WP 2.7 & 2.8 Technoeconomic Modelling (Existing & Future)

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Project Consortium

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Abbreviations and Acronyms

BESS	Battery Energy Storage Systems
DER	Distributed Energy Resource
CER	Customer Energy Resource
PV	Photovoltaic
EV	Electric Vehicle
V2G	Vehicle-to-Grid
kW	Kilowatt
kWh	Kilowatt-Hour
MW	Megawatt
kVA	Kilo-Volt-Ampere
PU	Per Unit
AC	Alternating Current
LV	Low-Voltage
DNSP	Distribution Network Service Provider
NPV	Net Present Value
HEMS	Home Energy Management System
SOC	State-of-Charge
OCPP	Open Charge Point Protocol
ROI	Return on Investment
HWS	Hot Water System
ADMD	After Diversity Maximum Demand
PVUF	Phase Voltage Unbalanced Factor
LUoS	Local Use of Service
DOE	Dynamic Operating Envelope

Executive summary

This report presents an in-depth analysis of Distributed Energy Resource (DER) instruments as solutions to address demand-side management challenges within low-voltage (LV) distribution networks. The study is specifically focused on mitigating issues such as transformer overloading, voltage limit breaches, and hosting capacity constraints associated with high DER penetration, including solar photovoltaic (PV) systems and electric vehicles (EVs). It is important to note that the scope of the analysis is limited to LV distribution network issues and does not encompass broader system-level or market-related functions. This distinction is critical, as the future management of DERs and community batteries is expected to involve a more integrated approach that considers consumer behaviour, system operations, market dynamics, and network management responses. By narrowing its focus to LV networks, this study provides targeted insights for Distribution Network Service Providers (DNSPs) seeking to optimise their local infrastructure.

To facilitate this analysis, a modelling tool was developed as part of this project. This tool enables DNSPs to input specific LV network data and simulate the application of DER management instruments under various operational scenarios. By populating the model with real-world network data, DNSPs can evaluate the effectiveness of instruments such as community batteries, EV charging through solar soaking, and Vehicle-to-Grid (V2G) technology in alleviating specific network issues. This model provides an actionable framework for DNSPs to make data-driven decisions on deploying DER instruments within their networks.

The analysis confirmed that under high DER penetration scenarios, such as those involving 100% adoption of EVs and rooftop PV systems, LV networks are at risk of transformer overloading and voltage stability issues. While these risks may appear intuitive, the study's key findings delve deeper into the extent to which DER instruments can be leveraged to avoid or mitigate such issues. For instance, community batteries, when strategically located and appropriately managed, can absorb excess solar generation during the day and discharge energy during peak demand periods, significantly reducing transformer loading and improving voltage stability. Similarly, EV charging through solar soaking —where EV charging is shifted to align with solar generation—and V2G technologies can play complementary roles in reducing network strain. The findings highlight not just the risks posed by DER penetration but the effectiveness of these instruments in addressing specific network challenges under various conditions.

One critical aspect of the findings is that the effectiveness of these DER instruments is highly dependent on the nature of their control and management. It is not merely the deployment of community batteries, EV charging through solar soaking, or V2G systems that mitigates network issues, but how these tools are applied and managed. For example, the placement of community batteries—whether near transformers or at the end of feeders—directly impacts their ability to stabilise voltage. Similarly, the coordination of EV charging through solar soaking and V2G operations, including parameters such as charging times, State-of-Charge (SoC) limits, and export constraints, is essential for achieving optimal outcomes. This report emphasises the critical role of control strategies in maximising the benefits of DER instruments.

The modelling results provide several key insights into the technical impact of DER instruments and the conditions under which they are most effective. Community batteries, for example, are most beneficial in urban networks with high solar penetration and dense customer connections, where they can prevent backflow issues and defer costly transformer upgrades. Conversely, rural networks benefit from V2G technology, where the distributed nature of EVs offers flexibility in managing voltage constraints. While these findings do not constitute a full economic assessment, they provide a basis for understanding the circumstances under which specific DER solutions are viable. Further consideration of techno-economic models is recommended to evaluate the costeffectiveness of deploying these instruments across diverse network types.

The recommendations provided in this report are grounded in the insights gained from the modelling exercise. First, DNSPs could consider prioritising the deployment of community batteries in areas with high solar PV penetration, particularly at locations where voltage stability is a recurring issue. Second, EV charging through solar soaking could be incentivised through customer programs that encourage daytime charging, leveraging tariff structures or direct engagement strategies. Third, V2G technology could be explored for networks with significant EV penetration, with careful attention to export limits and SoC thresholds to balance grid stability with customer preferences. These recommendations highlight the importance of tailored strategies that consider the unique characteristics of each network and the specific functionality of DER instruments.

The limitations of this study are also worth noting. As mentioned earlier, the analysis does not extend to system-level or market-related functions, which are likely to play a significant role in the future integration of DERs. For instance, community batteries and V2G systems might increasingly interact with market mechanisms such as frequency control ancillary services (FCAS) and wholesale energy trading. While these aspects are beyond the scope of this report, they represent critical areas for future investigation and policy development. Additionally, the modelling focused on limited specific network types and may not capture the full diversity of Australia's and Victoria's representative LV networks. Expanding the dataset to include more varied network configurations will enhance the robustness of the findings.

1 Project Overview

The project addresses the critical challenge of managing the increasing integration of DERs within Australia's low-voltage electricity distribution networks. As the adoption of technologies like rooftop PV systems and EVs grows, these networks face significant stress, including transformer overloading, voltage breaches, and limitations in hosting capacity. This challenge is particularly acute in scenarios involving high DER penetration, such as 100% adoption of EVs and PV systems, which place unprecedented demands on grid infrastructure. Traditional electricity networks in Australia were designed for unidirectional power flows, with energy generated centrally and distributed to end users. The proliferation of DERs introduces bidirectional flows that these systems were not built to handle. Rooftop PV systems often generate excess energy during the day, creating reverse power flows that lead to transformer stress and voltage imbalances. Meanwhile, EV charging—particularly during evening peaks—further exacerbates transformer loading, creating a risk of overloading and reduced asset lifespan. Urban networks, which serve higher densities of customers with more varied energy demands, experience these challenges more severely than rural networks, though both face significant operational pressures. The variability of DER outputs, influenced by seasonal changes, adds complexity to grid management. For example, higher solar generation during summer months and increased electricity consumption during winter strain the grid differently throughout the year. These dynamics, coupled with rising DER adoption rates, are pushing the hosting capacity of many Australian networks to their limits, potentially requiring costly infrastructure upgrades.

The project models and evaluates three key DER management solutions: community batteries, EV charging through solar soaking, and V2G technology. These DER instruments are designed to mitigate grid challenges by improving network performance and extending hosting capacity. Community batteries store surplus solar energy generated during the day, discharging it during evening peaks to reduce transformer loading and smooth power flows. EV charging through solar soaking shifts charging behaviour to align with peak solar generation hours, decreasing reliance on the grid during high-demand periods. V2G technology transforms EVs into mobile energy storage units, enabling them to discharge energy back into the grid, alleviating strain during demand spikes. This project also explores the practical challenges of deploying these technologies, including financial, regulatory, and behavioural barriers. The high initial costs of infrastructure, coupled with regulatory constraints on DER participation in energy markets, pose significant obstacles. Furthermore, the success of solutions like EV charging through solar soaking and V2G is contingent on customer willingness to participate, highlighting the need for well-designed incentives and cost-effective pricing mechanisms.

Through detailed modelling and case studies of representative rural and urban networks, the project demonstrates the potential for these DER management tools to resolve network issues. It provides insights into how such solutions can reduce transformer overloading, stabilise voltage levels, and delay the need for expensive network upgrades. The project highlights the importance of integrated planning, stakeholder collaboration, and supportive policy frameworks to ensure that Australia's electricity networks can accommodate the growing presence of DERs sustainably and efficiently.

Work packages 2.7 and 2.8 aim to achieve three main objectives focused on the impact analysis of demand-side flexibility options within the context of Distributed Energy Resources (DERs) and electrification flexibility:

1. *Model DER instruments (Existing & Future) for DER Management (**DER Instruments**):* This objective seeks to create detailed models of DER instruments that facilitate the management of DERs. It aims to identify effective structures for integrating and optimising DERs. The goal is to ensure that market designs can support the efficient and reliable operation of DERs, maximising their benefits to the grid.
2. *Model Network-Aware Management of DER:* The second objective focuses on developing models that incorporate network-awareness into the management of DERs. This means creating systems that not only manage DERs based on market dynamics but also consider the physical constraints and operational needs of the distribution network. Network-aware management ensures that DER operations align with grid stability, reliability, and efficiency requirements.
3. *Analyse Impact on Network Load Profiles and Hosting Capacity:* The final objective aims to analyse how different market structures impact network load profiles and the hosting capacity of the distribution network. Hosting capacity refers to the amount of DERs that can be accommodated by the network without compromising its performance. By examining various scenarios and their effects on load profiles, this objective seeks to identify potential bottlenecks, areas for improvement, and strategies to enhance the grid's ability to integrate more DERs. This analysis is crucial for planning future network upgrades, developing regulatory policies, and designing incentive programs that support DER adoption.

1.1 Community Battery DER Instrument

Community batteries, often referred to as neighbourhood batteries, represent a new and innovative approach to energy storage and distribution within local communities. These batteries, typically ranging up to 5 MW in power capacity [1] or a capacity from 100 kWh up to 5 MWh [2], are strategically connected to electricity distribution networks. They play a critical role in the transition towards a decentralised and renewable energy grid by providing local energy storage solutions that balance supply and demand, enhance grid reliability, and support the integration of DERs like solar Photovoltaic (PV) systems.

Unlike traditional household batteries, which are designed to store energy for individual homes, community batteries serve entire neighbourhoods. They store excess energy generated by local solar panels during the day and discharge it during peak demand periods, thereby improving energy efficiency and reliability within the local grid. This approach ensures that renewable energy is utilised more effectively and reduces the need for extensive and costly upgrades to the distribution infrastructure.

The deployment of community batteries is gaining traction globally, with numerous pilot projects and feasibility studies highlighting their potential benefits [3]. For instance, the Electric Avenue

Feasibility Study conducted in Victoria, Australia, identified various use cases and commercial models for community batteries, demonstrating their viability and the multiple streams of benefits they can provide to local communities and the broader energy system [4].

1.1.1 Benefits of Community Battery for Distribution Networks

One of the primary benefits of community batteries is their ability for demand management and solar soak. By storing excess energy during periods of low demand and releasing it during peak times, community batteries help to smooth out fluctuations in the energy supply. This capability is particularly valuable in areas with high penetration of renewable energy sources, such as solar and wind, which are inherently variable and can create challenges for grid operators [1].

Community batteries facilitate higher levels of solar penetration within local grids by addressing the issue of solar export constraints. In many regions, the rapid uptake of rooftop solar PV systems has led to challenges in managing the excess energy generated, especially during midday when solar production peaks. Community batteries can absorb this excess energy, thereby preventing backflow issues and maintaining grid stability. This support for increased solar penetration aligns with broader environmental and renewable energy goals, helping communities to reduce their carbon footprint and achieve sustainability targets [4].

The ability of community batteries to manage local energy demand and supply effectively can defer the need for costly network upgrades. Traditional approaches to addressing increased energy demand or integrating more renewable energy often involve significant investment in upgrading the distribution infrastructure, such as building new substations or reinforcing existing lines.

Community batteries offer a more cost-effective alternative by optimising the existing network's capacity and delaying or even eliminating the need for such upgrades [1,5]. Community batteries can also participate in network services markets, providing valuable support to the overall electricity grid. These services include frequency regulation, voltage support, and contingency reserves, which are essential for maintaining grid stability and reliability. By offering these services, community batteries can generate additional revenue streams, enhancing their economic viability and contributing to the financial sustainability of the local energy system [5,6].

In regions prone to extreme weather events or natural disasters, community batteries could enhance energy resilience by providing backup power during outages. This capability is particularly important for remote or isolated communities that may face extended periods without grid power.

1.1.2 High Level Techno-economic of Community Battery

The ownership and operation of community batteries can follow various models, each with distinct implications for stakeholders. Common models include DNSP-owned, third-party owned, and community-owned batteries. DNPS-owned batteries are typically integrated into the distribution network by the utility company, optimising network performance and providing grid services. Third party-owned models involve private investors or energy service companies operating the batteries, often focusing on maximising economic returns through market participation and ancillary services. Community-owned models emphasise local control and benefit-sharing, where community groups or local governments own and manage the batteries, prioritising local energy needs and community engagement [5,7].

The implementation of community batteries faces several regulatory and technical challenges that must be addressed to realise their full potential. Regulatory barriers include restrictions on who can own and operate storage assets, as well as limitations on the types of services that can be provided [8]. For example, distribution network service providers in Victoria are prohibited from participating in energy markets, which limits their ability to maximise the value of community batteries. Technical challenges involve integrating batteries into existing grid infrastructure, ensuring interoperability with other DERs, and managing the complex control systems required for optimal battery operation [9].

Community engagement is a critical component of successful community battery projects. Engaging residents and stakeholders in the planning and decision-making process helps to build trust, ensure transparency, and address any concerns about the project's impact on the community. Effective community engagement strategies include public consultations, informational campaigns, and opportunities for local participation and investment. Ensuring that the benefits of community batteries are equitably distributed and aligned with community values is essential for gaining public support and fostering a sense of ownership and pride in the project [5,4].

The financial viability of community batteries depends on several factors, including initial capital costs, ongoing maintenance expenses, and potential revenue streams. Key cost drivers include the price of the battery itself, control systems, and network connection fees. Potential revenue sources include participation in energy markets, providing ancillary services, and receiving payments for network support. Financial models must carefully consider these factors to ensure that community battery projects are economically sustainable. Additionally, securing funding and investment, whether through grants, community contributions, or private investment, is crucial for the successful deployment of community batteries [4,10].

One of the key economic advantages of community batteries is their cost-effectiveness compared to individual household batteries. As of 2022, the cost of a community battery was approximately $700 per kW, significantly lower than the $1300 per kW for household batteries. Larger batteries, such as those with a capacity of 500 kWh, tend to be more cost-efficient than smaller ones, providing additional savings at scale. This cost advantage also extends to increasing the network's capacity to host more solar PV installations, which benefits both customers and operators by reducing congestion and deferring network upgrades. Feasibility studies, such as those conducted by Ausgrid, the Central Victorian Greenhouse Alliance, and the Australian National University (ANU), underscore the financial viability of community batteries. These studies highlight the benefits of community batteries in managing network demand, providing congestion relief, and supporting resource adequacy. The studies also demonstrate that batteries of varying sizes can effectively meet the energy needs of different community sizes and levels of solar PV penetration.

The financial viability of community batteries is further enhanced when they can access multiple revenue streams, such as wholesale market participation, network services, and customer involvement. This is particularly true for batteries owned by Distribution Network Service Providers (DNSPs) but operated by third parties, as these arrangements are often more costeffective than DNSP-owned and operated models. An example of this is ElectraNet's ESCRI battery at Dalrymple substation in South Australia, which provides both regulated and market services, showcasing the potential for community batteries to offer diverse value propositions.

However, the success of community battery projects depends on several factors, including their location, the specific network limit breaches they address, and the energy usage patterns of customers. Despite these challenges, the potential for community batteries to break even on a Net Present Value (NPV) basis as early as 2023 is promising, according to the KPMG report for Ausgrid. The cost of battery storage, which stood at $1,000 per kW in 2021, is projected to decrease by half by 2030, further improving the economics of community batteries. The CSIRO GenCost 2023-24 report [22] estimates the cost of utility-scale battery energy storage systems (two-hour duration) at approximately AUD $860/kWh in 2023, with costs expected to decline significantly as economies of scale and global learning rates improve. Household batteries are reported to cost between AUD $1,100 and $1,400/kWh, reflecting higher installation and balance-of-system expenses tailored to individual homes. Community batteries, while not explicitly detailed in the GenCost report, are mid-scale systems typically deployed in neighbourhoods or local distribution networks. Their costs are inferred to fall between those of household and utility-scale batteries, ranging from AUD $1,000 to $1,300/kWh, depending on factors such as system size, integration requirements, and site-specific expenses. These systems benefit from some economies of scale but also face higher costs due to network integration and installation complexities, especially in urban areas.

Current trends indicate that the cost of community batteries is projected to decrease, driven by technological advancements and economies of scale. This reduction in cost strengthens their economic viability, particularly for applications in urban and suburban networks, where they can offset infrastructure upgrades. While the potential for community batteries to break even in 2023 is supported by earlier studies, more recent data is limited in academic literature, requiring readers to focus on real-world pilot projects and industry reports, such as ARENA's 2024 market snapshot. The ARENA Community Battery Market Snapshot (**ARENA Snapshot**) [23] published in November 2024 highlights the economic dynamics and financial viability of community batteries in Australia, offering valuable insights for project development. These financials are based on community battery projects funded by ARENA amounting to 370 batteries. Project costs for community batteries vary widely, with per-unit storage costs ranging from $730/kWh to $4,100/kWh. The average weighted cost is $1,790/kWh, with larger batteries demonstrating economies of scale. Batteries with capacities of 500 kWh or more achieve lower costs per unit by distributing fixed expenses such as land, planning, and installation over larger volumes. The

ARENA snapshot suggests that Behind-the-meter (BTM) batteries – usually used as non-network solution – are generally more cost-efficient than front-of-meter (FoM) batteries – usually used as network solution – with average costs of $1,330/kWh compared to $2,300/kWh, respectively. These cost advantages make BTM batteries an attractive option for commercial operators seeking to integrate energy storage with existing infrastructure. Similar to Ausgrid and ANU Community battery reports, ARENA snapshot indicate that revenue for community batteries is derived from diverse streams, including energy arbitrage, frequency control ancillary services, demand charge reduction, and network support agreements. For BTM batteries, reducing peak demand charges can generate a significant proportion of revenue, particularly for sites with high energy consumption. FoM batteries often rely on network support agreements to defer infrastructure upgrades, though these arrangements can be less financially lucrative than other value streams. Despite the diversity of these revenue sources, there are challenges associated with their predictability. For example, fluctuating FCAS prices and non-alignment of demand charge reductions with actual network congestion can impact the reliability of income. Capital expenditure remains one of the primary challenges for community battery projects. Initial costs include the purchase of battery systems, site preparation, and integration with existing networks. These expenses are influenced by regional factors, with remote areas often incurring higher construction costs. In addition to upfront investment, ongoing operational expenses such as software updates, monitoring, and maintenance contribute to the overall cost profile of community batteries. Applicants to the ARENA program identified several key risks, including potential delays in battery supply, fluctuating revenue streams, and site access or stakeholder concerns. Early engagement with stakeholders, robust procurement processes, and conservative revenue modelling are being employed to mitigate these risks and ensure the financial sustainability of projects.

The ARENA snapshot report concludes that community batteries are positioned as a costcompetitive option within the broader energy storage market. They compare favourably to residential-scale batteries, such as the Tesla Powerwall 2, which has an installed cost of $1040/kWh, and utility-scale batteries, which average $640/kWh. This mid-scale solution is particularly well-suited to applications that require local energy storage, making them an essential tool in Australia’s transition to a decentralised, renewable energy system. However, ensuring their success requires addressing challenges related to revenue volatility, regulatory complexity, and site-specific constraints. Community battery projects offer significant potential to enhance grid stability, defer infrastructure investment, and increase renewable energy utilisation, making them a critical component of Australia’s energy strategy.

1.2 Vehicle-to-Grid DER Instrument

Vehicle-to-Grid (V2G) technology represents an advancement in the integration of Electric Vehicles (EVs) into power grids. This technology allows for the bi-directional flow of electricity between EVs and the power grid, enabling EVs not only to draw power from the grid for charging but also to supply power back to the grid when needed. This capability transforms EVs into mobile energy storage units that can contribute to grid stability and provide various ancillary services, thereby enhancing the overall efficiency and resilience of the power grid [11]. The fundamental components of a V2G system include EVs equipped with bi-directional chargers, communication infrastructure for data exchange between EVs and grid operators, and control systems that manage the flow of electricity based on grid requirements and the state of EV batteries. These systems can be integrated into existing smart grid frameworks, leveraging advanced algorithms and optimisation techniques to maximise efficiency and minimise costs. The technology not only benefits the power grid but also provides economic incentives to EV owners who can earn money by participating in demand response programs and selling electricity back to the grid [12]. The concept of V2G is grounded in the flexibility it offers to both EV owners and grid operators. For EV owners, V2G provides an opportunity to monetise their vehicles' battery storage capabilities by selling surplus energy back to the grid during peak demand periods. For grid operators, V2G represents a dynamic tool for balancing supply and demand, managing peak loads, and supporting the integration of DERs. This synergy between EVs and the grid can enhance the stability and resilience of power distribution networks, making them more adaptable to fluctuating energy demands and generation patterns.

1.2.1 Benefits of V2G for Distribution Networks

V2G technology offers potential for demand management within distribution networks. By controlling the charging and discharging of EVsT, grid operators can smooth out demand curves, reducing the strain on the grid during peak hours. This is achieved through smart charging strategies that shift EV charging to off-peak times and discharge power during peak demand periods. Studies have shown that V2G can reduce peak demand by up to 40% compared to unidirectional smart charging, which solely shifts charging times without providing power back to the grid [13].

Demand management is crucial for maintaining grid stability and efficiency. Uncoordinated charging of EVs can lead to significant spikes in electricity demand, particularly during evening hours when many EV owners return home and plug in their vehicles. This sudden increase in demand can strain the grid infrastructure, leading to potential overloads and power outages. V2G helps mitigate these issues by enabling EVs to discharge electricity back to the grid during peak periods, thus balancing the load and reducing the risk of grid congestion. Additionally, V2G can support demand response programs, where EV owners are incentivised to adjust their charging and discharging patterns based on real-time grid conditions. These programs help to align electricity consumption with generation, particularly from intermittent renewable sources such as wind and solar. By participating in demand response programs, EV owners can reduce their energy costs and contribute to a more sustainable and resilient power grid.

Grid congestion occurs when the demand for electricity exceeds the capacity of the power lines and substations, leading to potential overloads and voltage issues. V2G can alleviate congestion by providing localised power support. During periods of high demand, EVs can discharge stored energy back into the grid, helping to balance loads and maintain voltage stability. This is particularly useful in residential areas with a high penetration of EVs, where uncoordinated charging can lead to grid stress [14]. The ability of V2G to manage grid congestion is particularly relevant in urban and suburban areas where the density of EVs is high. In such areas, the simultaneous charging of numerous EVs can create substantial peaks in electricity demand, overwhelming the capacity of local distribution networks. V2G addresses this challenge by utilising the stored energy in EV batteries to supply power during peak periods, thereby reducing the load on transformers and distribution lines. Furthermore, V2G can enhance the reliability of power supply in congested areas. By providing additional power during critical times, V2G can prevent voltage drops and maintain the quality of electricity supply. This is essential for ensuring the smooth operation of sensitive electronic equipment and appliances that rely on stable voltage levels. The integration of V2G into distribution networks thus represents a proactive approach to managing grid congestion and enhancing the overall performance of the power grid.

Transformers are critical components in power distribution networks, converting high-voltage electricity from transmission lines to lower voltages suitable for consumer use. Overloading of transformers can lead to overheating, reduced lifespan, and potential failures. V2G helps mitigate transformer loading by distributing the load more evenly across the network. During peak periods, the discharging of EVs can reduce the burden on transformers, preventing overloads and extending their operational life [15]. Transformers are designed to handle a certain capacity of electrical load, and exceeding this capacity can cause thermal stress and degradation. Over time, this can result in the need for costly repairs or replacements. V2G addresses this issue by acting as a supplementary power source during peak demand periods, thereby reducing the load on transformers and other critical infrastructure components. The benefits of V2G in managing transformer loading are particularly evident in residential and commercial areas with high electricity consumption. V2G helps to level out the load on transformers, by enabling EVs to discharge power back into the grid, ensuring that they operate within their safe limits. This not only enhances the reliability of the power supply but also reduces maintenance costs and extends the lifespan of transformers, providing long-term economic benefits for grid operators.

1.2.2 Insights into the Use of V2G

Effective implementation of V2G requires robust operational frameworks that integrate EVs seamlessly into the grid. This includes the development of standards for bi-directional chargers, communication protocols, and grid management systems. The use of multi-agent systems and fuzzy cognitive maps has been proposed to manage the complex interactions between EVs and the grid, optimising charging and discharging schedules based on real-time data and predictive analytics [14]. They offer a sophisticated approach to managing the dynamic interactions within a V2G system. Multi-agent systems involve multiple autonomous agents, each representing a component of the grid, such as EVs, charging stations, and grid operators. These agents communicate and collaborate to optimise the overall performance of the system. Fuzzy cognitive, on the other hand, provide a graphical representation of the causal relationships between different variables in the system, enabling the identification of optimal strategies for charging and discharging EVs. The integration of multi-agent systems and fuzzy cognitive maps into V2G systems allows for real-time monitoring and control of electricity flows, ensuring that the system operates efficiently and reliably. These technologies can be used to predict demand patterns, identify potential bottlenecks, and implement corrective actions to prevent grid instability. The use of advanced algorithms and machine learning techniques further enhances the capabilities of multi-agent systems and fuzzy cognitive maps, enabling them to adapt to changing conditions and optimise system performance continuously.

The economic benefits of V2G include reduced energy costs for EV owners through participation in demand response programs and potential earnings from selling electricity back to the grid. Additionally, V2G contributes to environmental sustainability by supporting the integration of renewable energy sources. EVs can store excess energy generated from renewables, thus reducing reliance on fossil fuels [16]. The financial incentives for EV owners to participate in V2G programs are a key driver of its adoption. By providing power back to the grid during peak periods, EV owners can earn money and offset their electricity costs. This creates a win-win situation where both the grid and EV owners' benefit. Moreover, the ability to store and utilise renewable energy enhances the environmental credentials of V2G, contributing to the reduction of greenhouse gas emissions and promoting a cleaner energy future. V2G also supports the broader transition to a low-carbon energy system. By facilitating the integration of renewable energy sources, V2G helps to stabilise the grid and reduce the need for fossil fuel-based peaking power plants. The combination of economic and environmental benefits makes V2G an attractive proposition for both policymakers and consumers, driving its adoption and integration into modern power systems.

Despite its benefits, V2G faces several challenges. The high initial cost of bi-directional chargers and the potential for accelerated battery degradation are significant barriers. Additionally, the complexity of establishing market mechanisms and regulatory frameworks to facilitate V2G adoption cannot be underestimated. Effective policies and incentives are required to encourage EV owners to participate in V2G programs [17]. The cost of bi-directional chargers is more expensive than standard unidirectional chargers due to their increased complexity and functionality. The potential for battery degradation is another concern, as frequent charging and discharging cycles can reduce the lifespan of EV batteries. Addressing these challenges requires technological advancements that improve the efficiency and durability of bi-directional chargers and EV batteries. Establishing market mechanisms and regulatory frameworks to support V2G is also critical. This includes the development of pricing structures that incentivise EV owners to participate in V2G programs and policies that ensure the reliability and stability of the power grid.

Collaboration between government agencies, grid operators, and the private sector is essential to create a conducive environment for V2G adoption.

Several pilot projects and case studies have demonstrated the feasibility and benefits of V2G. For instance, Crozier et al. [13] conducted trials using Alternating Current (AC) low power V2G chargers in residential networks using dataset from the US and the UK, showing promising results in reducing peak demand and improving grid stability and the potential for V2G to support grid operations in regions with high EV penetration. Pilot projects are essential for testing and refining V2G technologies and operational frameworks. These projects provide valuable insights into the practical challenges and benefits of V2G, helping to inform the development of policies and standards. Research and development efforts are focused on improving the efficiency and durability of bi-directional chargers, enhancing the energy density and lifespan of EV batteries, and developing sophisticated algorithms for optimising V2G operations [18]. One area of innovation is the development of fast-charging bi-directional chargers that can provide quick and efficient energy transfer between EVs and the grid. These chargers can reduce charging times and increase the flexibility of V2G systems, making them more attractive to consumers. Additionally, advancements in battery technology, such as solid-state batteries, offer the potential for higher energy densities and longer lifespans, addressing concerns about battery degradation. Another area of focus is the integration of V2G with renewable energy sources. Advanced algorithms and machine learning techniques are being developed to optimise the charging and discharging schedules of EVs based on real-time data from renewable energy sources and grid conditions.

1.3 EV Charging through Solar Soaking DER Instrument

EV charging combined with PV generation (EV charging through solar soaking) provides numerous advantages, particularly for home charging systems. By harnessing solar energy to power EVs, this combination reduces dependence on the grid and decreases electricity costs. One significant benefit is the potential for cost savings, as homeowners can use solar energy from PV systems during daylight hours, reducing their electricity bills. When paired with smart charging, which schedules EV charging during peak solar generation periods, the use of renewable energy is maximised, further lowering costs. In terms of grid stability and load management, smart charging systems optimise charging times to avoid peak demand, reducing strain on the grid. This coordination with high PV generation periods not only prevents grid overloads but also helps stabilise the overall system. Additionally, using solar energy for EV charging reduces greenhouse gas emissions, making a significant contribution to carbon neutrality by combining two green technologies. Homeowners also benefit from increased energy independence by generating and consuming their own electricity, protecting themselves from fluctuations in electricity prices and potential grid outages. Another benefit is the increased utilisation of PV energy, as smart charging ensures that more solar energy is used to charge EVs rather than being wasted or sold back to the grid at lower rates.

EV charging through solar soaking works by using advanced technology to optimise charging time and rate. It involves scheduling charging during times when electricity rates are lower or renewable energy production is higher, often managed through mobile apps or home energy management systems. Load management ensures that the home's overall electricity use is balanced, preventing overloads while maintaining the smooth operation of other appliances. Some systems can also respond dynamically to grid signals, adjusting charging rates based on demand or available renewable energy. The technical aspects of EV charging through solar soaking include smart chargers, which communicate with the EV, home energy management system, and grid, enabling programmable schedules and dynamic load management. A Home Energy Management System (HEMS) integrates household energy sources, such as the PV system, and prioritises PV energy for EV charging. Communication protocols, like the Open Charge Point Protocol (OCPP), enable real-time data exchange to optimise charging. The PV system must be capable of producing sufficient energy, often requiring an inverter to manage bidirectional power flow, and smart charging systems need to be connected to the grid to adjust the charging process based on real-time data.

The implementation of EV charging combined with PV generation also requires regulatory changes. Adjustments to tariff structures might need to be considered to incentivise charging during high solar generation or low grid demand periods. Standardising communication protocols, such as OCPP, is crucial to ensure interoperability between different chargers, EVs, and energy management systems, as well as better grid integration. Regulatory support, including subsidies, tax incentives, and streamlined approval processes, will encourage the integration of PV systems with EV chargers. As more households adopt smart charging with PV, upgrades to local grid infrastructure are needed to manage distributed energy resources and bi-directional energy flow.

Economically, the initial cost of installing a solar PV system, smart charger, and potentially a battery storage system can be significant but varies based on location and incentives. In Victoria, residential solar PV systems typically cost between $5,000 and $10,000 out of pocket[1] after accounting for widely accessible state rebates and federal incentives, significantly less than the pre-rebate range of $8,000 to $15,000. Smart chargers range from $500 to $2,000, while battery storage systems add $5,000 to $10,000, although these costs are forecast to decline significantly as battery technology improves and economies of scale are realised. Despite these upfront costs, the operational savings can be substantial. By using solar energy for EV charging, homeowners reduce electricity bills, particularly in regions with high electricity rates or time-of-use tariffs. For example, in areas where grid electricity costs are highest during peak periods, charging EVs during peak solar generation times or periods of low grid prices can dramatically cut costs. While specific economic assessments are not applied in this section, the Return on Investment (ROI) for combined solar and smart charging systems generally depends on factors like local electricity prices, solar production, and EV usage patterns. Typical payback periods range from five to ten years, with government incentives such as rebates and net metering further improving economic feasibility. The falling cost of battery systems will likely shorten these payback periods in the future, making integrated solar and battery systems increasingly accessible and economically attractive.

[1] https://www.solarchoice.net.au/solar-panels/solar-power-system-prices/

2 Methodology

The framework, shown in Figure 1, is followed in the project to obtain the project objectives.

2.1 Inputs

The three required inputs are:

- Energy generation and usage profiles,
- EV profiles, and • Network models.

Energy generation profiles are essentially rooftop PV profiles of residential customers. Usage profiles refer to base load and Hot Water System (HWS) profiles. EV profiles are EV charging profiles. The network data represents the distribution transformer rating, feeder line data, and lengths between residential customers, and unbalanced structure. The initial models created in WP 1.4 of ESP project are used as inputs for the modelling studies in this project This is because the final models of WP 1.4 were not available within the deadline of WP 2.7 & 2.8.

2.2 Main Tasks

The project framework consists of four main tasks:

- Modelling existing DER penetration (business as usual DER penetration scenario, e.g., 10% EV customers),
- Modelling future DER penetration (increased DER penetration scenario, e.g., 100% EV customers),
- Deploying modelled existing and future DER penetration in low-voltage distribution, i.e., residential, networks to investigate the impacts on the network profiles (ADMD, and transformer loading and voltage profiles),
- Modelling DER instruments (e.g., community battery, EV charging through solar soaking , and V2G) and deploying them in modelled networks to investigate the impacts on the network profiles and compare the results with the base case, i.e., without DER instruments; and solve any potential issues with the network, such as transformer overloading and voltage limit breaches.

2.3 Control Mechanism

For the community battery modelling, it is assumed that the community battery is centrally controlled by the DNSPs to provide demand-side management to reduce transformer loading. The reactive power support from the community battery is also activated by the central control mechanism.

For the EV charging through solar soaking modelling, full behaviour shifting is achieved through the central control, whereas partial behaviour shifting reflects the preference of EV customers while imposing behavioural change in EV charging.

For V2G modelling, the same export limit is considered for all EV customers through the central control. However, EV customers are provided with the opportunity to use their available SOC for V2G, which varies between customers.

2.4 Outputs

The three main outputs include analysis of the impacts on ADMD, and distribution transformer loading and network voltage profiles.

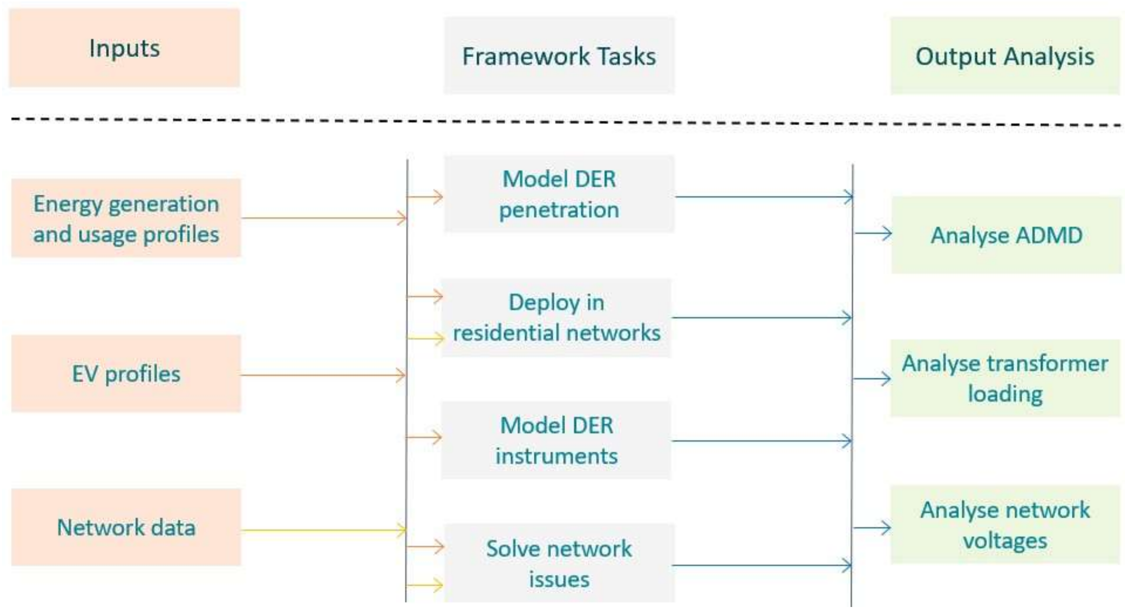


Figure 1: Project framework

2.5 Implementation Steps

To model DER instruments, such as community battery, EV charging through solar soaking , and V2G separately and concurrently, in any distribution networks and assess the network impacts, the following steps are required for each DER instrument.

2.1.1 Steps for Implementing Community Battery

- Step 1: Run the three-phase AC power flow with the base customer profiles and network data for all intervals and record the ADMD, and transformer loading and network voltage profiles.
- Step 2: Select normal power flow and reverse power flow intervals
- Step 3: Locate the community battery in the network (e.g., close to the transformer/far end of the feeder).
- Step 4: Charge the community battery during reverse power flow intervals.

- Step 5: Discharge the community battery during normal power flow intervals.
- Step 6: Run the three-phase AC power flow (considering the base customer profiles and network data used in Step 1) with community battery charging and discharging profiles (obtained in Step 4 and Step 5) and record intervals with voltage limit breaches.
- Step 7: Activate reactive power support from the community battery during voltage breach intervals.
- Step 8: Run the three-phase AC power flow (considering the base customer profiles and network data used in Step 1) with community battery charging and discharging profiles (obtained in Step 4 and Step 5) and reactive power support (provided in Step 7) and record the ADMD, and transformer loading and network voltage profiles.
- Step 9: Finally, compare the ADMD, and transformer loading and network voltage profiles between Step 1 and Step 8.

2.5.2 Steps for Implementing EV charging through solar soaking

- Step 1: Run the three-phase AC power flow with the base customer profiles and network data for all intervals and record the ADMD, and transformer loading and network voltage profiles.
- Step 2: Select reverse power flow intervals and intervals with peak demand profiles, causing transformer overloading and voltage limit breaches.
- Step 3: Select the percentage of EV customers interested in solar soaking.
- Step 4: Shift their peak EV loads to excess PV hours and record the updated profiles of EV customers.
- Step 5: Run the three-phase AC power flow with the updated EV profiles and network data (without changing other customer profiles used in Step 1) and record the ADMD, and transformer loading and network voltage profiles.
- Step 6: Finally, compare the ADMD, and transformer loading and network voltage profiles between Step 1 and Step 5.

2.5.3 Steps for Implementing V2G

- Step 1: Run the three-phase AC power flow with the base customer profiles and network data for all intervals and record the ADMD, and transformer loading and network voltage profiles.
- Step 2: Select intervals with peak demand profiles, causing transformer overloading and voltage limit breaches.
- Step 3: Select the percentage of EV customers interested in V2G.

- Step 4: Calculate V2G export profiles based on the available State-of-Charge (SOC) and export limit.
  Step 5: Update EV profiles by incorporating V2G export profiles.
- Step 6: Run the three-phase AC power flow with the updated EV profiles and network data (without changing other customer profiles used in Step 1) and record the ADMD, and transformer loading and network voltage profiles.
- Step 7: Finally, compare the ADMD, and transformer loading and network voltage profiles between Step 1 and Step 6.

2.5.4 Steps for Implementing EV charging through solar soaking , V2G, Community Battery

- Step 1: Run the three-phase AC power flow with the base customer profiles and network data for all intervals and record the ADMD, and transformer loading and network voltage profiles.
- Step 2: Select intervals with reverse power flow and intervals with peak demand profiles, causing transformer overloading and voltage limit breaches.
- Step 3: Select the percentage of EV customers interested in solar soaking.
- Step 4: Shift their peak EV loads to excess PV hours and record the updated profiles of EV customers.
- Step 5: Run the three-phase AC power flow with the updated EV profiles and network data (without changing other customer profiles used in Step 1) and record the ADMD, and transformer loading and network voltage profiles.
- Step 6: Select intervals with peak demand profiles, causing transformer overloading and voltage limit breaches, after EV charging through solar soaking .
- Step 7: Select the percentage of EV customers interested in V2G.
- Step 8: Calculate V2G export profiles based on the available SOC and export limit.
- Step 9: Update EV profiles by incorporating V2G export profiles.
- Step 10: Run the three-phase AC power flow with the updated EV profiles and network data (without changing other customer profiles used in Step 1) and record the ADMD, and transformer loading and network voltage profiles.
- Step 11: Select normal power flow and reverse power flow intervals.
- Step 12: Locate the community battery in the network (e.g., close to the transformer/far end of the feeder).
- Step 13: Charge the community battery during reverse power flow intervals.
- Step 14: Discharge the community battery during normal power flow intervals.

-
- Step 15: Run the three-phase AC power flow (considering the customer profiles and network data used in Step 1) with community battery charging and discharging profiles (obtained in Step 13 and Step 14) and record intervals with voltage limit breaches.
  Step 16: Activate reactive power support from the community battery during voltage breach intervals.
- Step 17: Run the three-phase AC power flow (considering the customer profiles and network data used in Step 1) with community battery charging and discharging profiles (obtained in Step 13 and Step 14) and reactive power support (provided in Step 16) and record the ADMD, and transformer loading and network voltage profiles.
- Step 18: Finally, compare the ADMD, and transformer loading and network voltage profiles between Step 1 and Step 17.

3 Case Study

In this section, case studies are carried out on initial models of WP 1.4 LV networks to investigate the impacts of modelled DER instruments, such as community battery, EV charging through solar soaking, and V2G, on network profiles. Please see section 2 for detailed implementation steps of these modelled DER instruments.

Various types of residential customers are considered for simulation studies, including PV customers, load customers, HWS customers, and EV customers. Since required profiles were not available from other WPs, the profiles of net power (the difference between load and PV profiles) and HWS are taken from real-world smart meters from another project. Additionally, the EV charging profiles are created through EV battery optimisation, considering existing EV charging plans and ensuring distributed charging patterns throughout different intervals of a sample day.

Once representative models of WP 1.4 LV networks and customer profiles become available, new case studies can be conducted to examine the real-world network impacts. For this purpose, a dashboard/tool is also modelled in this project. An overview of this dashboard is demonstrated in Section 4.

3.1 Modelled LV Distribution Networks

While acknowledging the fact that the customer and network fuses can prevent extreme overloading of transformers, their ratings are not considered in this case study as they were not modelled in the initial models of WP 1.4 networks. In addition, inverter sizes of PV customers were not available, and there are no defined inverter/converter response mode settings to recover significant voltage drops while enabling EV customers to charge one or more EVs. Thus, volt-var and volt-watt settings at the EV customer connection are not considered.

3.1.1 Modelled Rural Network

One rural LV network (fed by LV transformer number 4) from WP 1.4 networks is selected as a modelled LV distribution network. In this network, the LV transformer size is 200 kVA. The lower and upper voltage limits are set to 0.94 pu and 1.1 pu, respectively [19]. Figure 2 represents a single-line diagram of a modelled LV rural network. A 22 kV/0.433 kV transformer supports 20 residential customers and 1 commercial customers.

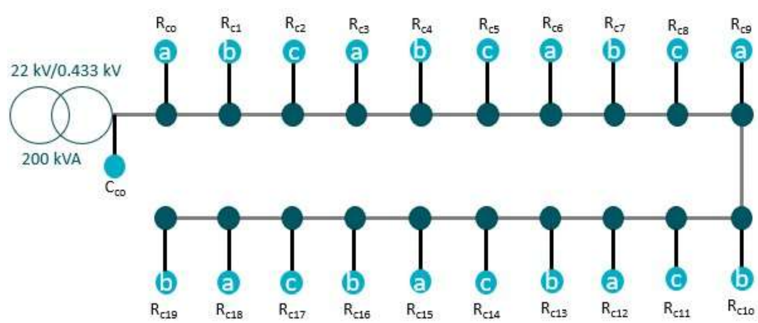


Figure 2: Single-line diagram of a modelled LV rural network.

3.1.2 Modelled Urban Network

One urban LV network (fed by LV transformer number 12) from WP 1.4 networks is selected as the modelled LV distribution networks. In this network, the LV transformer size is also 200 kVA. The lower and upper voltage limits are set to 0.94 pu and 1.1 pu, respectively [19], similar to the modelled rural network. A single-line diagram of a modelled LV urban network is provided in Figure 3, which shows 38 residential and 1 commercial customer are served by a 22 kV/0.433 kV transformer.

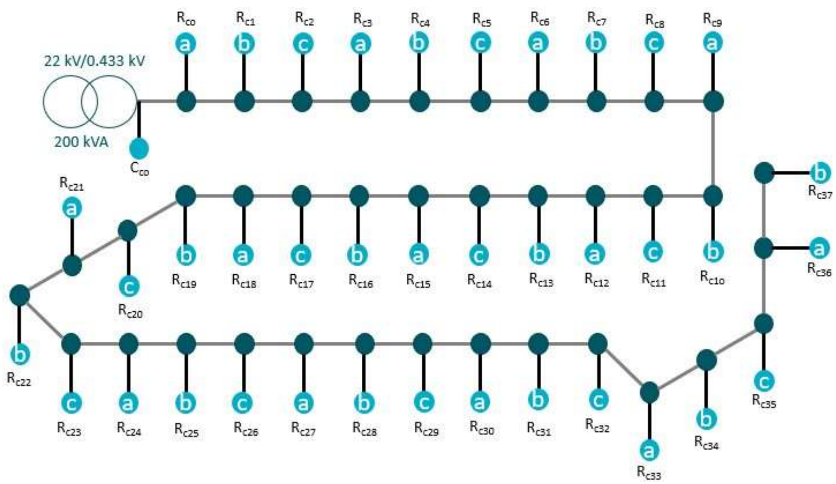


Figure 3: Single-line diagram of a modelled LV urban network.

3.2 Modelled DER Penetrations

Three scenarios of DER penetrations are considered to represent existing, near future, and potential future DER penetration scenarios. Existing DER penetration scenario (scenario A) consists of customers with 30% PV and 10% EV, whereas near future DER penetration scenario (scenario B) comprises customers with 50% PV and 50% EV. On the other hand, customers with 100% PV and 100% EV are considered in potential future DER penetration scenario (scenario C). All DER customers are also assumed to have HWS. With these scenarios, three-phase AC power flow analyses are performed to examine the impacts on the modelled LV networks in terms of transformer overloading and voltage limit breaches (considering all network nodes).

3.2.1 Rural Network Impacts

Figure 4 depicts the impact of DER penetration scenario A on the rural network transformer profiles over the course of a sample day, which suggests that the transformer is not overloaded. Although transformer export and import loading profiles increase with the increase in DER penetration, e.g., scenario B, the transformer does not experience overloading, as captured in Figure 5. However, Figure 6 shows that the transformer can get overloaded due to 100% EV charging, i.e., DER penetration scenario C.

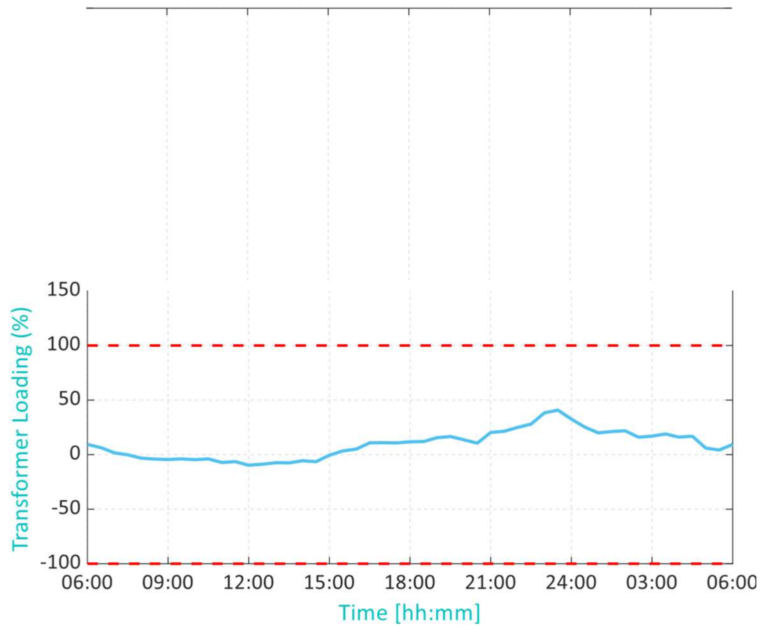


Figure 4: Impact on rural network transformer profiles with DER penetration scenario A.

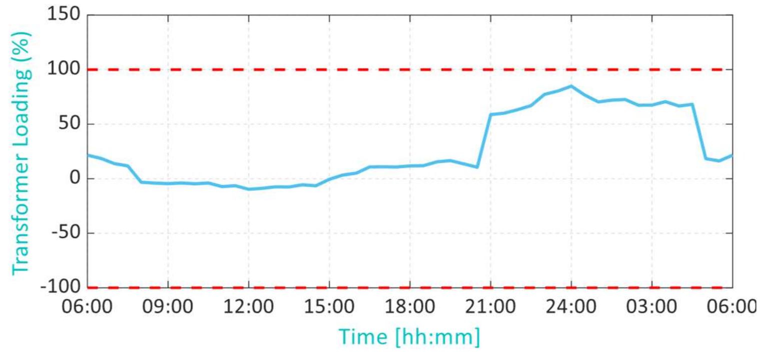


Figure 5: Impact on rural network transformer profiles with DER penetration scenario B.

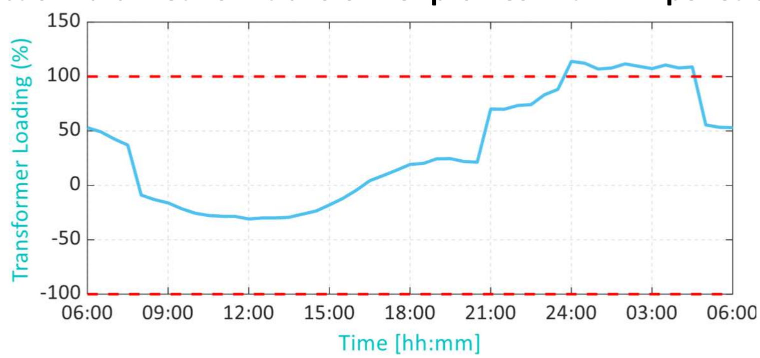
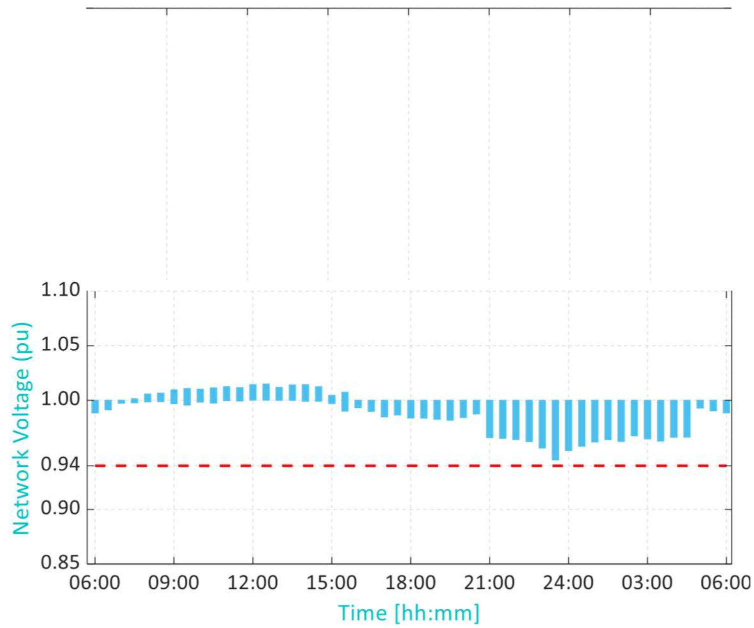


Figure 6: Impact on rural network transformer profiles with DER penetration scenario C.

Figure 7 illustrates the impact of DER penetration scenario A on the rural network voltage profiles over the course of a sample day, suggesting that all node voltages of the network are within the



prescribed limits. The consideration of DER penetration scenario B, i.e., increase in DER penetrations, creates slight undervoltage problems, as demonstrated in Figure 8.

Figure 7: Impact on rural network voltage profiles with DER penetration scenario A.

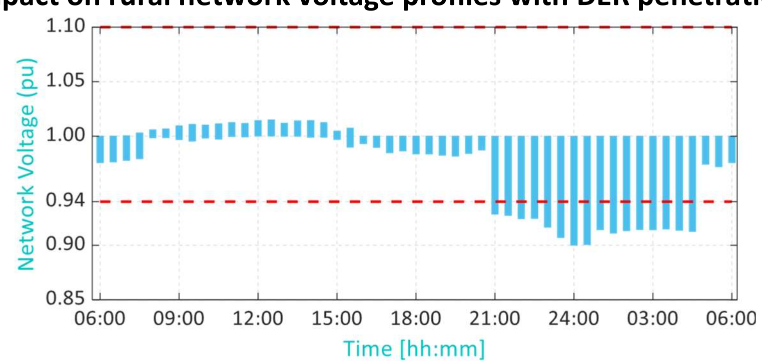


Figure 8: Impact on rural network voltage profiles with DER penetration scenario B.

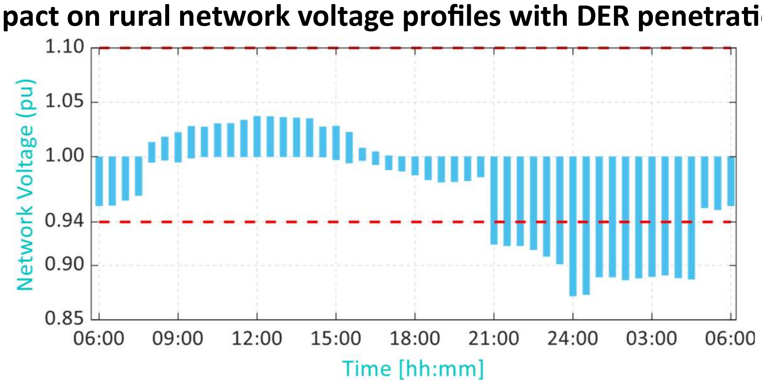


Figure 9: Impact on rural network voltage profiles with DER penetration scenario C.

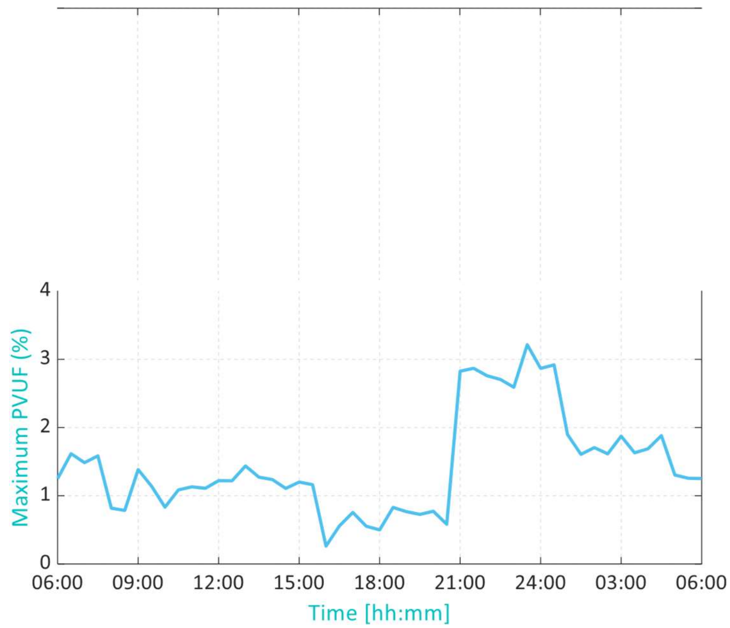


Figure 10: Impact on rural network PVUF with DER penetration scenario C.

Table 1: Impact on rural network ADMD with different DER penetration scenarios.

DER penetration scenario	ADMD (kVA)
Scenario A: 30% PV and 10% EV	3.95
Scenario B: 50% PV and 50% EV	7.94
Scenario C: 100% PV and 100% EV	10.54

According to Figure 9, further increase in DER penetrations, i.e., DER penetration scenario C, causes considerable undervoltage problems. The subsequent implication on the percentage of maximum Phase Voltage Unbalanced Factor (PVUF) is also provided in Figure 10.

Table 1 reveals the ADMD values for three scenarios of DER penetrations. In DER penetration scenario A, the ADMD is 3.95 kVA. It rises to 7.94 kVA with 50% PV and 50% EV in DER penetration scenario B. The consideration of DER penetration scenario C accelerates the ADMD to 10.54 kVA.

3.2.2 Urban Network Impacts

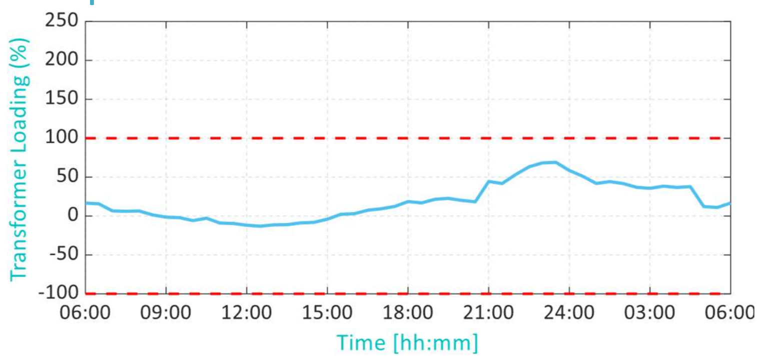


Figure 11: Impact on urban network transformer profiles with DER penetration scenario A.

Figure 11 depicts the impact of DER penetration scenario A on the urban network transformer profiles over the course of a sample day, which suggests that the transformer is not overloaded like the rural network, but transformer loading profiles become higher as the number of residential customers rises from 20 to 38. Nevertheless, both transformer export and import loading profiles increase with the increase in DER penetration, e.g., scenario B, and the transformer experiences overloading, as captured in Figure 12. However, Figure 13 shows that the transformer can get severely overloaded due to 100% EV charging, i.e., DER penetration scenario C.

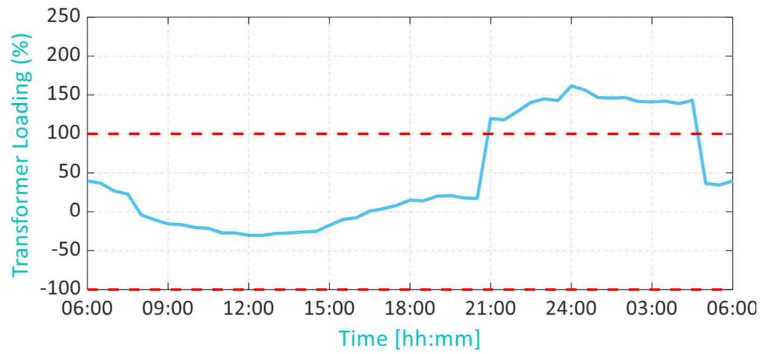


Figure 12: Impact on urban network transformer profiles with DER penetration scenario B.

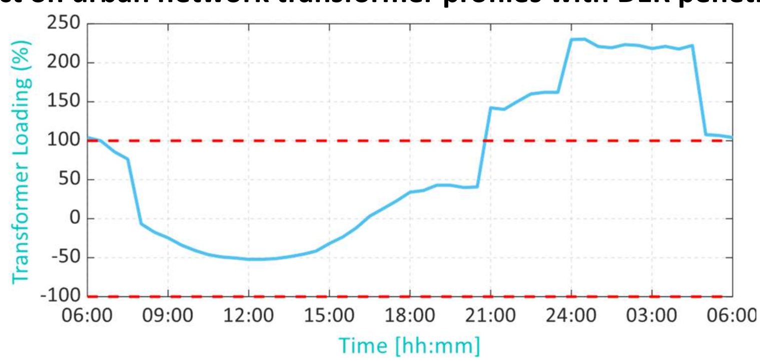


Figure 13: Impact on urban network transformer profiles with DER penetration scenario C.

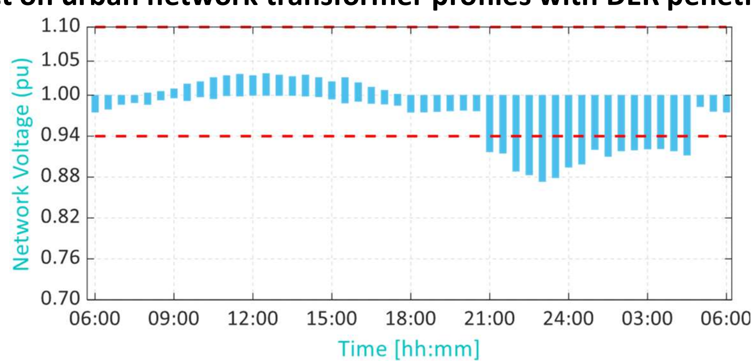


Figure 14: Impact on urban network voltage profiles with DER penetration scenario A.

Figure 14 illustrates the impact of DER penetration scenario A on the urban network voltage profiles, suggesting that some node voltages of the network experience undervoltage problems unlike the rural network. The consideration of DER penetration scenario B, i.e., increase in DER penetrations, enhances undervoltage problems significantly, as demonstrated in Figure 15.

According to Figure 16, further increase in DER penetrations, i.e., DER penetration scenario C, causes severe undervoltage problems (more voltage drops are observed compared to the rural network due to the increased number of EV charging). The subsequent implication on the percentage of maximum PVUF is also provided in Figure 17.

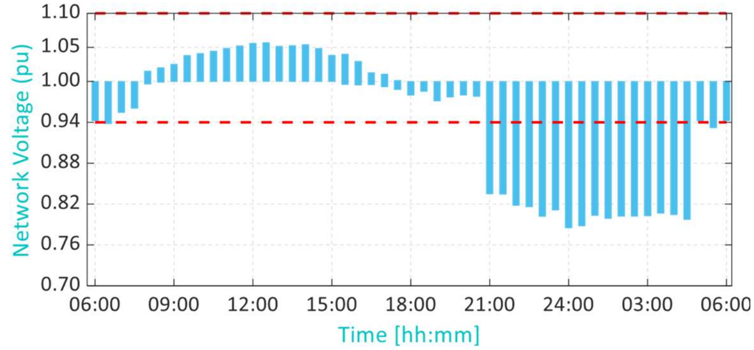


Figure 15: Impact on urban network voltage profiles with DER penetration scenario B.

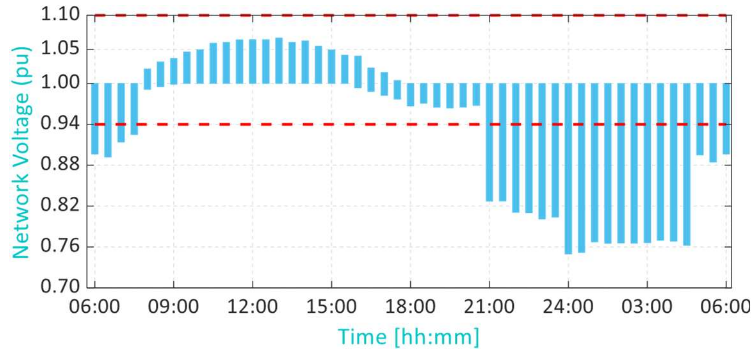


Figure 16: Impact on urban network voltage profiles with DER penetration scenario C.

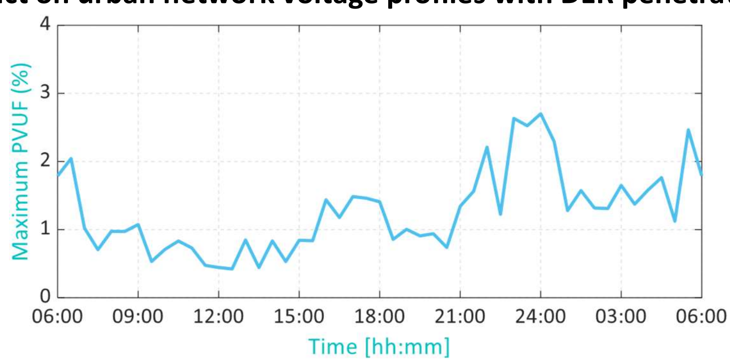


Figure 17: Impact on urban network PVUF with DER penetration scenario C.

Table 2: Impact on urban network ADMD with different DER penetration scenarios.

DER penetration scenario	ADMD (kVA)
Scenario A: 30% PV and10% EV	3.41
Scenario B: 50% PV and 50% EV	7.40

Scenario C: 100% PV and 100% EV	10.38

The ADMD values for three different DER penetration scenarios are demonstrated in Table 2. The ADMD in DER penetration scenario A is 3.41 kVA. With 50% PV and 50% EV, it increases to 7.9 kVA in DER penetration scenario B. The ADMD is accelerated to 10.38 kVA if DER penetration scenario C is considered.

3.3 Hot Water System Impacts

The used HWS profiles indicate that some HWS customers activate their HWSs during solar hours, implying solar soaking is already in place for some customers., whereas other customers activate their HWSs during non-solar periods. The impacts on transformer and voltage profiles with and without HWSs in scenario C are evaluated in this section.

3.3.1 Rural Network Impacts

Figure 18 compares the transformer loading profiles of the rural network with and without HWS profiles. Without HWS profiles, the transformer import loading profiles reduce, as the power demand profiles of the network reduce. The transformer export loading profiles improve due to the consideration of HWS as solar soaking is operated. The impacts on rural network voltage profiles are demonstrated in Figure 19. The voltage profiles improve during import periods due to the reduction in power demand profiles of the network.

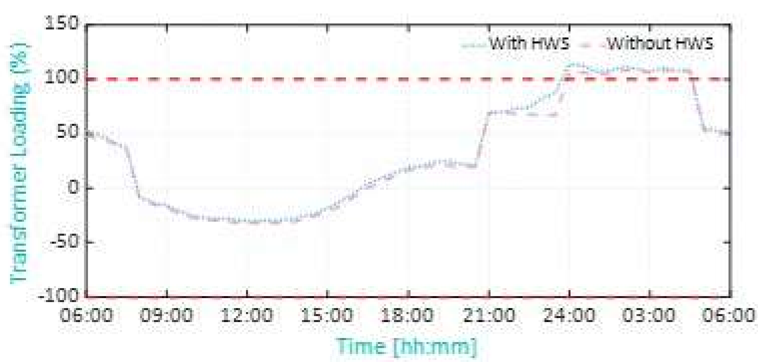


Figure 18: Impact on rural network transformer profiles with and without HWS.

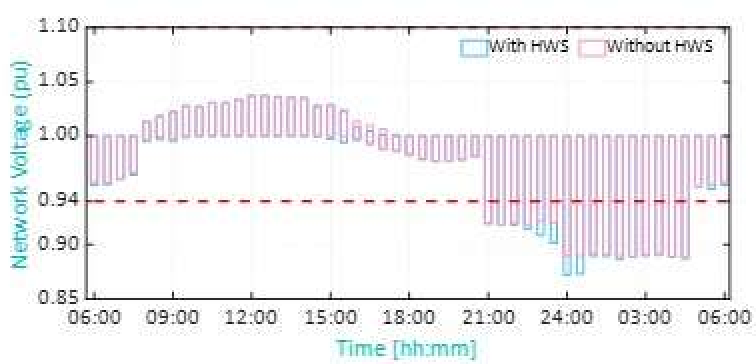


Figure 19: Impact on rural network voltage profiles with and without HWS.

3.3.2 Urban Network Impacts

The transformer loading profiles of the urban network with and without HWS profiles are contrasted in Figure 20. In the absence of HWS profiles, the transformer import loading profiles decrease in tandem with the network's power demand profiles. Because HWS is considered while solar soaking is operating, the transformer export loading profiles improve like Figure 18. Figure 2 illustrates the effects on urban network voltage profiles. Because the network's power demand profiles are lower during import periods, the voltage profiles get better.

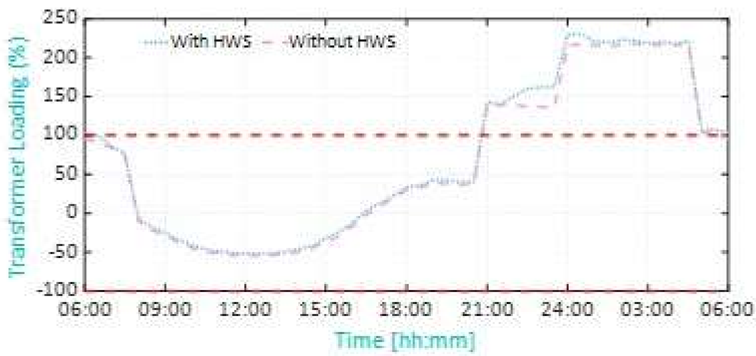


Figure 20: Impact on urban network transformer profiles with and without HWS.

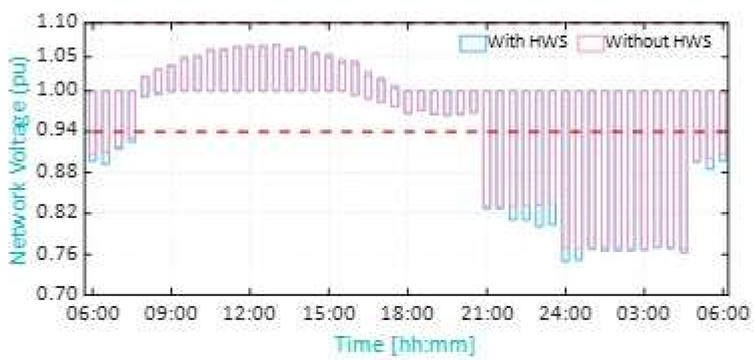


Figure 21: Impact on urban network voltage profiles with and without HWS.

3.4 Modelled DER Instruments

Three DER instruments are employed, namely community battery, EV charging through solar soaking , and V2G, to mitigate network limit breaches caused by the potential futuristic high DER penetrations, e.g., scenario C. The motivation of considering network limit breaches with high DER penetrations is to examine the performances of the DER instruments in extreme conditions (likely to happen in the future beyond 2030 when fuel cars are projected to be replaced by EVs) and demonstrate their effectiveness in handling less severe conditions, e.g., scenario A and scenario B (existing and near future scenarios).

Three-phase AC power flow results of DER instruments are compared with those of the base scenario, i.e., scenario C with HWS, to analyse the network impacts in terms of transformer overloading and voltage limit breaches.

3.4.1 Application of Community Battery

Two locations are chosen to connect a community battery within the modelled networks: close to the distribution transformer (location 1) and towards the end of the feeder (location 2). A community battery with a size of 500 kWh, 400 kW [5] is utilised to store excess PV energy and provide customer-side demand supports. Both exporting and sinking reactive power supports are also activated according to the AS/NZS 4777.2 standard [20].

3.4.1.1 Rural Network Impacts

Figure 22 and Figure 23 exhibit impacts on transformer and voltage profiles (over the course of a sample day) of the rural network, respectively, with the community battery if it is connected at location 1, which indicate that the application of community battery reduces network limit breaches, both transformer overloading and voltage limit breaches. The reduction in network limit breaches can be expanded by increasing the community battery size. However, that may involve higher capital and operational expenditures.

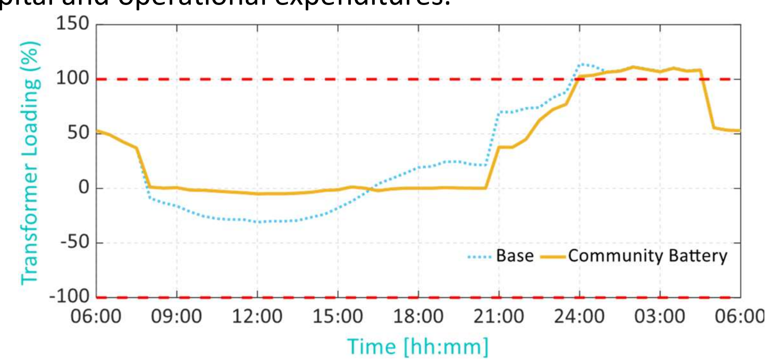


Figure 22: Impact on rural network transformer profiles with community battery at location 1

If the community battery is placed towards the end of the feeder (location 2), the transformer profiles of the rural network, as depicted in Figure 24, vary insignificantly in comparison with Figure 22. However, the network voltage profiles are improved noticeably compared to location 1, please see Figure 25, because of decreased voltage drops across the network.

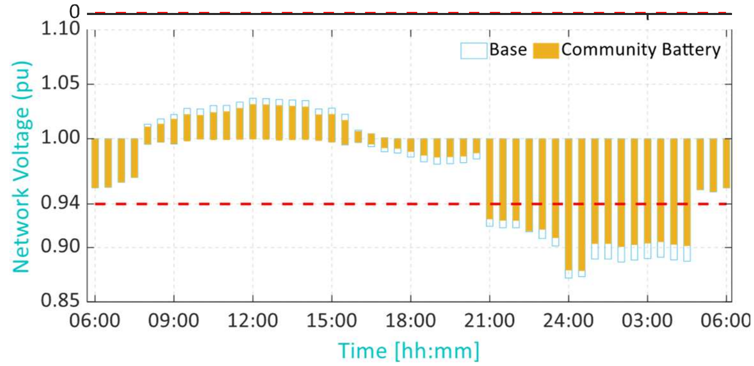


Figure 23: Impact on rural network transformer profiles with community battery at location 1.

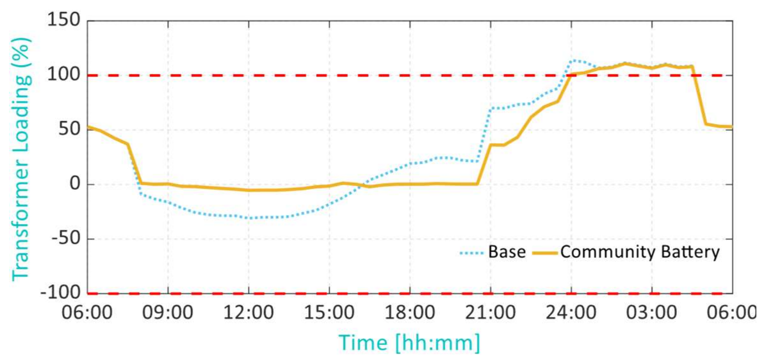


Figure 24: Impact on rural network transformer profiles with community battery at location 2.

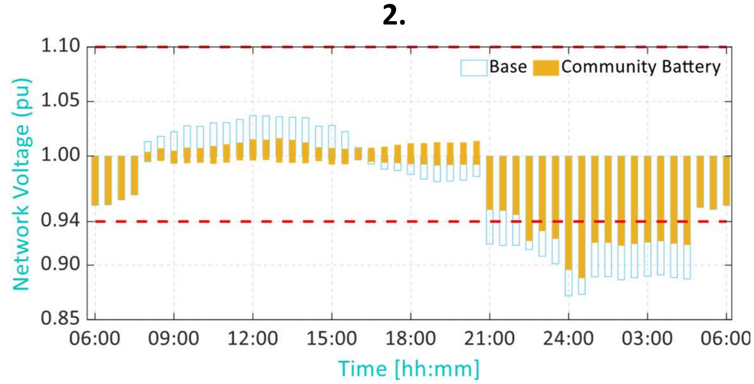


Figure 25: Impact on rural network voltage profiles with community battery at location 2.

3.4.1.2 Urban Network Impacts

Figure 26 and Figure 27 display effects on transformer and voltage profiles (over the course of a sample day) of the urban network, respectively, with the community battery if it is connected at location 1, which indicate that the application of community battery reduces network limit breaches, both transformer overloading and voltage limit breaches, similar to the performance found in the rural network. Increasing the size of the community battery can further reduce network limit breaches. That may, however, come with greater costs.

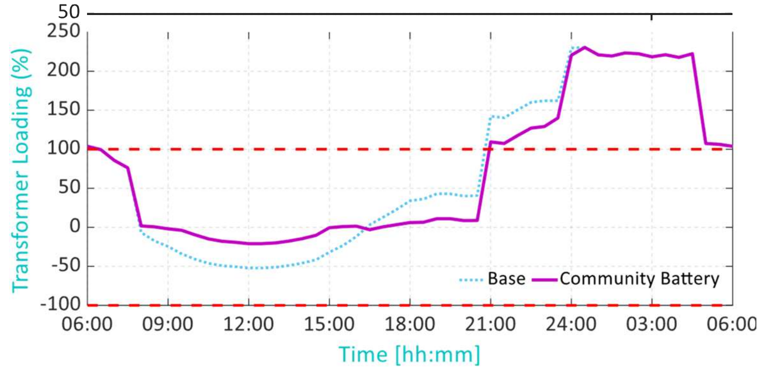


Figure 26: Impact on urban network transformer profiles with community battery at location 1.

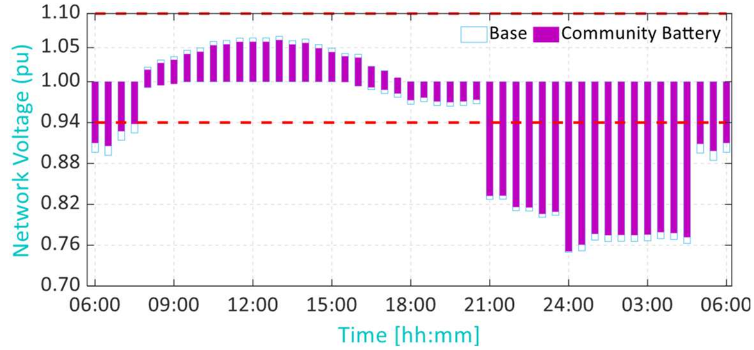


Figure 27: Impact on urban network voltage profiles with community battery at location 1.

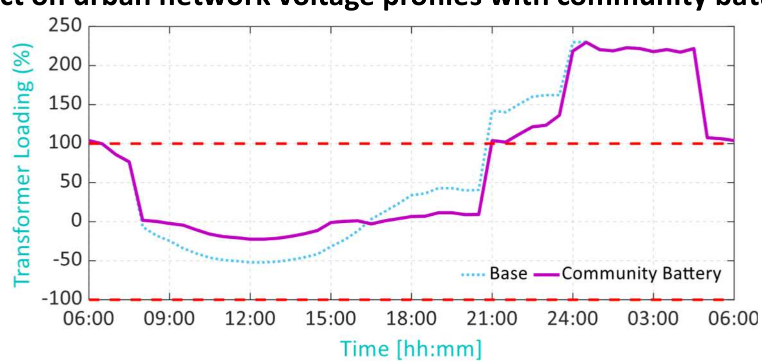


Figure 28: Impact on urban network transformer profiles with community battery at location 2.

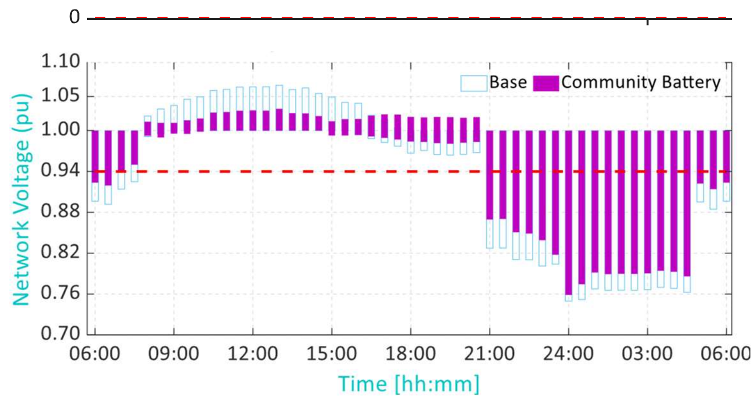


Figure 29: Impact on urban network voltage profiles with community battery at location 2.

When the community battery is positioned at location 2, toward the end of the feeder, the urban network's transformer profiles, as depicted in Figure 28, differ slightly from Figure 26. On the contrary, as Figure 29 illustrates, the network voltage profiles are noticeably better than at location 1 due to a reduction in network voltage drops.

3.4.2 Application of EV charging through solar soaking

The percentages of EV customers willing for solar soaking (percentages of EV charging through solar soaking) are varied from 0% to 75% to investigate the impacts on the modelled LV networks. Both full and partial shifting of EV charging behaviours are considered. In full behaviour shifting, EV customers shift their entire EV charging demand to solar soaking periods, whereas they shift a portion of their EV charging demand to solar soaking periods in partial behaviour shifting.

3.4.2.1 Rural Network Impacts

Figure 30 and Figure 31 illustrate impacts on transformer and voltage profiles (over the course of a sample day) of the rural network, respectively, with various percentages of EV charging through solar soaking. As is seen from these figures, both transformer loading and voltage profiles are improved with an increase in EV charging through solar soaking percentage, e.g., 75% EV charging through solar soaking performs better than 25% EV charging through solar soaking . Also, full behaviour shifting impacts more on the reduction of network limit breaches, both transformer overloading and voltage limit breaches, compared to partial behaviour shifting.

Figure 30: Impact on rural network transformer profiles with EV charging through solar soaking .

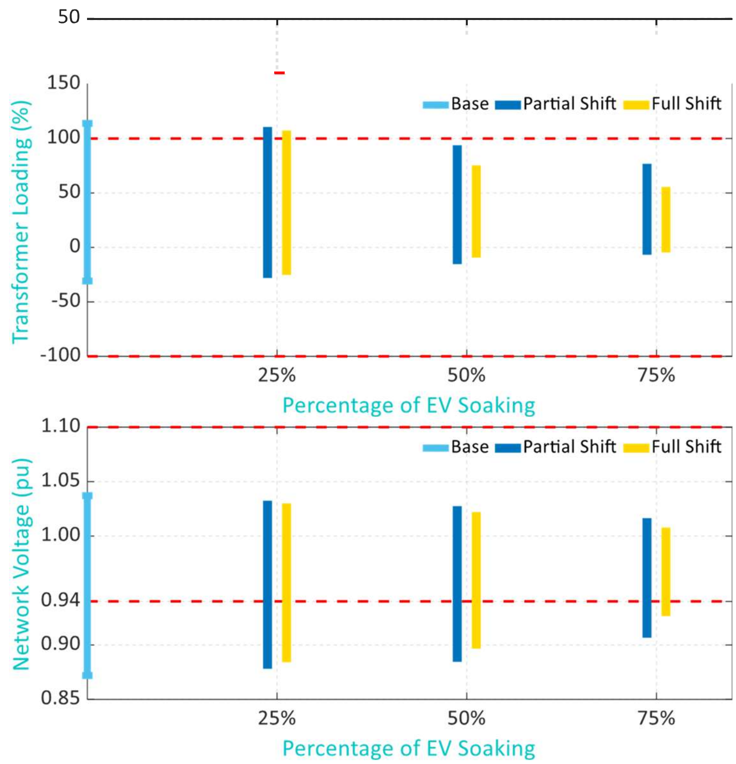


Figure 31: Impact on rural network voltage profiles with EV charging through solar soaking .

3.4.2.2 Urban Network Impacts

Figure 32 and Figure 33 depict impacts on transformer and voltage profiles (over the course of a sample day) of the urban network, respectively, with various percentages of EV charging through solar soaking. Similar to the rural network, both transformer loading and voltage profiles are improved with an increase in EV charging through solar soaking percentage, e.g., 75% EV charging through solar soaking performs better than 25% EV charging through solar soaking . Furthermore, full behaviour shifting has a greater effect on lowering network limit breaches, both transformer overloading and voltage limit breaches, than partial behaviour shifting.

Moreover, Figure 32 and Figure 33 reveal that higher percentages of EV charging through solar soaking are required to reduce network limit breaches contrasting to that shown in Figure 30 and Figure 31, as the modelled urban network contains more residential customers than the modelled rural network.

Figure 32: Impact on urban network transformer profiles with EV charging through solar soaking .

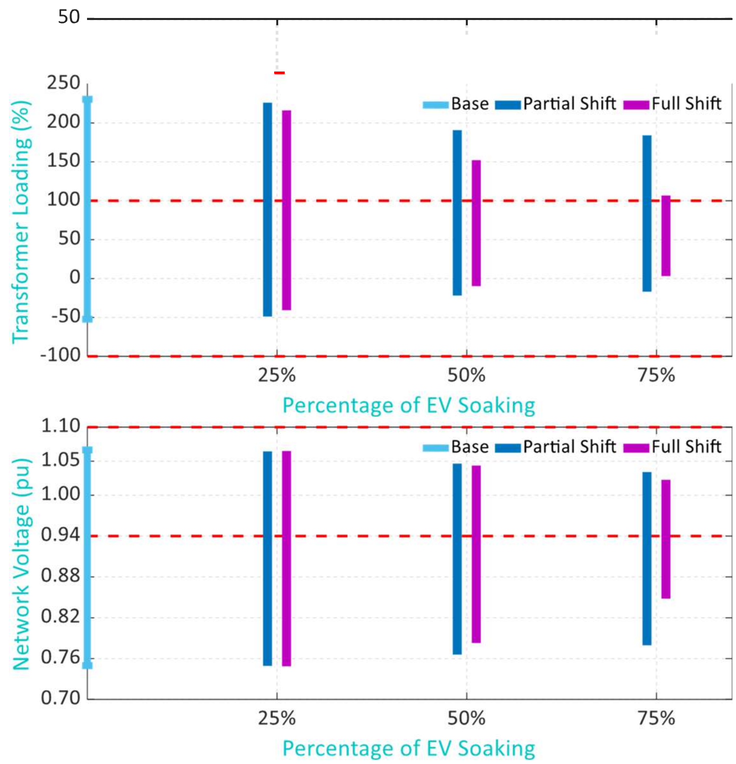


Figure 33: Impact on urban network voltage profiles with EV charging through solar soaking .

3.4.3 Application of V2G

The percentages of EV customers willing for V2G (percentages of V2G) are varied from 0% to 50% during peak EV charging times to examine the impacts on the modelled LV networks. The maximuareV2G export is set to 7 kW [21], and the battery SOC range available for V2G among EV customers is varied between 20% and 30%.

3.4.3.1 Rural Network Impacts

Figure 34 and Figure 35 illustrate impacts on transformer import and minimum voltage profiles (over the course of a sample day) of the rural network, respectively, with various percentages of V2G. Both transformers import loading and minimum voltage profiles are decreased and increased, respectively, with an increase in V2G percentage, e.g., 50% V2G performs better than 10% V2G. In fact, network limit breaches, both transformer overloading and voltage limit breaches, are eradicated with the consideration of 50% V2G.

Figure 34: Impact on rural network transformer profiles with V2G.

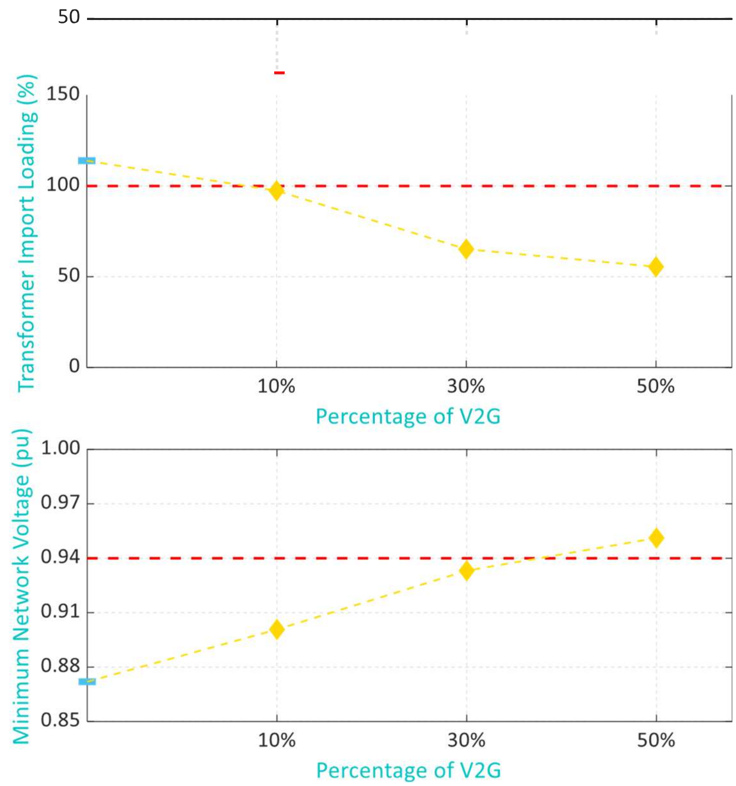


Figure 35: Impact on rural network voltage profiles with V2G.

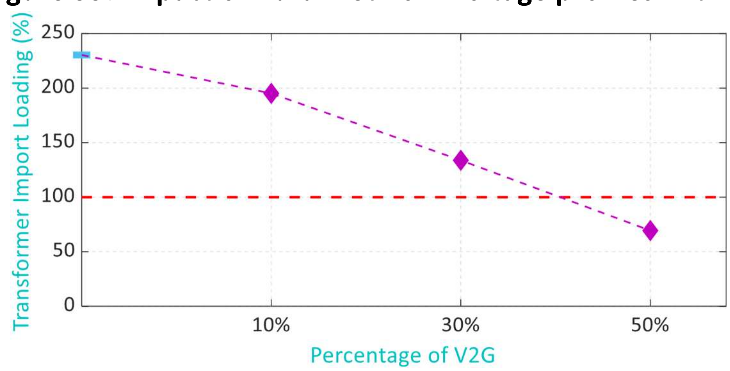


Figure 36: Impact on urban network transformer profiles with V2G.

3.4.3.2 Urban Network Impacts

Impacts on transformer import and minimum voltage profiles (over the course of a sample day) of the urban network with different percentages of V2G are shown in Figures 36 and 37, respectively. Transformer import loading and minimum voltage profiles are lowered and raised, respectively, with an increase in V2G percentage; for example, 25% V2G outperforms 50% V2G. This behaviour is similar to that of the rural network. In actuality, network limit breaches, both transformer overloading and voltage limit breaches, are eliminated when 50% V2G is considered.

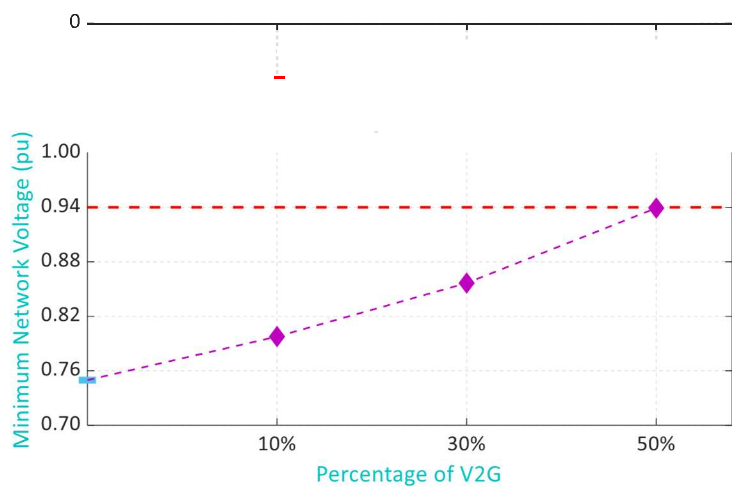


Figure 37: Impact on urban network voltage profiles with V2G.

Additionally, as the modelled urban network has more residential customers than the modelled rural network, Figures 36 and 37 imply that higher percentages of V2G are needed to mitigate network limit breaches, in contrast to Figures 34 and 35 .

3.4.4 Concurrent Applications of EV charging through solar soaking, V2G and Community Battery

Three DER instruments are applied concurrently, and the impacts on modelled LV networks are analysed.

3.4.4.1 Rural Network Impacts

Figure 38 and Figure 39 depict impacts on transformer and voltage profiles (over the course of a sample day) of the rural network, respectively, with various DER instruments. According to these figures, all three DER instruments (a 500 kWh-sized community battery placed at location 2, 30% EV charging through solar soaking , and 30% V2G) individually facilitate in the reduction of network limit breaches, but none of them completely eradicates. The network limit breaches, both transformer overloading and voltage limit breaches, are resolved by the concurrent application of these DER instruments.

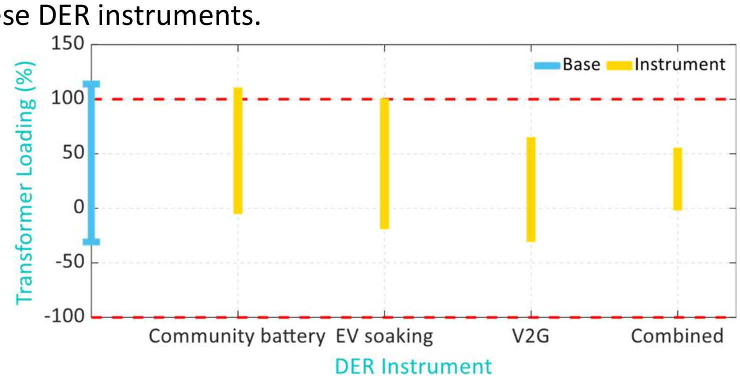


Figure 38: Impact on rural network transformer profiles with DER instruments.

The ADMD values of the rural network with different DER instruments are illustrated in Table 3. The concurrent application of EV charging through solar soaking , V2G, and community battery reduces the most ADMD (reduced by 5.18 kVA compared to the base scenario), in which the major role is played by V2G followed by EV charging through solar soaking and community battery.

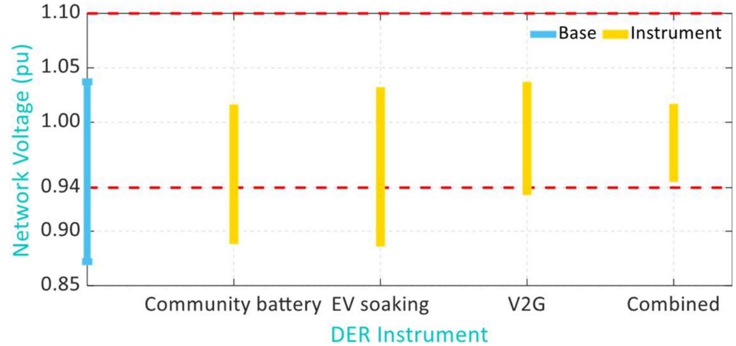


Figure 39: Impact on rural network voltage profiles with DER instruments.

Table 3: Impact on rural network ADMD with different DER instruments.

DER instrument	ADMD (kVA)
Base scenario (scenario C)	10.54
Community battery	10.37
EV charging through solar soaking	9.35
V2G	6.26
EV charging through solar soaking , V2G, Community battery	5.36

3.4.4.2 Urban Network Impacts

Impacts on the transformer and voltage profiles (over the course of a sample day) of the urban network with different DER instruments are exhibited in Figures 40 and 41 , respectively. These numbers indicate that while each of the three DER instruments (a 500 kWh-sized community battery placed at location 2, 50% EV charging through solar soaking, and 50% V2G) helps to reduce network limit breaches on their own, none of them does so entirely. The concurrent use of these DER instruments completely overcomes the network limit breaches, both transformer overloading and voltage limit breaches.

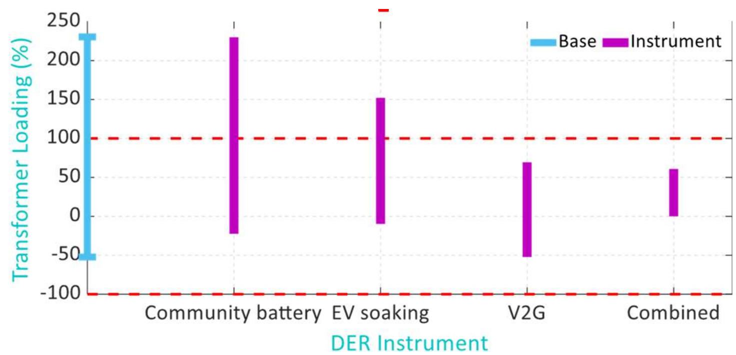


Figure 40: Impact on urban network transformer profiles with DER instruments.

To resolve network limit breaches, however, higher percentages of EV charging through solar soaking and V2G are required in the urban network in contrast with the rural network due to accommodating a greater number of residential customers.

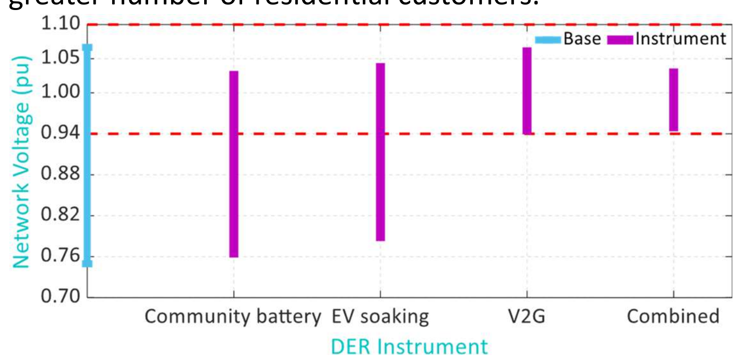


Figure 41: Impact on urban network voltage profiles with DER instruments.

Table 4: Impact on urban network ADMD with different DER instruments.

DER instrument	ADMD (kVA)
Base scenario (scenario C)	10.38
Community battery	10.38
EV charging through solar soaking	6.93
V2G	3.48
EV charging through solar soaking , V2G, Community battery	3.08

Table 4 shows the ADMD values of the urban network using several DER instruments. The greatest reduction in ADMD (reduced by 7.72 kVA compared to the base scenario) occurs when EV charging through solar soaking , V2G, and community battery are used concurrently. In this reduction, V2G plays the primary part like the rural network, followed by EV charging through solar soaking , community battery, and V2G.

3.4.5 Seasonal Analysis

The customer daily profiles from four Australian seasons, namely summer, autumn, winter, and spring, are considered, and impacts on the modelled LV networks are evaluated.

3.4.5.1 Rural Network Impacts

Figure 42 and Figure 43 depict impacts on transformer and voltage profiles of the rural network, respectively, with various DER instruments under sample days from four seasons. As is observed from these figures, all three DER instruments (a 500 kWh-sized community battery placed at location 2, 30% EV charging through solar soaking , and 30% V2G) individually minimise network limit breaches in all four seasons, but none of them completely eradicates. The network limit breaches, both transformer overloading and voltage limit breaches, are resolved by the concurrent application of these DER instruments in all four seasons.

3.4.5.2 Urban Network Impacts

Impacts on the transformer and voltage profiles of the urban network with different DER instruments under sample days from four seasons are illustrated in Figures 44 and 45 , respectively. These numbers indicate that while each of the three DER instruments (a 500 kWhsized community battery placed at location 2, 50% EV charging through solar soaking , and 50% V2G) assists in mitigating network limit breaches, both transformer overloading and voltage limit breaches, on their own, none of them does so entirely in all four seasons. To do so, a concurrent adoption of these DER instruments is required.

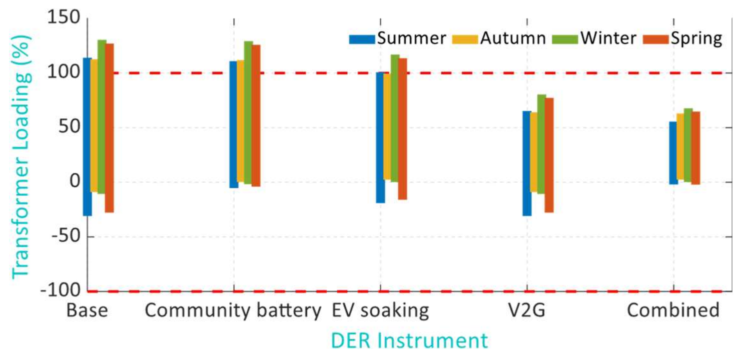


Figure 42: Seasonal impact on rural network transformer profiles with DER instruments.

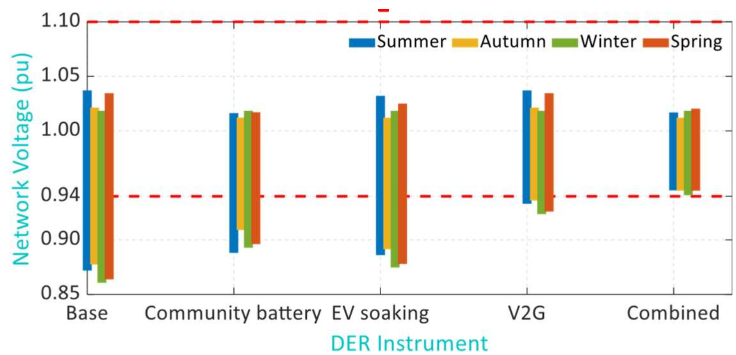


Figure 43: Seasonal impact on rural network voltage profiles with DER instruments.

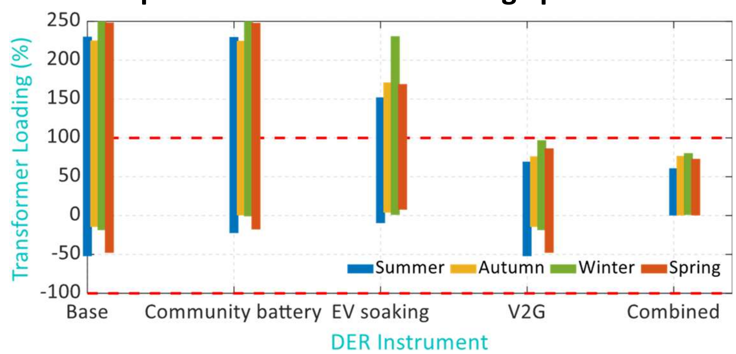


Figure 44: Seasonal impact on urban network transformer profiles with DER instruments.

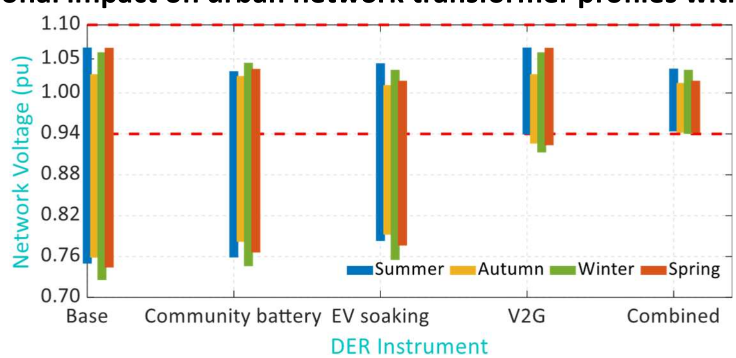


Figure 45: Seasonal impact on urban network voltage profiles with DER instruments.

Compared to the rural network, the urban network requires higher percentages of EV charging through solar soaking and V2G to address network limit breaches, both transformer overloading and voltage limit breaches, in all four seasons because it serves a larger number of residential customers.

A comparison between modelled rural and urban networks is summarised in Table 5.

Table 5: Comparison between modelled rural and urban networks.

Modelled network	Issues due to high DER penetration	Application of DER instruments	Additional network solutions
Rural network	Considerable transformer overloading, severe voltage limit breaches,	Improve transformer loading and network voltage profiles. Resolve network limit breaches with moderate penetrations of EV charging through solar soaking and V2G.	Not required
Urban network	Severe transformer overloading, severe voltage limit breaches,	Improve transformer loading and network voltage profiles. Resolve network limit breaches with high penetrations of EV charging through solar soaking and V2G.	Not required

3.5 Case Study Summary

The key findings, specific to the case study, are summarised below.

- Three scenarios of DER penetrations have been considered to represent existing, near future, and potential future DER penetration scenarios, and their impacts on modelled rural and urban networks, through three-phase AC power flow analyses, have been identified, implying discernible network impacts with increased DER penetrations.
- The consideration of potential futuristic high DER penetrations, e.g., 100% PV and 100% EV customers, has caused significant breaches in network limits, e.g., transformer

overloading and voltage limit breaches, in both modelled LV networks. Although such worst-case network limit breaches are not visible in most LV networks at present, those can be found in the future and would require potential network-aware approaches to resolve.

- The impacts of solar soaking-facilitated HWS have been evaluated for both modelled networks. It has been found that the greater solar soaking through the HWS would be better for the network in terms of reducing transformer overloading and voltage limit breaches.
- Three DER instruments, namely community battery, EV charging through solar soaking , and V2G, have been applied separately and concurrently to solve network limit breaches, and results have been compared with the base scenario (without DER instruments) to analyse the effectiveness. The concurrent application of DER instruments has been found to be more fruitful in alleviating network impacts.
- Two locations of the community battery have been considered, such as close to the transformer (location 1) and towards the end of the feeder (location 2). Also, the reactive power support has been activated to improve voltage profiles. Placing a community battery at location 2 has been found to improve voltage profiles better compared to location 1 due to reducing voltage drop across the network.
- The percentage of EV customers willing for solar soaking (percentages of EV charging through solar soaking) have been varied to investigate the implications on the network. It has been observed that full behaviour shifting of EV customers would impact improving network profiles, e.g., transformer loading and voltage profiles, more than partial behaviour shifting of EV customers.
- The percentage of EV customers willing for V2G (percentages of V2G) have also been varied to investigate the implications on the network. Since V2G has been activated during peak EV charging periods (without a loss of generality), transformer import, and minimum voltage profiles have been improved.

Please see Section 5 for general insights of the project.

3.6 Remark on Dynamic Operating Envelope (DOE)

As is observed from Table 5, the DER instruments can resolve transformer overloading and voltage limit breaches for modelled rural and urban networks used in this project. However, using only DER instruments may not be sufficient for a wide range of representative networks (e.g., CSIRO LV network models) and customer profiles (e.g., customers with larger solar PV systems).
In such cases, the adoption of alternative network solutions, such as dynamic operating envelope (DOE), would be fruitful in resolving transformer overloading and voltage limit breaches.

A combination of DER instruments and DOEs for different representative networks can be used, e.g., transformer overloading and voltage limit breaches can be minimised first by the application of available DER instruments and then the DOE is implemented, as this would reduce energy curtailments required to ensure network integrity.

3.7 Use of Other Potential Appliances as DER Instruments

Although the demonstrated case studies use community battery, EV charging through solar soaking , and V2G as DER instruments, other potential appliances, such as heating and cooling systems, hot water systems, and home battery systems, can also be considered to extend the analysis. However, for accurate modelling of these potential appliances, real-world profiles, specifications, and standards are necessary.

Without a loss of generality, the consideration of business-as-usual profiles of heating and cooling systems and hot water systems would increase the energy demand of the customers. Shifting the activation of these systems of some customers to solar periods would decrease some portion of energy demand during non-solar periods. Also, excess solar generation can be utilised. This would result in improving both transformer loading and voltage profiles, like EV charging through solar soaking .

On the other hand, home battery systems would store excess solar and supply during non-solar periods. This would also contribute to improving both transformer loading and voltage profiles similar to the community battery.

3.8 Necessity of Tariff Modelling

As is observed from the simulation results, the transformer loading and voltage profiles can be impacted significantly by the applications of DER instruments. However, the effectiveness of these instruments would rely mainly on the acceptance and participation of electricity customers. Thus, introducing cost-effective pricing structures would be necessary. In other words, innovative tariff structures (considering customers' physical attributes, that include location, size, and availability) need to be modelled to motivate them financially to take part in network services through their DER instruments.

4 Overview of Modelling Dashboard

In this project, a dashboard/tool has been modelled using impacts of different DER penetrations (e.g., customer profiles) and DER instruments on various types of networks (could be rural, urban, suburban, or CBD) can be analysed. Several variables have been made flexible to mimic different choices of customers and DNSPs. A summary of considered inputs, flexible variables, and expected outputs is provided in Table 6.

The updated network models and customer profiles of other ESP WPs can be uploaded in this Dashboard to analyse the network performance. A separate user manual will also be provided to operate this Dashboard.

Table 6: An overview of the modelled Dashboard.

Key Features	Descriptions	Remarks
Inputs	• Net profiles from smart meters. • EV profiles. • HWS profiles. • Space heating profiles. • Customer IDs. • LV transformer voltage profiles. • OpenDSS circuit of the network.	• In this project case studies, space heating profiles are not used. • Also, LV transformer voltage profiles are set to 1 pu.
Flexible Variables	• Upper and lower voltage limits. • Size of the transformer • Size and location of the community battery. • Average EV per customer. • Percentage of EV charging through solar soaking and V2G.	• Two locations of the community battery are considered. For any other locations, OpenDSS circuit needs to be revised. • Consideration of high EV penetrations can allow more customers to participate in EV charging through solar soaking and V2G.

	• Available SOC for V2G and V2G export limit.	
Outputs	• Impact on transformer loading. • Impact on voltage profiles. • Impact on ADMD.	Impacts with DER instruments are compared with the base case (without DER instruments) to visualise the improvements.

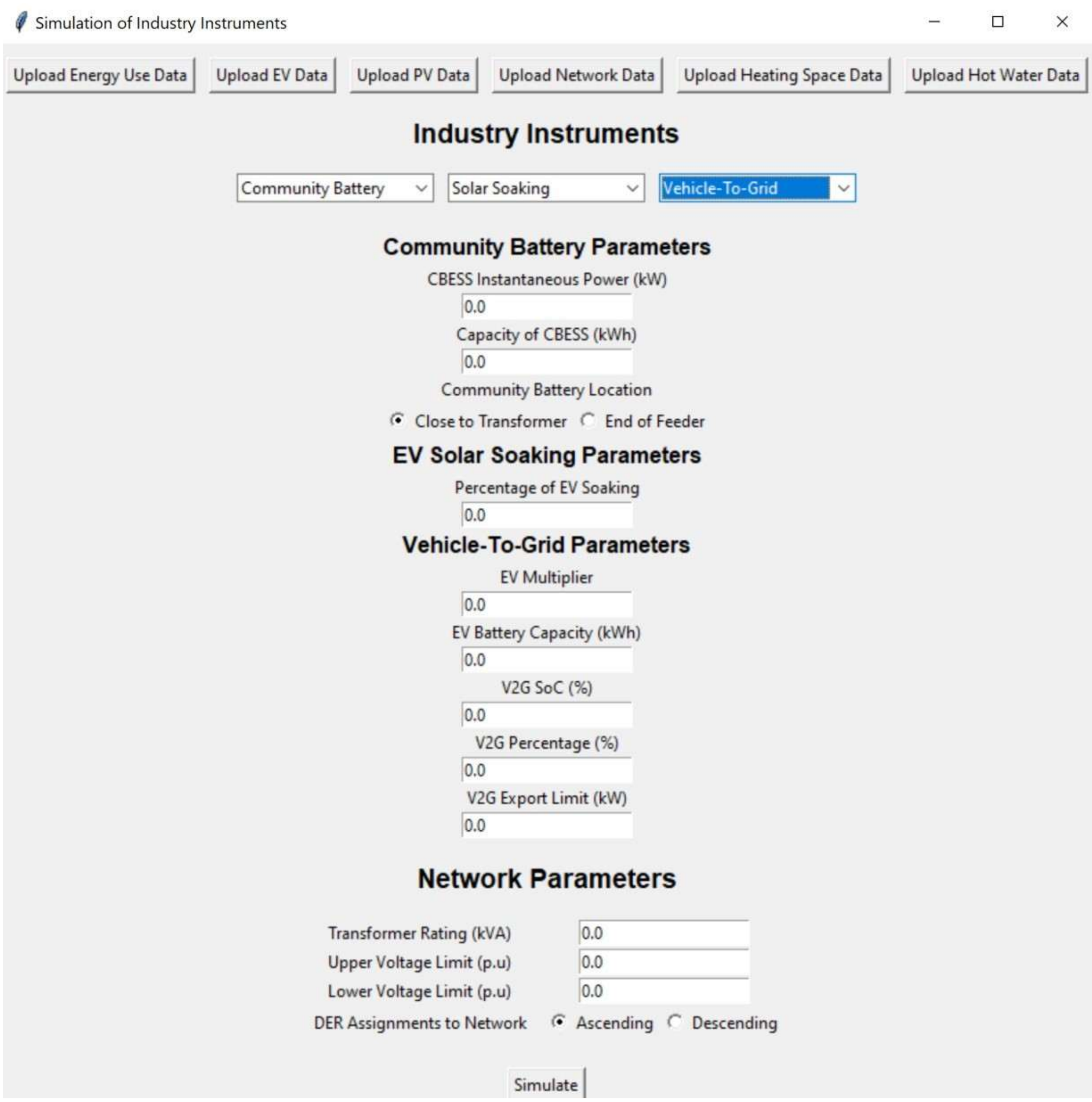


Figure 46: Graphical User Interface for modelling DER instruments

5 Project Insights

Based on the analyses undertaken in this project and its key findings, some general insights can be drawn regarding the application of DER instruments, which are listed below:

- High PV and EV penetrations in the future can cause breaches in network limits, such as transformer overloading and voltage limit breaches. The intensity of network limit breaches could vary depending on network types and configurations (e.g., rural, urban, suburban, and CBD would demonstrate dissimilar performances).
- The location and size of the community battery can play a vital role in reducing network limit breaches. The performance of the community battery in improving voltage profiles can be accentuated further by providing reactive power supports. The market and network services of the community battery would mostly depend on the ownership.
- The more EV customers participate in EV charging through solar soaking, the better for the network in terms of reducing network limit breaches. Although he full behaviour shifting of EV customers would have more impacts on the network than partial behaviour shifting, the effectiveness of the EV charging through solar soaking would rely mainly on the acceptance and participation of EV customers Thus, introducing cost-effective pricing structures would be necessary.
- The network is expected to experience less transformer overloading and voltage limit breaches if more EV customers participate in V2G. The performance of V2G can be impacted greatly by the V2G export and available EV SOC. Like EV charging through solar soaking, the effectiveness of the V2G would also rely on the willingness of EV customers. In addition, defining connection agreements and incentives would be necessary for the widespread adoption of V2G technology.
- A combined application of different DER instruments can resolve network limit breaches, caused by futuristic PV and EV penetrations, for some networks, but they may not be sufficient for a wide range of representative networks. Thus, to safeguard the long-term integrity of different networks, alternative mechanisms such as the DOE can be explored. A combination of DOEs and DER instruments can be used for different networks (i.e., transformer overloading and voltage limit breaches are minimised first by the application of available DER instruments and then the DOE is implemented), as this would reduce energy curtailments required to ensure network integrity.

6 Recommendations

1. Application of DER Instruments:

The analyses in this project suggest that the application of DER instruments, such as community battery, EV charging through solar soaking, and V2G can impact the network performance significantly in terms of reducing transformer overloading and voltage limit breaches. Implementing DER instruments can also improve network hosting capacity, and hence, can potentially reduce or defer network upgrade costs. Additionally, in some cases, solar PV export curtailment can be avoided, as demonstrated in modelled networks analysed in this project. Thus, it is recommended to utilise these DER instruments, especially during high DER penetration scenarios. Since the role of customers would impact greatly on the use and effectiveness of the DER instruments, it is recommended to consider their physical attributes, that include location, size, and availability, while offering appropriate incentives.

2. Ensuring Long-term Network Integrity:

While DER instrument implementation can help with alleviating network limit breaches for some networks (e.g., modelled networks considered in this project), they may not be sufficient for a wide range of representative networks and customer profiles. Thus, to safeguard the long-term integrity of networks, it is recommended to explore alternative mechanisms such as the DOE. Insights and learnings from trials such as Project EDGE can be utilised to design and implement DOEs. It is recommended to use a combination of DER instruments and DOEs for different representative networks (e.g., transformer overloading and voltage limit breaches can be minimised first by the application of available DER instruments and then the DOE is implemented), as this would reduce energy curtailments required to ensure network integrity.

3. Regulatory Assessments and Incentives:

The project highlights the importance of determining the optimal size and location of community batteries to improve network performance. Given the limited public data on which specific locations would offer the most value, it is recommended to assess the accurate size and most suitable location of the community battery for different networks. Additionally, making data and maps publicly available to identify areas most in need of community batteries would help maximise the benefits of battery deployment across the network. Regulatory frameworks also need to be reconsidered to appropriately reward community batteries for the value and different services they provide. This can be achieved by enabling these batteries to participate in various markets, ensuring they are fairly compensated for their contributions to the grid. While the activation of EV charging through solar soaking and V2G can offer network support services, as observed in this project, the EV batteries could be overused and may result in their premature depletion.

To address this, it is recommended to introduce cost-reflective pricing structures that account for the costs associated with providing network services via EVs. Such pricing would give EV owners the necessary information to make informed and efficient decisions regarding the use of their batteries. Also, it is recommended to define connection agreements for the widespread adoption of V2G technology.

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