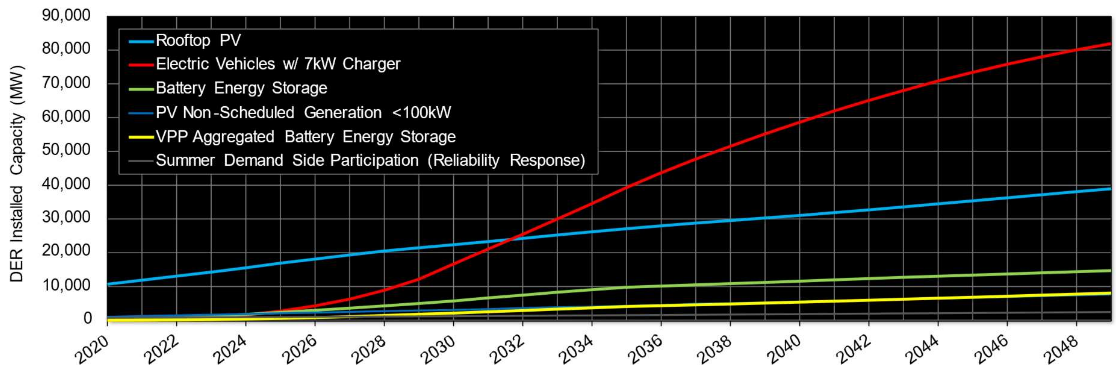

Figure 1. DER Installed Capacity Forecast [1]

In the context of Victoria, according to the State Government's vision [3], 1 in 3 households will have solar PVs installed by 2025, which can deliver up to 60% of our energy demand at times. A total of 740MWh of residential batteries will be available by 2025 (equivalent to the capacity of 25 Ballarat Energy Storage Systems [4]). 50% of all new light-duty vehicle sales are projected to be EVs by 2030. Moreover, a gas substitution roadmap was released in 2022 to speed up the home electrification. The rapid uptake of various DER technologies will help Victoria meet its legislated renewable energy targets of 40% by 2025, 50% by 2030, and ultimately net-zero emissions by 2050.

However, in the meantime, these DER technologies will potentially pose significant challenges to the power grid, particularly on the very infrastructure they are connected to: the distribution networks (the 'poles and wires'). Distribution networks were originally designed to cope with peak residential demand, and they are not engineered to host massive solar PV generation (which can lead to excessive voltage rise [5], [6]) and/or the additional EV demand (which can exacerbate voltage drops, also leading to asset congestion [7], [8]). According to the forecast daily load profile from the Victorian Annual Planning Report [9], shown in Fig. 2, a significant increase in both the reverse power flow during midday (11am-1pm) and peak demand during the night (6pm-8pm) is expected from the massive PV generation and EV demand, respectively. Given this, customer voltages can get close to both the upper and lower limits at different times of the day, posing larger challenges to distribution companies for voltage regulation. On the other hand, the initiative of gas electrification in Victoria will result in increased electricity demand, potentially exacerbating challenges similar to those observed with EVs, which requires further investigation for the network impacts.

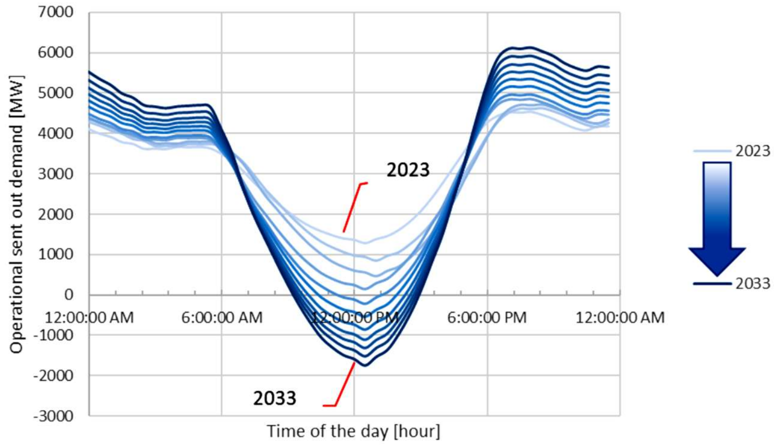

Figure 2. Victorian Daily Load Profile Forecast (2023-33) - Minimum Demand Day [9]

Consequently, to accommodate more DERs within Victorian distribution networks, it is critical for distribution companies to understand the potential challenges posed by a mix of DER technologies (e.g., voltage issues and/or asset congestion), as well as the solutions to address these technical barriers.

1.2 Overview of WP1.5

1.2.1 Aims and Objectives

WP1.5 *"Integrated MV-LV Network Studies to Assess Electrification Impacts",* as part of the C4NET's Enhanced System Planning (ESP) project, aims to:

- Assess the electrification impacts on Medium Voltage (MV, e.g., 22kV line-to-line) and Low Voltage (LV, e.g., 400V line-to-line) parts of distribution networks considering various scenarios (with considering different DER technology mixes, network types as well as DER management strategies);
- Model electrified demand profiles at zone substations for the sub-transmission network impact assessment;
- Provide after diversity maximum demand (ADMD) values that can help distribution companies with their network planning.

Overall, WP1.5 will provide valuable recommendations to Victorian distribution companies about network planning beyond 2030. These recommendations will ultimately help accelerate the electrification of distribution networks towards the Victorian goal of net-zero emissions.

1.2.2 Key Milestones

The key milestones, their timeline, and the corresponding linkages are shown in Fig. 3, with further details presented below.

Milestone 1: Literature Review on Electrification Impacts (Delivery: May 2024)

A short literature review report summarizing the state-of-the-art DER studies and providing recommendations on approaches to be adopted for Milestone 2.

Milestone 2: Electrification Impact Assessment (Delivery: Aug 2024)

A workshop presenting the findings from the electrification impact assessment on Victorian integrated MV-LV distribution networks. This assessment will carry out multi-scenario power flow analysis based on the outputs from WP1.1-1.4, including:

- Electrified heating/cooling profiles - From WP1.1 *"Technical modelling of electrification of heating and cooling profiles"*, considering different dwelling types, climate zones;
- EV charging profiles - From WP1.2 *"Technical modelling of electrification of transport profiles"*, considering different charging levels, day types, PV status;
- Scenario settings – From WP1.3 *"Scenario Planning"*, considering different DER technology mixes, types of customers, type of networks/areas;
- Integrated MV-LV network models - From WP1.4 *"Victoria whole-distribution network architecture via synthetic network models"*, representing different types of networks.

Milestone 3: Aggregate Demand Profiles & ADMD (Delivery: Nov 2024)

Two products are expected based on the modelling and results from Milestone 2:

- A set of electrified demand profiles at zone substations for the sub-transmission network impact assessment in WP1.6 *"Whole-State Network Impact Assessment"*;
- A set of ADMD values to inform distribution companies about their network planning.

Milestone 4: Final Report (Delivery: February 2025)

A final report presenting the findings of the 1-year project WP1.5, with a summary of input data and assumptions (suitable for "Assumptions Book"), as well as case studies.

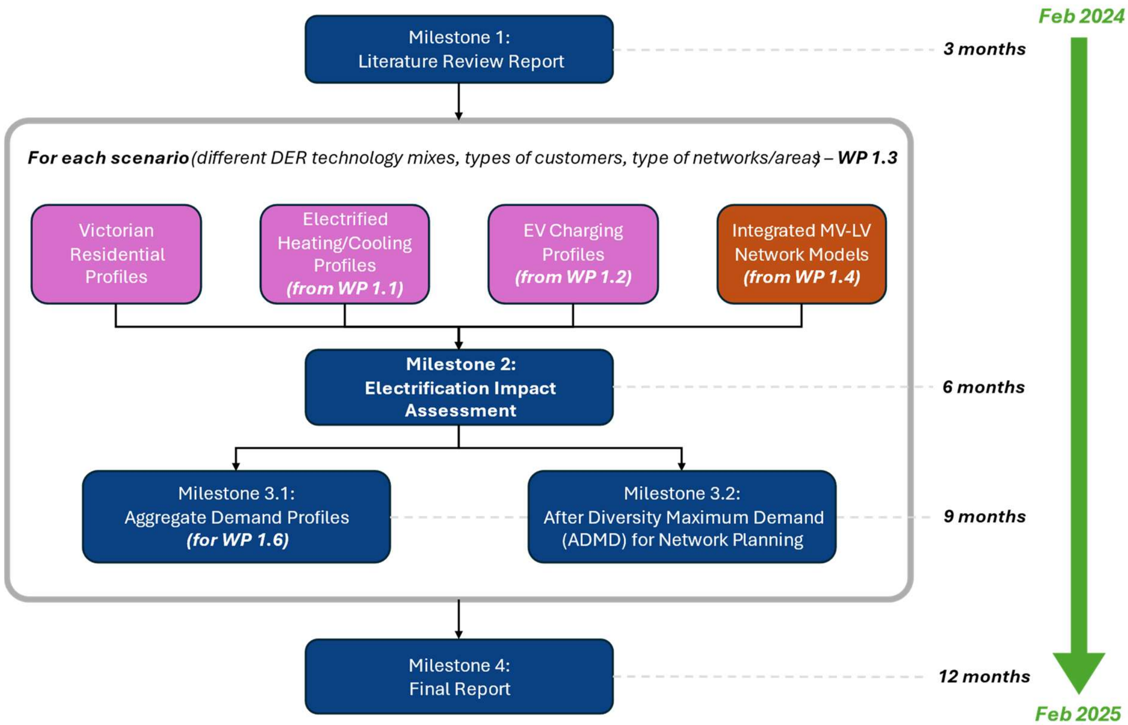

Figure 3. WP1.5 Milestones, Timeline, and Linkages

2 Literature Review

With the increasing adoption of various DER technologies around the world, many studies have been conducted to understand the potential challenges and opportunities related to their integration with the power grid. However, only a few of them consider the very infrastructure DERs are connected to: the distribution networks. This literature review delves into recent studies on DER uptake and distribution network planning, aiming to provide a thorough summary of the existing approaches of electrification impact assessment, as well as the DER management strategies adopted worldwide.

Since DER technologies can vary among regions of the world (e.g., residential solar PVs and batteries in Australia, EVs and heat pumps in the USA and Europe), different technical challenges are faced by distribution networks. To capture all the potential challenges and corresponding solutions, 14 DER studies from around the world are selected (including 8 from Australia, 3 from the USA and, 3 from Europe). Most of these studies were carried out in the past 5 years (2019-2024) in response to the surging uptake of DERs and the consequent need for effective solutions. Table 1 presents a comprehensive summary of these DER studies, including their scope and objectives, DER technologies considered, impact assessment methodology, network studied and potential solutions.

Among these studies, it is often the case that only one or two DER technologies are investigated according to their regions. For instance, Australia has the world's highest residential PV penetration (almost 1 in 3 houses have rooftop PVs), and the adoption of residential batteries along with PVs is also increasing rapidly. Thus, more efforts have been made to understand the potential network impacts of PV generation in Australia, as well as the solutions to increase the PV hosting capacity [10]-[14]. On the other hand, in the USA and Europe, light-duty EVs and electrified heating/cooling appliances (e.g., heat pumps) are the predominant technologies being adopted, resulting in extra demand that congests the existing network assets. Therefore, most studies aim to forecast the demand for electrification of transportation and heating, and thus, assess their potential impacts on distribution networks [15]-[18]. Only one EU study [19] and one Australian study [20] consider the mix of three DER technologies. However, either the impacts are assessed separately for each technology [19], or the DER management strategy is not fully modelled [20], which can lead to an under or overestimation of impacts. Therefore, an adequate impact assessment of a mix of DERs is still required to understand the actual scale of the challenges. Similarly, potential solutions must consider a mix of DERs to truly capture their effectiveness.

Furthermore, many studies adopt a simple approach to assess utilisation levels (of conductors and transformers) using demand/generation forecasts, which can provide a rough estimation. However, the potential customer voltage issues are often neglected in these studies [14], [15], [20], [21]. To evaluate both the voltage and asset utilisation aspects, a model-based approach (which requires detailed electrical network models for power flow simulations) is adopted in several advanced DER studies [10], [11], [13], [16]-[19], [22], [23]. However, in practice, most distribution companies do not possess detailed electrical models of their distribution networks, typically the LV part. In light of this, a model-free approach (which does not require explicit network models but needs historical smart meter data for machine learning) is also suggested by the research carried out by The University of Melbourne [10], [12]. These two approaches can be further investigated for their application in the electrification impact assessment, and both the customer voltage and asset utilisation aspects should be catered for in the assessment.

Table 1. Summary of DER Studies in AU, US and EU

Ref.	Type	Year	Lead Organisation	Scope & Objectives	DER Technology				Methodology	Network Studied			Potential Solutions	
					PV	EV	Heat pump	Bat tery		Dist. (LV)	Dist. (MV)	Trans.	Network solutions	Non-network solutions
[10]	Industrial project	2019-2021	The University of Melbourne (AU)	To investigate how distribution companies can make the most of their networks to facilitate high penetrations of residential solar PV.	•			•	Model-based power flow analysis & Model-free approach (supervised univariate regression model)	•	•		Reinforcements, Voltage regulation devices	Tailored PV inverter settings, Network smart energy storage systems
[11]	Industrial project	2020-2023	The University of Melbourne (AU)	To demonstrate the concept of "operating envelopes (OE)"—time-varying, meter-level export/import limits that a distribution company issues to aggregators—to ensure network integrity while facilitating DER services.	•			•	A data-driven approach of electrical mode validation & Model-based power flow analysis	•	•		/	Operating envelopes (i.e., flexible export limits)
[12]	Industrial project	2021-2023	The University of Melbourne (AU)	To provide the technical foundations for distribution companies to carry out voltage calculations without employing electrical models of LV circuits but, instead, exploiting primarily historical smart meter data.	•			•	Model-free approach using neural networks	•	•		/	Operating envelopes (i.e., flexible export limits)
[13]	Industrial project	2017-2020	University of Queensland (AU)	To support connection assessment for mid-sized PV systems (30-1500 kW) that are connected to MV network or to the LV terminals of distribution transformers.	•				Clustering analysis & Model-based power flow analysis		•		/	/
[14]	Industrial project	2019-2020	AEMO (AU)	To assess the power system limits as the penetration of distributed PV grows and how these limits may restrict PV export.	•				PV penetration and generation forecast (no power flow)	•	•	•	Rebalancing customer connections, Voltage regulation devices, Reinforcements	PV curtailment, DER orchestration
[15]	Industrial project	2020	Eugene Water & Electric Board (US)	To quantify the electrification impacts using data-driven analysis and to help the utility understand the policies, technologies and infrastructure needed to meet customers' changing needs.		•	•		EV and building heating demand forecast (no power flow)		•	•	/	Demand side management, Energy storage technology, Pricing and rate design

[16]	Academic Research	2022	University of California (US)	To advise the PG&E distribution infrastructure planning by modelling load shapes for electrified residential heating and EV charging.		●	●		Bottom-up load shapes modelling & Model-based power flow analysis	●			Reinforcements	Energy storage, Demand response
[17]	Industrial project	2022	NYSERDA (US)	To estimate the load and cost impacts of various clean transportation futures on New York State's electric distribution system, from both technical and economic perspectives.		●			Model-based power flow analysis & Multi-scenario assessment	●	●		Reinforcements, Voltage regulation device	Smart charging
[18]	Academic Research	2024	University of Würzburg (EU)	To analyse how the increase in power flow due to EV and heat pumps could result in coincident electricity demand and its impact on future Swiss distribution network investments.		●	●		A novel model for designing electricity distribution networks & Model-based power flow analysis	●			/	/
[19]	Industrial project	2019	Imperial College London (EU)	To accommodate accelerated electrification at manageable cost; carry out the necessary reinforcements; deploy the necessary generation capacity; and deliver the level of demand response needed.	●	●	●		Model-based power flow analysis	●	●		Reinforcements	New renewable generation capacity, Smart charging, Batteries and demand response
[20]	Industrial project	2024	SA Power Networks (AU)	To outline the methodology used to model the impact of future growth in DER on the distribution network, forecast demand for export services for the 2025-30 Regulatory Control Period, and explore the costs and benefits of different investment strategies.	●	●		●	DER penetration and net demand forecast (no power flow)	●			Reinforcements, Voltage regulation devices	Flexible export limits, Demand response, Time-of-use tariffs
[21]	Industrial project	2018	Evenergi (AU)	To understand the impact of PEVs on the South Australian power networks.		●			EV penetration and demand forecast (no power flow)		●		Reinforcements	Price signals, Smart charging
[22]	Industrial project	2020-2022	The University of Melbourne (AU)	To explore customer acceptance and expectations around EVs, distribution network impacts from unmanaged EVs, integration of EVs using active management strategies, and techno-economic aspects.		●			Model-based power flow analysis	●	●		/	EV management, Time-of-use tariffs
[23]	Academic Research	2016	KU Leuven (EU)	To assess the impacts of heat pump and PV on residential LV distribution grids as a function of building and district properties.	●		●		Model-based power flow analysis & Multi-scenario Monte-Carlo assessment	●			/	/

Nonetheless, most studies often do not consider the interactions between the Medium Voltage (MV, e.g., 22kV line-to-line) and Low Voltage (LV, e.g., 400V line-to-line) parts of distribution networks. Instead, only one voltage level is considered in many studies(either the MV part only [13], [15], [21] or the LV part only [16], [18], [20], [23]), which cannot lead to a complete assessment across the whole MV-LV distribution networks. For those that manage to consider both MV and LV parts, it is often the case that assessment is conducted separately, thus the voltage fluctuations and interactions are not captured, leading to under or overestimate the impacts from DERs as well as the benefits from potential solutions [14], [17]. Therefore, an integrated network impact assessment is required to simultaneously consider MV feeders down to LV single-phase customers, to fully capture the interactions between the voltage levels as well as their three-phase unbalanced nature.

In addition to impact assessment, different solutions are evaluated in these studies for their effectiveness to increase DER hosting capacity. They include both network solutions (i.e., leveraging network controllable elements or upgrading assets) and non-network solutions (i.e., managing customer-owned DERs). The network solutions, mostly as conventional options, are commonly adopted by distribution companies in Australia and worldwide (e.g., network augmentation [10], [14], [16], [17], [19]-[21], voltage regulation devices [10], [14], [17], [20] and customer connections rebalancing [14]). However, these network solutions can be costly and time-consuming (e.g., significant labour, expensive assets). On the other hand, the non-network solutions can be more cost-effective in eliminating technical issues using different DER management strategies (e.g., PV inverter control [10], [14], EV smart charging [17], [19], [21], [22], smart energy storage systems [10], [14]-[16], [19], [20], operating envelopes [11], [12], [20], demand response [15], [16], [19], [20] and time-of-use (TOU) tariffs [15], [20]-[22]). Thus, it is critical for WP1.5 to investigate both network and non-network solutions, so that the value brought by advanced DER management strategies can be compared with conventional options. With this comparison, a more practical and cost-effective solution mix can be offered to distribution companies.

Based on the comprehensive literature review on existing electrification impact studies around the world (and the corresponding research gaps) presented above, it can be recommended that WP1.5 should carry out impact assessment studies that cater for both voltage and asset utilization by considering integrated MV-LV distribution networks as well as a mix of DER technologies. To address the potential technical impacts, it is recommended that WP1.5 investigates, to the extent that is possible, both network solutions (e.g., conventional network augmentation) and non-network solutions (e.g., advanced DER management strategies) to provide a more effective solution mix.

3 State-of-the-Art Australian DER Studies

This section provides an overview of state-of-the-art Australian DER studies that will inform the approaches to be adopted by WP1.5, including DER modelling, network impact assessment and DER management strategies.

3.1 DER modelling

This part introduces the key modelling aspects and considerations for each DER technology that are recommended to be adopted by WP1.5.

3.1.1 Rooftop solar PV

A realistic solar PV modelling is proposed in the ARENA and AusNet-funded project "Advanced Planning of PV-Rich Distribution Networks" [10]. The key modelling aspects include:

- Irradiance (i.e., the power of solar radiation received by PV systems per unit area),
- Panel sizes (i.e., the PV installed capacity),
- Inverter settings (e.g., Australian standard Volt-Watt and Volt-var settings [24]).

3.1.2 Light-duty EV

A realistic light-duty EV modelling is proposed in the ENA and C4NET-funded project "EV Integration" [22]. The key modelling aspects include:

- Charging start time and duration (i.e., the timeframe from charging beginning to end),
- Daily charging times (i.e., the plug-in times per day),
- Daily plug-in factor (i.e., the percentages of EVs that will be charged for a certain day),
- EV charger sizes (i.e., the EV charger capacity),
- Power factor (i.e., the ratio of active power to apparent power drawn by EV chargers).

Since EV charging behaviours can vary greatly depending on the regions and type of customers (e.g., early adopters), it is critical to model the charging demand based on the analysis of local EV usage data. Therefore, a pool of realistic EV demand profiles from the ESP WP1.2 can be used to represent the latest Victorian EV customer charging behaviours [25].

3.1.3 Residential battery

As proposed in the project "Advanced Planning of PV-Rich Distribution Networks" [10], without any advanced control strategy applied, the residential batteries can be modelled with basic "off-the-shelf" operating principles: when PV generation exceeds household demand, the battery charges from all the surplus generation; when PV generation falls below the household demand, the battery discharges to meet the demand. Note that this basic battery control has a disadvantage: batteries can reach full state-of-charge very early, hence they become inadequate to reduce reverse power flow from excessive PV generation afterwards.

3.1.4 Gas electrification

The impacts of gas electrification (e.g., heat pumps) has not yet been adequately investigated in the existing Australian DER studies, since the gas substitution initiative has just come into effect. To enable a realistic modelling, a pool of electrified heating and cooling demand profiles from the ESP WP1.1 (considering different dwelling types, insulation types, building sizes and climate zones) can be used [26].

3.2 Network Impact Assessment

This part presents two approaches of network impact assessment: a model-based approach (which requires detailed network models for power flow simulations), and a model-free approach (which doesn't require explicit network models but needs historical smart meter data for machine learning). Given the integrated MV-LV network model from WP1.3, the model-based approach is recommended as it is more adaptable to various control techniques. Additionally, it is critical for this approach to consider the unbalanced nature of distribution networks, as well as the time-varying nature of demand and generation.

3.2.1 Model-based approach

A model-based approach can be used to assess the network impacts by running power flow simulations using specialised software packages [10], [11], [22] (e.g., OpenDSS [27]). It requires detailed electrical network models (i.e., topology, customer phase, and line impedance) and demand/generation profiles for different scenarios. The advantage of this model-based approach is that it is adaptable, i.e., network elements and customers can be changed, and control techniques can be implemented through power flows. Indeed, this is a conventional approach widely adopted by distribution companies in Australia and around the world to plan and improve their distribution networks.

To make the model-based approach highly effective to investigate the network impacts of residential DER technology mixes, it is critical for it to capture the unbalanced nature by running three-phase power flows, given that many residential customers (and, DERs) can be single-phase connected in distribution networks. However, in practice, most distribution companies do not possess detailed electrical models of their LV networks as required (i.e., only models of MV networks are readily available). To address this challenge, recent studies have provided solutions for LV network modelling, including a pseudo-LV feeder modelling method [28], [29] (which models LV networks realistically following LV design principles), and an LV network model construction method [30] (which exploits historical smart meter data to identify network models). Furthermore, it is also crucial for the time-varying nature (i.e., day-to-day and across various seasons) of demand and generation to be catered for considering adequate time-series simulations (e.g., 30-min intervals).

Consequently, the model-based approach shows greater potential for the impact assessment to be done by WP1.5 and to test different potential solutions.

3.2.2 Model-free approach

Given the challenges of acquiring detailed MV-LV network models, model-free approaches are reported in recent studies as a promising alternative to the conventional model-based approach [12], [31], [32]. To assess the thermal aspects using a model-free approach, the asset utilization can be estimated using either the aggregate net demand of corresponding customers (from smart meters) or available network monitoring data (per phase and per feeder). To assess the voltage aspects, different machine learning techniques are employed for customer voltage calculations, e.g., neural networks [31] and regression models [32].

However, since a complete model-free approach would require historical smart meter data of most residential customers, it is not recommended for WP1.5.

3.3 DER Management Strategies

This part introduces DER management strategies that, depending on time availability, could be investigated by WP1.5. These strategies include the use of flexible export limits, smart EV charging, and similar. The value brought by such strategies can then be compared with conventional options used by distribution companies (e.g., network augmentation).

3.3.1 Flexible export limits

A major barrier for distribution companies to eliminate technical issues brought by DERs is that they cannot directly manage behind-the-meter DERs or aggregators. In this context, a novel concept of flexible export limits (as known as operating envelopes) has been developed in "Project Edge" [11], [33], and officially published by Australian Energy Regulator in July 2023 [34]. It is defined as a "time-varying meter-level export limit" that a distribution company issues to aggregators, ensuring network integrity while facilitating residential DER services. Distribution companies only need to calculate and publish flexible export limits in advance (e.g., hours ahead), while aggregators subscribe to these limits to manage their DER portfolios.

Since flexible export limits will be soon an option for Victorian residential customers, it is critical for WP1.5 to assess its effectiveness in combination with other solutions.

3.3.2 Tailored PV inverter settings

For grid connections, default PV inverter settings are mandated to be embedded in residential PV systems. Victoria follows the Australian Standard AS/NZS 4777.2:2020 [24] which specifies Volt-Watt and Volt-Var PV inverter settings. These settings provide significant benefits to both customers (i.e., significantly less PV curtailment) and distribution networks (i.e., reduction of voltage rise issues). However, voltage issues are still not fully mitigated [35]. Therefore, tailored (stricter) Volt-Watt and Volt-Var PV inverter settings are recommended as a better solution to increase PV hosting capacity, involving the full curtailment of PV generation when reaching the upper voltage limit [36].

3.3.3 EV charging management and TOU tariffs

To increase the EV hosting capacity, two potential strategies are recommended in the studies: a direct approach that manages EV charging in real time [8], [37], and an indirect approach that adopts Time-of-Use (TOU) tariffs [37]. The direct approach is achieved through the remote control of EV charging points (by disconnecting and reconnecting or adjusting the charging demand) in response to real-time measurements. The indirect approach of adopting TOU tariffs assumes that EV customers will change their charging behaviours as they will be discouraged financially from charging during peak hours. This, in turn, can reduce coincident EV charging events and mitigate network impacts.

4 Conclusions and Recommendations

In conclusion, this report offers a comprehensive literature review of existing electrification impact studies carried out in both Australia and around the world (and the corresponding research gaps). It helps inform the state-of-the-art approaches to be adopted by WP1.5, including DER modelling, network impact assessment, as well as DER management strategies. WP1.5 will ultimately provide recommendations to Victorian distribution companies about network planning beyond 2030, thereby achieving the net-zero emissions by 2050.

The key findings and recommendations are outlined below:

Victorian DER Uptake and Challenges

- The adoption of DERs is on the rise in Victoria, with many households embracing new technologies such as rooftop solar photovoltaics (PVs), electric vehicles (EVs), residential batteries as well as gas electrification (e.g., heat pumps).
- While this surge in DER adoption aligns with the Victorian Government's renewable energy targets, it poses technical challenges (such as voltage issues and/or asset congestion) to the distribution networks (the 'poles and wires') as they have not been designed to host excessive generation from solar PVs and new demand from EVs/gas electrification.

Research Gaps

- Many studies focus on asset congestion issues based on net demand forecasts which neglects potential customer voltage issues. Studies that cater for both thermal and voltage issues carry out power flow simulations. However, those studies often do not consider the interactions between the Medium Voltage (MV, e.g., 22kV line-to-line) and Low Voltage (LV, e.g., 400V line-to-line) parts of distribution networks. Instead, such studies are done for either the MV or LV part. This leads to an incomplete assessment that can under or overestimate the impacts from DERs as well as the benefits from potential solutions.
- Most studies around the world focus on one or two DER technologies according to their regions (e.g., residential solar PV and batteries in Australia, EVs and heat pumps in the USA and Europe). The quantification of impacts from a mix of DER technologies has not been adequately covered and this can mask the actual scale of the challenges. Similarly, potential solutions must consider a mix of DERs to truly capture their effectiveness.

Recommendations on Electrification Impact Assessment

- An advanced and realistic model-based approach is recommended to assess the electrification impacts in integrated MV-LV distribution networks. This requires detailed network electrical models for power flow simulations, which will be produced by WP1.3. It is critical for this approach to consider the unbalanced nature of distribution networks by running three-phase power flows, as well as the time-varying nature of demand and generation by considering adequate time-series simulations (e.g., 30-min intervals).
- The realistic modelling of DERs (i.e., time-series profiles and technical behaviour of solar PVs, EVs, batteries and gas electrification) is also recommended for the impact assessment. Furthermore, realistic DER management strategies can also be assessed. For Australia, in particular, this includes the use of flexible export limits, smart EV charging, and similar. The value brought by such strategies can then be compared with conventional options used by distribution companies (e.g., network augmentation).

References

[1] L. Ochoa, A. Gonçalves Givisiez, D. Jaglal, M. Liu, and W. Nacmanson, *CSIRO Australian Research Planning for Global Power Systems Transformation Topic 8 "Distributed Energy Resources"*. 2021. [Online]. Available: https://www.researchgate.net/publication/354907244_CSIRO_Australian_Research_Planning_for_Global_Power_Systems_Transformation_Topic_8_Distributed_Energy_Resources

[2] '2022 ISP inputs, assumptions and scenarios', AEMO, 2022. [Online]. Available: https://aemo.com.au/en/energy-systems/major-publications/integrated-system-plan-isp/2022-integrated-system-plan-isp/2022-isp-inputs-assumptions-and-scenarios

[3] 'Harnessing Victoria's Distributed Energy Resources', The State of Victoria Department of Environment, Land, Water and Planning, 2022. [Online]. Available: https://www.energy.vic.gov.au/__data/assets/pdf_file/0042/579966/Harnessing-Victorias-Distributed-Energy-Resouces.pdf

[4] 'Ballarat Battery Energy Storage System Final Report', AusNet Services, Oct. 2021. [Online]. Available: https://arena.gov.au/assets/2021/10/ballarat-bess-final-report.pdf

[5] A. Navarro-Espinosa and L. F. Ochoa, 'Probabilistic Impact Assessment of Low Carbon Technologies in LV Distribution Systems', *IEEE Trans. Power Syst.*, vol. 31, no. 3, pp. 2192–2203, May 2016, doi: 10.1109/TPWRS.2015.2448663.

[6] A. T. Procopiou and L. F. Ochoa, 'Asset Congestion and Voltage Management in Large-Scale MV-LV Networks With Solar PV', *IEEE Trans. Power Syst.*, vol. 36, no. 5, pp. 4018–4027, Sep. 2021, doi: 10.1109/TPWRS.2021.3067838.

[7] J. Zhu, W. J. Nacmanson, L. F. Ochoa, and B. Hellyer, 'Assessing the EV Hosting Capacity of Australian Urban and Rural MV-LV Networks', *Electr. Power Syst. Res.*, vol. 212, p. 108399, 2022, doi: https://doi.org/10.1016/j.epsr.2022.108399.

[8] J. Quiros-Tortos, L. F. Ochoa, S. W. Alnaser, and T. Butler, 'Control of EV Charging Points for Thermal and Voltage Management of LV Networks', *IEEE Trans. Power Syst.*, vol. 31, no. 4, pp. 3028–3039, Jul. 2016, doi: 10.1109/TPWRS.2015.2468062.

[9] '2023 Victorian Annual Planning Report', AEMO, Oct. 2023. [Online]. Available: https://aemo.com.au/-/media/files/electricity/nem/planning_and_forecasting/vapr/2023/2023-victorian-annual-planning-report.pdf?la=en

[10] 'Advanced Planning of PV-Rich Distribution Networks', The University of Melbourne, Feb. 2021. [Online]. Available: https://electrical.eng.unimelb.edu.au/power-energy/projects/pv-rich-distribution-networks

[11] 'Project EDGE', The University of Melbourne, Apr. 2023. [Online]. Available: https://electrical.eng.unimelb.edu.au/power-energy/projects/project-edge

[12] 'Model-Free Operating Envelopes at NMI Level', The University of Melbourne, 2023. [Online]. Available: https://electrical.eng.unimelb.edu.au/power-energy/projects/model-free-operating-envelopes

[13] 'Solar Enablement Initiative', University of Queensland, Dec. 2019. [Online]. Available: https://arena.gov.au/assets/2018/02/uq-solar-enablement-initiative-final-report.pdf

[14] 'Renewable Integration Study Stage 1 - Appendix A: High Penetrations of Distributed Solar PV', AEMO, Apr. 2020. [Online]. Available: https://aemo.com.au/-/media/files/major-publications/ris/2020/ris-stage-1-appendix-a.pdf?la=en

[15] 'Electrification Impact Analysis', Eugene Water & Electric Board, Oct. 2020. [Online]. Available: https://www.eweb.org/documents/Reports%20and%20Publications/electrification-study-phase1-for-publication.pdf

[16] S. Elmallah, A. M. Brockway, and D. Callaway, 'Can distribution grid infrastructure accommodate residential electrification and electric vehicle adoption in Northern California?', *Environ. Res. Infrastruct. Sustain.*, vol. 2, no. 4, p. 045005, Dec. 2022, doi: 10.1088/2634-4505/ac949c.

[17] 'Transportation Electrification Distribution System Impact Study', NYSERDA, May 2022. [Online]. Available: https://www.nyserda.ny.gov/-/media/Project/Nyserda/Files/Publications/Research/Transportation/22-13-Transportation-Electricification-Distribution-System-Impact-Study.pdf

[18] G. Gust, A. Schlüter, S. Feuerriegel, I. Úbeda, J. T. Lee, and D. Neumann, 'Designing electricity distribution networks: The impact of demand coincidence', *Eur. J. Oper. Res.*, vol. 315, no. 1, pp. 271–288, May 2024, doi: 10.1016/j.ejor.2023.11.029.

[19] 'Accelerated electrification and the GB electricity system', Imperial College London, Apr. 2019. [Online]. Available: https://www.theccc.org.uk/wp-content/uploads/2019/05/CCC-Accelerated-Electrification-Vivid-Economics-Imperial.pdf

[20] 'CER Integration Modelling Methodology', SA Power Networks, 2024. [Online]. Available: https://www.aer.gov.au/documents/sapn-579-cer-integration-modelling-methodology-january-2024

[21] 'Managing the Impacts of Renewably Powered Electric Vehicles on Distribution Networks', Evenergi, 2018. [Online]. Available: https://arena.gov.au/assets/2019/03/managing-the-impacts-of-renewably-powered-electric-vehicles-on-distribution-networks.pdf
[22] 'EV Integration', The University of Melbourne, Sep. 2022. [Online]. Available: https://electrical.eng.unimelb.edu.au/power-energy/projects/ev-integration
[23] C. Protopapadaki and D. Saelens, 'Heat pump and PV impact on residential low-voltage distribution grids as a function of building and district properties', *Appl. Energy*, vol. 192, pp. 268–281, Apr. 2017, doi: 10.1016/j.apenergy.2016.11.103.
[24] 'AS/NZS 4777.2:2020 Grid connection of energy systems via inverters, Part 2: Inverter requirements'. 2020.
[25] H. Wang, A. Liebman, R. Razzaghi, M. Salehi, M. Jalili, and K. Hasan, 'WP1.2 Technical modelling of electrification of transport profiles - Task 1: Literature review', C4NET, Nov. 2023.
[26] A. De Corato, S. Mhanna, and P. Mancarella, 'WP1.1 Technical modelling of electrification of heating (and cooling) profiles - Task 1: Literature review', C4NET, Apr. 2023.
[27] R. C. Dugan and T. E. McDermott, 'An open source platform for collaborating on smart grid research', in *2011 IEEE Power and Energy Society General Meeting*, IEEE, 2011, pp. 1–7.
[28] A. T. Procopiou *et al.*, 'On the role of integrated MV-LV network modelling in DER studies', in *Proceedings of the CIRED Workshop, Berlin, Germany*, 2020, pp. 22–23.
[29] A. Procopiou and L. Ochoa, 'Advanced Planning of PV-Rich Distribution Networks - Deliverable 1: HV-LV modelling of selected HV feeders', 2019. [Online]. Available: https://www.researchgate.net/publication/334458042_Deliverable_1_HV-LV_modelling_of_selected_HV_feeders
[30] E. Karunarathne, L. F. Ochoa, M. Z. Liu, and T. Alpcan, 'Using Real Smart Meter Data to Construct Three-Phase Low Voltage Network Models', *Submitt. IEEE Trans. Power Syst.*.
[31] V. Bassi, L. F. Ochoa, T. Alpcan, and C. Leckie, 'Electrical Model-Free Voltage Calculations Using Neural Networks and Smart Meter Data', *IEEE Trans. Smart Grid*, pp. 1–1, 2022, doi: 10.1109/TSG.2022.3227602.
[32] A. Procopiou and L. Ochoa, 'Advanced Planning of PV-Rich Distribution Networks - Deliverable 2: Innovative Analytical Techniques', Oct. 2019. [Online]. Available: https://www.researchgate.net/publication/337853057_Deliverable_2_Innovative_Analytical_Techniques
[33] M. Z. Liu, L. F. Ochoa, P. K. C. Wong, and J. Theunissen, 'Using OPF-Based Operating Envelopes to Facilitate Residential DER Services', *IEEE Trans. Smart Grid*, vol. 13, no. 6, pp. 4494–4504, Nov. 2022, doi: 10.1109/TSG.2022.3188927.
[34] 'Flexible Export Limits: Final response and proposed actions', Australian Energy Regulator, Jul. 2023. [Online]. Available: https://www.aer.gov.au/system/files/Flexible%20Export%20limits%20Final%20Response%20-%20July%202023_1.pdf
[35] A. Procopiou and L. Ochoa, 'Advanced Planning of PV-Rich Distribution Networks - Deliverable 3: Traditional Solution', Feb. 2020. [Online]. Available: https://www.researchgate.net/publication/339472314_Deliverable_3_Traditional_Solutions
[36] A. Procopiou, M. Liu, W. Nacmanson, and L. Ochoa, 'Advanced Planning of PV-Rich Distribution Networks – Deliverable 4: Non-Traditional Solutions', Aug. 2020. [Online]. Available: https://www.researchgate.net/publication/344038943_Deliverable_4_Non-Traditional_Solutions
[37] W. J. Nacmanson, J. Zhu, and L. F. Ochoa, 'EV Integration - Milestone 8: EV Management and Time-of-Use Tariff Profiles', May 2022. [Online]. Available: https://www.researchgate.net/publication/360887067_Milestone_8_EV_Management_and_Time-of-Use_Tariff_Profiles