Title: **Advanced Planning of PV-Rich Distribution Networks – Deliverable 6: Consolidation of Findings (Final Report)**

Synopsis: This report consolidates the findings from the "Advanced Planning of PV-Rich Distribution Networks" project and provides a series of planning recommendations to help DNSPs in Australia, and internationally, take adequate planning actions that facilitate the widespread adoption of residential PV in a cost-effective and practical manner. The report also provides recommendations for DNSPs that wish to carry out advanced PV hosting capacity calculations to enable more accurate assessments of connection requests and/or potential solutions using model-based and smart meter-driven approaches. A summary of the investigated complete solutions and their costs for the four fully-modelled HV-LV feeders (including urban and rural) are presented considering PV penetrations in the short-to-medium and long terms.

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Executive Summary

This report presents the work and findings corresponding to Task 6 "Consolidation of Findings" part of the project "Advanced Planning of PV-Rich Distribution Networks" with funding assistance by the Australian Renewable Energy Agency (ARENA) as part of ARENA's Advancing Renewables Program and AusNet Services, and which is led by The University of Melbourne. It consolidates the findings of the 2-year project and, in particular, provides a series of recommendations to help DNSPs in Australia, and internationally, take adequate planning actions that facilitate the adoption of residential PV in a cost-effective and practical manner.

The modelling and analysis tasks carried out within this project have allowed the detailed quantification of the effects that different penetrations of residential PV can have on the studied urban and rural HV-LV feeders when considering a range of potential solutions. This, in turn, has made it possible to estimate not only the increase in PV hosting capacity that each solution can achieve per HV-LV feeder type but also the associated cost.

To help DNSPs in Australia, and internationally, take adequate planning actions that facilitate the adoption of residential PV in a cost-effective and practical manner, a series of recommendations are given based on the findings from Tasks 3 to 5 (reported in Deliverables 3 to 5 [1-3]). These planning recommendations are divided into two planning horizons: short-to-medium term (10-20 years from 2021) and long term (20-40 years from 2021), which are expected to reach around 40-60% of PV penetration and beyond 60%, respectively[1].

Furthermore, to provide guidance for DNSPs to carry out advanced PV hosting capacity calculations that will enable the assessment of connection requests and/or potential solutions, model-based and smart meter-driven (data analytics) recommendations are given based on the methods developed in Tasks 1 to 4 (reported in Deliverables 1 to 4 [1, 2, 5, 6]).

Planning Recommendations for PV-Rich Distribution Networks

The following planning recommendations consider the complete solutions investigated in this project[2] (ranging from the use of off-load and on-load tap changers to PV inverter settings to residential batteries, all combined augmentation), their cost-effectiveness with respect to the short-to-medium and long terms, and the practicalities surrounding their potential adoption by DNSPs.

These planning recommendations are made from the point of view of DNSPs to increase PV hosting capacity, i.e., focusing on the necessary DNSP-related investments and the effects on customers but excluding potential externalities (e.g., system-level effects on energy prices due to PV).

In the Short-to-Medium Term (40-60% PV Penetration):

1. ***Continue Enabling Volt-Watt & Volt-var Settings***. The Victorian PV inverter requirements (VicSet) established in 2019 should be emulated by DNSPs outside Victoria not yet doing something similar. Crucially, the amount of PV curtailment required by the VicSet is, in average, much smaller than that required by the Australian standard, thereby also bringing benefits to customers.

2. ***Continue Exploiting Existing Assets.*** DNSPs should adjust the off-load tap changer position of distribution transformer and/or the voltage target at zone substations to lower customer voltages and, hence, reduce voltage rise issues due to PV.

[1] These expected PV penetrations are based on the forecasts produced by AusNet for the analysed HV feeders [1, 2] in combination with the current PV penetration in Australia (more than 1 in 5 houses in Australia have a PV installation, i.e., approximately 20% PV penetration) [4]. These expected PV penetrations are, however, indicative as, ultimately, they depend on the type of HV feeder and the corresponding socio-economic characteristics. Some HV feeders might achieve very high PV penetrations much sooner.

[2] There is a myriad of innovative solutions that involve the orchestration of PV systems (e.g., using dynamic settings or export limits). However, the cost and technical aspects associated with them are not clear enough to be compared with the complete solutions and, hence, have been excluded from this project.

3. ***Adopt Stricter Volt-Watt & Volt-var Settings***. DNSPs should pursue the further improvement of the Victorian inverter settings (VicSet) that are stricter when dealing with voltage rise[3]. This can be done by adopting Volt-Watt settings that start curtailing at 1.09 p.u. (250.7V) and do not allow PV generation beyond 1.10 p.u. (253V), and Volt-var settings that absorb reactive power up to 1.09 p.u. (250.7V). Whilst, in average, curtailment does increase compared to VicSet, it is only marginal; hence, bringing benefits to both networks and customers.

4. ***Implement Intelligent Voltage Control at Zone Substations***. DNSPs should adopt intelligent approaches that exploit the existing flexibility provided by OLTCs at zone substations. By using intelligent voltage control that can estimate PV generation downstream (or its effects on customer voltages) and adjust the OLTC voltage target accordingly, voltage issues in LV feeders can be alleviated.

5. ***Implement Network-Friendly Battery Connection Requirements***. DNSPs should seize the opportunity and champion adequate battery connection requirements (or standards) for the long term. These requirements (like the investigated 'Network Smart') need to be enacted in the short-to-medium term so that, in the long term, most residential batteries can reduce grid exports due to PV generation, hence, mitigating voltage and congestion issues.

6. ***Other Considerations***. Despite the flexibility provided by LV OLTC-fitted transformers (effectively enabling high PV hosting capacities for all types of HV feeders), it is much more expensive than the other investigated solutions. This is because old transformers cannot be retrofitted with OLTCs, thus needing a brand new one. Even if the cost of an OLTC-fitted transformer were equal to a normal transformer, many devices would need to be replaced to manage voltage issues.

In the Long Term (Beyond 60% PV Penetration):

1. ***Adopt Stricter Volt-Watt & Volt-var Settings***. DNSPs should pursue stricter Volt-Watt and Volt-var settings as they can manage voltage problems due to reverse power flows for all feeder types and PV penetrations. Augmentation should be used in combination to solve asset congestion issues which, at high PV penetrations, involves not only distribution transformers but can also involve HV conductors.

2. ***Implement Intelligent Voltage Control at Zone Substations***. DNSPs should adopt intelligent voltage control at zone substations that can estimate the effect of PV generation downstream and adjust the OLTC voltage target, accordingly, thus alleviating voltage issues in LV feeders. Augmentation should be used in combination to solve asset congestion issues.

3. ***Implement Network-Friendly Battery Connection Requirements***. DNSPs should exploit the flexibility of residential batteries by mandating network-friendly connection requirements. Network-friendly control strategies, such as the investigated 'Network Smart', can be cost-effective in achieving high to full PV penetrations on all HV feeder types, mitigating both voltage and congestion issues. If actions are taken in the short-medium term to ensure that, in the long term, enough batteries have the updated requirements, then it will be highly effective. In urban feeders it can considerably reduce, or eliminate, augmentation costs, making it a much cheaper alternative while achieving high PV penetrations.

4. **Other Considerations**. The flexibility provided by LV OLTC-fitted transformers can be used to effectively manage voltage rise issues across all PV penetrations and feeders. Furthermore, this flexibility could also be applied to deal with voltage drop issues due to the future demand from electric vehicles (EVs) in the long term (e.g., at night) whilst also managing voltage rise issues due to high penetrations of PV systems (e.g., midday). However, LV OLTCs are inherently an expensive solution due to the large number of devices that need to be installed (one per LV feeder that requires voltage management).

[3] The study considered a homogenous approach to PV installations, i.e., all PV inverters were considered to have the same settings in all penetrations. In practice, there will be installations with old settings and, therefore, the overall benefits are likely to be less. However, as time goes on, old installations also get updated/upgraded, eventually using the new settings and increasing the corresponding benefits. The same homogenous approach was applied to residential batteries, i.e., all installations with the same control strategy.

Advanced PV Hosting Capacity Calculations

Model-based Recommendations:

The advantage of the model-based approach is that it is adaptable, network elements and participants can be added, removed or changed and control techniques can be implemented and tested through simulations. This makes the model-based approach highly effective if used to investigate the effectiveness of various solutions to various problems such as those related to the increase of PV hosting capacity.

1. ***Explicitly Model LV Feeders.*** DNSPs should consider the use of integrated HV-LV feeder models, i.e., explicitly modelling LV feeders (or pseudo LV feeders) down to customer connection points. This is necessary to fully capture the response of voltage-related control actions from residential PV systems as well as network elements and, hence, correctly quantify voltage rise issues and benefits from potential solutions.

2. ***Perform Time-Series Simulations.*** Time-series simulations should be conducted by DNSPs to adequately capture time-dependent aspects of demand, PV irradiance and controllable elements in the network including those on the customer side. This enables a more accurate assessment of voltages and power flows in time and the corresponding effects on PV curtailment and asset congestion.

3. ***Cater for Uncertainties.*** DNSPs should account, to the extent that is possible, for uncertainties related to PV location, PV size, irradiance profiles and demand profiles.

4. ***Other considerations.*** Although HV feeders can have significantly different characteristics, the investigation of potential solutions can be done on a limited number to reduce the required modelling effort and time. The selection of HV feeders should consider several characteristics such as general type (e.g., rural, urban), length, number of customers, number of PV system installations, etc. that can be used to map the corresponding population and identify the most extreme cases (as explained in Deliverable 1 [5]). Using extreme cases demonstrates the viability of a potential solution and, therefore, that solution is likely to also work (and perform even better) in milder cases.

Smart Meter-Driven Recommendations:

By using power and voltage data from smart meter of all customers downstream of the selected transformer, it is possible to estimate the solar PV hosting capacity in any given LV network using smart meter data, with no explicit model, once a given PV penetration is achieved and corresponding data was recorded. This is done using a smart meter-driven approach that applies a simple yet practical machine learning algorithm, to produce a regression model to estimate the PV hosting capacity in any given LV network. This means no electrical model of the LV feeders are required to assess hosting capacity.

1. ***Run Trials on Actual Distribution Transformers.*** DNSPs with smart meter data should run trials of the proposed smart-meter driven approach and compare the results with their existing PV hosting capacity assessments.

2. ***Use Data that Covers a Minimum PV Penetration Increase***. For DNSPs to successfully use the proposed smart meter-driven approach, the historical data must cover a period where a minimum increase of PV penetration occurs: 30% for distribution transformers in urban HV feeders and 20% for those in rural HV feeders.

3. ***Other Considerations.*** Further analysis using SCADA data to represent the zone substation's OLTC actions was carried out. It was found that the resulting changes in voltages (due to tap changes) can slightly reduce the accuracy of the PV hosting capacity estimations. Furthermore, because the OLTC actions can create voltage spikes (and become outliers), the accuracy of the prediction limits also reduces.

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1 Introduction

According to the Australian PV Institute, the aggregated installed capacity of solar PV in Australia is currently (Feb 2021) exceeding 18 GW, with many of these installations being residential. The percentage of dwellings with solar PV varies from around 20% in Victoria to almost 40% in Queensland. This, combined with a growing number of commercial customers adopting the technology, is already posing significant technical challenges on the very infrastructure they are connected to: the low voltage (LV) and high voltage (HV) distribution networks. Due to the rapid uptake of the technology, many Distribution Network Service Providers (DNSPs) across the country have adopted the use of PV penetration limits based on the capacity of the distribution transformers feeding LV customers. Once this limit is reached, complex and time-consuming network analyses are often required to determine the need for any mitigating action due to voltage rise or asset congestion issues (e.g., use of off-load tap changers, network augmentation, etc.).

Whilst, in principle, the use of a PV penetration limit is a sensible approach to swiftly deal with many connection requests, the lack of advanced planning approaches has led DNSPs to adopt values that might under or over-estimate their actual hosting capacity, particularly due to voltage issues in LV networks and aggregated congestion issues in HV networks. Similarly, assessing the effectiveness of non-traditional solutions, such as actively controlling smart PV inverters or deploying distribution transformers fitted with on-load tap changers, becomes a task beyond typical planning studies carried out by DNSPs. All this, in turn, becomes a barrier for the widespread adoption of solar PV as it can create delays, increase cost, and could undermine the consumer attractiveness of the technology.

To help remove the aforementioned barriers and accelerate the adoption of solar PV in distribution networks, the project "Advanced Planning of PV-Rich Distribution Networks" funded by the Australian Renewable Energy Agency (ARENA) and AusNet Services, and led by The University of Melbourne was established in February 2019 to:

1) develop analytical techniques to rapidly assess residential solar PV hosting capacity of electricity distribution networks by leveraging existing network and customer data; and,
2) produce planning recommendations to increase the PV hosting capacity using non-traditional solutions that exploit the capabilities of PV inverters, voltage regulation devices, and battery energy storage systems.

The report at hand corresponds to Task 6 "Consolidations of Findings", the Final Report of the project. The key messages of this report are presented in Chapter 5 where a series of recommendations are drawn to help DNSPs in Australia, and internationally, as well as other stakeholders make informed decisions with respect to the planning of PV-rich distribution networks and the corresponding PV hosting capacity calculations.

- **Planning Recommendations for PV-Rich Distribution Networks**. Recommendations to help DNSPs in Australia, and internationally, take adequate planning actions that facilitate the widespread adoption of residential PV in a cost-effective and practical manner. Two planning horizons are considered: short-to-medium term (10-20 years from 2021) and long term (20-40 years from 2021), which are expected to reach around 40-60% of PV penetration and beyond 60%, respectively. These are based on the findings from Tasks 3 to 5 (reported in Deliverables 3 to 5 [1-3]).
- **Recommendations for Advanced PV Hosting Capacity Calculations**. Recommendations for DNSPs that wish to carry out advanced PV hosting capacity calculations to enable more accurate assessments of connection requests and/or potential solutions using model-based and smart meter-driven approaches. These are derived from the methods developed in Tasks 1 to 4 (reported in Deliverables 1 to 4 [1, 2, 5, 6]).

Chapter 2 of this document presents an overview of the project. Chapter 3 presents the problem of reverse power flows, how to accurately model this impact through HV-LV distribution network models, considerations for modelling, and a range of complete solutions to increase PV hosting capacity. Chapter 4 presents the techno-economic summary of complete solutions, both in terms of total cost and cost per MWh of PV generation.

2 Project Overview

This 2-year project, that ran from February 2019 to February 2021 and was delivered by The University of Melbourne in close collaboration with the Victorian DNSP AusNet Services, aimed at producing:

1) Innovative analytical techniques to assess network hosting capacity of solar PV using readily available network and customer data, with emphasis on high voltage (HV) networks and historical and current AMI measurement data (smart meters); and,
2) Planning recommendations to increase hosting capacity derived from detailed network studies involving traditional (network augmentation) and non-traditional solutions (exploiting the capabilities of PV inverters, voltage regulation devices, and battery energy storage systems).

The project was comprised of the following six tasks:

- Task 1: HV-LV modelling of selected HV feeders.
- Task 2: Innovative Analytical Techniques.
- Task 3: Traditional solutions.
- Task 4: Non-traditional solutions.
- Task 5: Cost comparison among potential solutions.
- Task 6: Consolidation of Findings.

The work done within each task and the corresponding findings are summarised below.

Task 1: HV-LV Modelling of Selected HV Feeders (Feb to Jun 2019)

Task 1 produced the integrated HV and LV three-phase network models. Using AusNet Service's expertise, four HV (22kV line-to-line) feeders were selected based on quality of available data (network, smart meter, GIS, etc.) as well as general characteristics (rural with SWER lines, semi-urban, urban, etc.) to capture different types (urban, short rural and long rural). These networks were modelled using the software OpenDSS (developed by the Electric Power Research Institute - EPRI, USA). Real, high granularity, time-series daily demand and PV generation profiles were derived from anonymised smart meter data corresponding to customers of the same type and considering different types of days. SCADA data was used for validation purposes. Given that LV (400V line-to-line) network models were not readily available from AusNet Services (as is also the case for most DNSPs), pseudo LV feeders were constructed based on the estimated number of customers per distribution transformer and LV design principles (e.g., length, conductor, distribution of customers, etc.).

- The full methodology as well as the initial results are reported in Deliverable 1 [5].

Task 2: Innovative Analytical Techniques (Jun to Oct 2019)

Task 2 defined and validated (through simulations) an analytical technique to estimate the PV hosting capacity of a given distribution transformer (and corresponding LV feeders) using only smart meter data. Two of the selected HV feeders, urban and rural, were modelled with growing PV penetrations in a horizon of 5 years to create a large realistic smart meter dataset that captures the evolving impacts on network performance and customers. Then, correlations between customer data and PV penetrations were investigated. The most promising correlation, maximum daily customer voltage and the corresponding aggregated net demand of customers, was identified and used to finally define the proposed analytical technique.

The findings show that the proposed smart meter-driven analytical technique provides adequate estimations of PV hosting capacity, making it a faster and simpler alternative to model-based approaches.

- The full methodology as well as the case studies and findings are reported in Deliverable 2 [6].

Task 3: Traditional Solutions (Oct 2019 to Feb 2020)

Task 3 investigated use of traditional solutions such as change of off-load and on-load tap changer positions and/or network augmentation to increase the hosting capacity of PV-rich distribution networks considering the new Victorian Volt-Watt and Volt-var settings (VicSet) which mandates since Dec 2019 that both power quality response modes are enabled. Studies were performed on the four fully-modelled HV-LV feeders considering time-series seasonal analyses with growing penetrations of solar PV.

Findings show that with the VicSet provides significant benefits to both DNSPs and customers. Voltage rise issues and curtailment are dramatically reduced, making it possible to host 20% of customers without the need for other solutions. Adopting traditional solutions can help increase the solar PV hosting capacity to 40% (excluding HV feeders with long SWER lines). However, beyond 40%, traditional solutions were found to have limited effectiveness in mitigating network issues.

- The full methodology, case studies, and findings are reported in Deliverable 3 [1].

<u>Task 4: Non-Traditional Solutions (Feb to Aug 2020)</u>

Task 4 investigated the use of non-traditional solutions such as strict Volt-Watt and Volt-Var PV inverter settings, OLTC-fitted LV transformers, residential batteries with Off-the-Shelf (OTS) controllers, batteries with smarter controllers, and dynamic voltage target at zone substation OLTC, in combination with traditional solutions aiming at increasing the solar PV hosting capacity of distribution networks. Studies were performed on the four fully-modelled HV-LV feeders considering time-series seasonal analyses with growing penetrations of solar PV.

Findings show that the adaptive control of OLTC-fitted LV transformers can effectively manage voltages and, in combination with network augmentation, can increase hosting capacity to 100%. OTS batteries do not change the hosting capacity as they are unable to reduce peak PV exports (they become full early in the day). However, advanced battery controllers that do reduce exports (such as the investigated Network Smart controller), could allow all houses to have PV without much need for network augmentation. The strict Volt-Watt and Volt-Var settings as well as the dynamic voltage target at zone substation OLTC are effective in mitigating voltage problems. However, asset congestion can still occur, limiting their ability to significantly increase hosting capacity.

- The full methodology, case studies, and findings are reported in Deliverable 4 [2].

<u>Task 5: Cost Comparison Among Potential Solutions (Aug to Dec 2020)</u>

Task 5 performed a cost comparison among potential solutions that can be used by DNSPs to increase residential PV hosting capacity. Different complete solutions (combinations of solutions investigated in Task 3 “Traditional Solutions” and Task 4 “Non-Traditional Solutions”) that mitigate both voltage and asset congestion problems to achieve 60% and 100% of PV hosting capacity in each of the four fully-modelled HV-LV feeders were compared considering, in most cases, the new VicSet. The cost comparisons were done considering net present value accounting for both the CapEx and OpEx of network assets, the year of required installation, the discount rate until installation and inflation.

Findings show that to achieve a 60% hosting capacity, for urban HV feeders, Network Smart Batteries with Augmentation and VicSet inverter settings is the cheapest complete solution. For rural HV feeders, the cheapest complete solution is Tailored Volt-Watt + Volt-Var settings with Augmentation. To achieve 100% hosting capacity, for all feeders, Network Smart Batteries with Augmentation with VicSet inverter settings is the cheapest complete solution. In general, it was found that rural feeders face a reduced selection of options to increase hosting capacity whilst also being much more expensive for the same desired hosting capacity.

- The full methodology, case studies, and findings are reported in Deliverable 5 [3].

<u>Task 6: Consolidation of Findings (Dec 2020 to Feb 2021)</u>

Task 6 consolidated the findings from Tasks 1 to 5 and produced a series of planning recommendations to help DNSPs in Australia, and internationally, take adequate planning actions that facilitate the widespread adoption of residential PV in a cost-effective and practical manner. Recommendations are also produced for DNSPs that wish to carry out advanced PV hosting capacity calculations to enable more accurate assessments of connection requests and/or potential solutions using model-based and smart meter-driven approaches.

3 Distribution Networks and PV Hosting Capacity

This chapter describes the problem of reverse power flows from high penetrations of residential PV systems and how to calculate the PV hosting capacity of distribution networks using the adopted advanced model-based approach (Tasks 1, 3 and 4 [1, 2, 5]) and the proposed smart meter-driven approach (Task 2 [6]). It then describes the four fully-modelled HV-LV feeders used in the project. Finally, the solutions investigated in the project to increase PV hosting capacity are presented and some key results discussed.

3.1 Network Impacts of PV

In Australia, more than 1 in 5 houses have a PV system installed [4], equating to more than 2.5 million PV installations with a combined capacity over 18GW in Australia [7], with a record of almost 3GW of small-scale systems installed in 2020 alone [8, 9]. These PV penetrations are only set to increase in time, including the average size of PV installations increasing [7], presenting a challenge for distribution networks.

Residential PV systems (and the corresponding houses) are connected to the power system via distribution networks and are customers first point of interaction with the wider power system. Therefore, distribution networks are the first bottleneck for the continued uptake of residential PV.

PV penetration can be defined in many ways, and in this project is defined as the percentage of residential customers with PV systems. As PV penetrations increase, so do the levels of reverse power flow and, consequently, voltages and asset utilisation – to the extent that can exceed the voltage statutory limits and/or the rated capacity of assets.

For a given LV (400V line-to-line) feeder, illustrated in Figure 3-1 (a), asset congestion is usually problematic towards the head as reverse power flows accumulate towards the distribution transformer. Meanwhile, voltage rise problems occur towards the ends of the LV feeder, because of the impedance of underground/overhead lines and new (reversed) direction of power flows. The amount of reverse power flow is also related to the amount of load within households. Typically, the point of greatest generation is also when houses are empty with relatively low loads (e.g., at work during midday), leading to high reverse power flows. Therefore, voltage rise violations and asset congestion occur during peak daylight hours. The same effects will be seen on HV (22kV) feeders, illustrated in Figure 3-1 (b), when the reverse power flows of many residential areas (LV feeders) meet upstream.

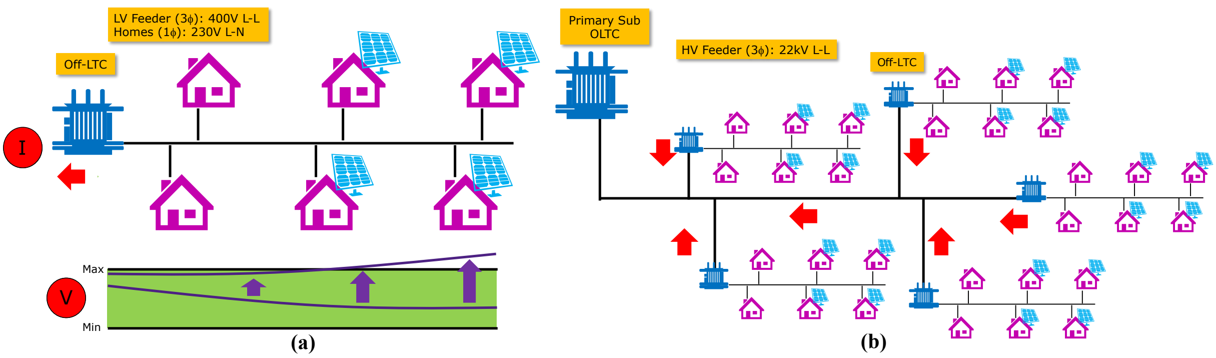


Figure 3-1 Illustration of PV impacts on (a) LV feeders and (b) HV feeders

Examples of these impacts from high levels of reverse power flows for various PV penetrations can be seen for the urban feeder CRE21, in spring across 24 hours, shown in Figure 3-2 to Figure 3-4 from Deliverable 3 [1]. It can be seen in Figure 3-2 that there is a voltage rise problem[4] in the LV feeders immediately at 20% PV penetration that continues up until 100% PV. The voltage rise problem in this instance does not exceed 1.12 p.u., despite increase in PV penetration, because of the action of the

[4] Customer voltages above 253V (1.10 p.u.) as per the Victorian Electricity Distribution Code [10].

VicSet inverter settings (more details in [1]). However, while the inverter action helps, it is not enough to keep customer voltages below the 1.10 p.u. upper voltage limit.

Asset utilisation of LV transformers and HV conductors also continues to increase with PV penetration. In the aggregate, PV reverse power flows still increase with PV penetration even with the curtailment resulting from VicSet due to voltages. Whilst this increase is within specification for the HV conductors, shown in Figure 3-3, this is problematic for the LV transformers shown in Figure 3-4. Some LV transformers within the HV feeder at 20% PV are overloaded, with more transformers overloading as PV penetration increases.

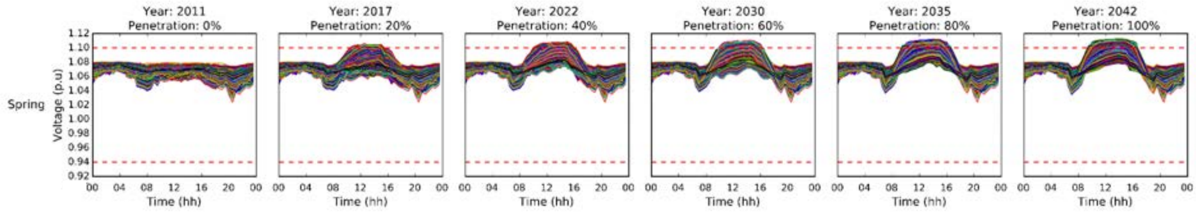


Figure 3-2 Voltage Rise Problems on LV feeder with VicSet Inverter Settings on CRE21

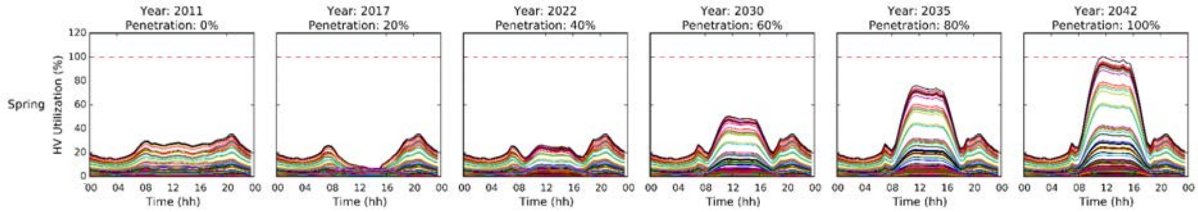


Figure 3-3 HV Line Utilisation with VicSet Inverter Settings on CRE21

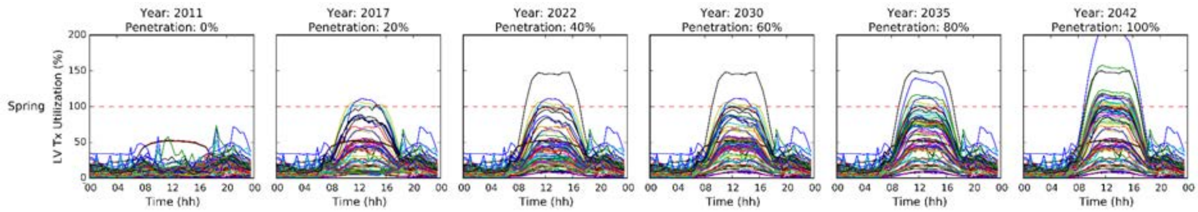


Figure 3-4 LV Transformer Asset Utilisation with VicSet Inverter Settings on CRE21

3.2 PV Hosting Capacity Calculations

PV Hosting Capacity is defined as the maximum amount of solar PV that a given distribution network (or part of it) can host without negatively affecting its normal operation at any point in time. Normal operation is defined by voltage being maintained within their statutory limits and asset utilisation in check (no congestion), with protection devices working as intended.

In the example of CRE21 (Figure 3-2 to Figure 3-4), if nothing is done, the hosting capacity is less than 20%, due to voltage violations at 20% in the LV feeders shown in Figure 3-2. However, even if voltage issues were to be solved independently (e.g., off-load tap adjustment of LV transformers), Figure 3-4 shows that also at 20% PV the LV transformer exceeds its maximum utilisation. For CRE21 to achieve 20% hosting capacity, the voltage issues need to be solved and the few LV transformers overloaded need to be replaced with a larger size of transformer. To increase hosting capacity further, then voltage issues would still require management and any additional asset congestion issues need to be rectified.

Based on the approaches and techniques adopted in this project, explained and demonstrated in Tasks 1 to 4 (reported in Deliverables 1 to 4 [1, 2, 5, 6]), two approaches were considered in this project that are capable of defining hosting capacity:

- (Advanced) Model-Based Approach (Tasks 1, 3 and 4 [1, 2, 5]); and,
- Smart Meter-Driven Approach (Task 2 [6]).

3.2.1 (Advanced) Model-Based Approach

In general, any model-based approach uses an explicit electrical model of the corresponding distribution network (including its topology, elements, parameters, etc.) that in turn allows to run power flow simulations (using specialised software packages) for different demand/generation scenarios. This is a well-known approach used routinely by DNSPs in Australia and around the world to design, plan and improve their networks. However, it is typically limited to HV feeders and to critical demand/generation scenarios.

The advantage of the model-based approach is that it is adaptable, network elements and participants can be added, removed or changed and control techniques can be implemented and tested through simulations. This makes the model-based approach highly effective if used to investigate the effectiveness of various solutions to various problems such as those related to the increase of PV hosting capacity.

In a model-based approach, to determine hosting capacity, firstly, distribution network planning standards and guidelines should be defined (e.g., voltage limits, rated capacity of assets, etc.). Then, power flow simulations are carried out considering the demand/PV scenarios of interest. Hosting capacity and the success of any solution is determined by the ability to keep voltages (particularly customer voltages), asset utilisation and any other critical parameter within pre-specified limits.

To move from a typical model-based approach to one that is more advanced and realistic and, hence, provide better quantifications and insights for DNSPs, various aspects need to be considered.

1. <u>LV Feeder Modelling</u>. Integrated HV-LV feeder models with LV feeders (or pseudo LV feeders constructed based on design principles), down to the (single-phase) house level, are necessary to fully capture voltage rise and asset congestion problems related to residential PV systems. This makes the adequate representation of three-phase LV feeders essential in the assessment of residential PV hosting capacity.
2. <u>HV Feeder Selection</u>. Although HV feeders can have significantly different characteristics, the investigation of potential solutions can be done on a limited number to reduce the required modelling effort and time. The selection of HV feeders should consider several characteristics such as general type (e.g., rural, urban), length, number of customers, number of PV system installations, etc. that can be used to map the corresponding population and identify the cases of interest. In practice, however, the selection of HV feeders will be a trade-off between the quality and availability of data (network, smart meter, GIS, etc.), existing PV system installations, etc., as well as the corresponding data extraction complexity.
3. <u>Time-Series Simulation</u>. Three-phase power flows need to be run to take account of demand and generation profiles changing across phases, day-to-day and across various seasons. Time-series simulations require time-series data (i.e., demand profiles, PV irradiance profiles) with adequate granularity. For instance, a granularity of at least 30-minute resolution can be an adequate trade-off between capturing time-dependent aspects, the corresponding computation time and the available historical data. In fact, this minimum resolution is aligned with what is typically available from historical smart meter data, SCADA measurements and meteorological data. Given that demand and PV generation can vary significantly between seasons and, hence, the corresponding voltage effects, PV curtailment, etc., time-series data needs also to cover – to some extent– seasonality.
4. <u>Uncertainty</u>. In planning studies, the exact locations, sizes, and irradiance corresponding to future PV installations are largely unknown. This also applies to the demand of those households. Therefore, uncertainty should be accounted for –to the extent that is possible– using, for instance, available PV statistics, diverse demand/generation profiles, Monte Carlo simulations, etc.
5. <u>PV and Battery Models</u>. If PV systems are meant to follow specific settings/requirements (e.g., Volt-Watt, export limits, etc.), then they need to be modelled so the corresponding interactions with voltages and power flows are adequately captured. This also applies to batteries and other behind-the-meter technologies.

Based on the above, the following considerations were implemented for the advanced model-based studies carried out in Task 3 and Task 4 that quantified the technical benefits (voltage compliance, asset utilisation and annual PV curtailment) of potential solutions for different PV penetrations.

1. **LV Feeder Modelling within the Project**
   - ✓ Given that LV network models were not readily available, LV networks needed to be modelled from the ground up. As is often the case, corresponding detailed data required to create a model was not complete. Following LV design principles as specified by Australian DNSPs [11-15], pseudo three-phase LV feeders were constructed/created by estimating the number of feeders per distribution transformer, number of single-phase customers per feeder, number of customers per phase, and length of feeders. More information in this project, including formulas, can be found in Deliverable 2 [6].

2. **HV Feeder Selection within the Project**
   - ✓ Due to time and data limitations, four HV feeders were selected. The selection considered several different feeder characteristics (rural, urban, length, number of customers, number of PV system installations, loading etc.) and identified the most extreme cases (as explained in Deliverable 1 [5]). Using extreme cases demonstrates the viability of a potential solution and, therefore, that solution is likely to also work (and perform even better) in milder cases.
   - ✓ PV penetrations, and corresponding horizons (years), are based on real forecasts from AusNet Services for each of the selected HV feeders. These forecasts are then extended to estimate the year 100% PV is reached for each HV feeder.

3. **Times-series considerations within the Project**
   - ✓ All the analyses in the project were carried out considering time-series three-phase (unbalanced) power flows across the selected HV-LV feeders using the software OpenDSS.
   - ✓ For residential demand, a pool of 30-min resolution, year-long (i.e., 17,520 points), anonymized smart meter demand data (i.e., P and Q) was used, collected from 342 individual residential customers in the year of 2014. Using this pool, the yearly demand profiles were broken down in daily profiles, resulting in a pool of ~30,000 daily demand profiles.
   - ✓ To provide a more realistic modelling of non-residential customers, real-world commercial and industrial load profiles made available by CSIRO are used to create daily load profiles for the 5 most common non-residential customers found in the selected feeders (i.e., Hospital, Prison, Sewerage, Water Treatment, Office/Shop). Using this data, profiles are created for a whole year (365 daily profiles) and for the 5 most common non-residential customers found in the feeders (i.e., Hospital, Prison, Sewerage, Water Treatment, Office/Shop). This non-residential data is then averaged and normalised for use in simulations.
   - ✓ Real irradiance pool of 30-min resolution, year-long (i.e., 17,520 points) real irradiance measurements facilitated by the AusNet Services. Using this pool, the yearly irradiance profile was broken down in 365 daily profiles. These profiles are used in the seasonal analysis (details in the following subsections) to cater for the seasonal effects of solar PV generation.
   - ✓ Supplementary time-series analyses showed that considering two weeks per season results in almost the same levels of energy curtailment (in %) when compared to a full year (365 days) time-series analysis. Consequently, all the seasonal analyses within the project consider 14 consecutive days in each season as it is an adequate trade-off between capturing seasonality and the corresponding computation time.

4. **Uncertainty within the Project**
   - ✓ All the simulations for seasonal analysis considered demand uncertainty by adopting different year-long demand profiles among customers. For PV irradiance, HV feeders are assumed to have the same year-long profile (as customers are roughly within the same geographical area). In both cases, demand and PV irradiance profiles captures not only half-hourly changes but also day to day changes for the selected weeks within each season. Therefore, there are multiple demand/generation scenarios being considered in the simulations.
   - ✓ The locations of PV system installations were considered to be randomly and unevenly distributed across distribution transformers and LV feeders. This is to avoid clusters at the end or beginning of the HV and LV feeders, which are cases that can lead to over or underestimations of potential PV impacts.

- ✓ Probabilistic uncertainty for size of PV installation was considered where the proportion of single-phase PV installations with 2.5, 3.5, 5.5, and 8kWp is 8, 24, 52 and 16%, respectively.
- ✓ Continuity was considered such as demand, PV locations and PV sizes remain consistent when PV penetrations increase and when different solutions are investigated.

5. **PV and Battery Models within the Project**
   - ✓ In most of the simulations, PV inverters use, as default settings, the new Victorian Volt-Watt and Volt-var (VicSet) settings which are defined by the new standard mandating both power quality response modes being enabled [16]. When VicSet is not used, other specific settings are investigated (e.g., stricter Volt-Watt and Volt-var settings).
   - ✓ When residential batteries are investigated (both off-the-shelf and Network Smart), the corresponding control strategies are modelled in detail. Furthermore, all customers with a PV system are assumed to have a battery. In practice, battery adoption lags the adoption of PV systems. This consideration was necessary to simplify the analysis.
   - ✓ In all simulations, the PV settings (and battery control strategies, where applicable) were adopted using a homogenous implementation, i.e., all PV inverters were considered to have the VicSet in all penetrations. In practice, in the short term, there will be PV inverters with old settings and, therefore, the overall benefits are likely to be less. However, as time goes on, old installations also get updated/upgraded, eventually using the new VicSet and increasing the corresponding benefits.

Further information on power flow considerations, smart meter profiles, and other modelling aspects of the analyses can be found in Deliverable 3 [1] and Deliverable 4 [2].

3.2.2 Smart Meter-Driven Approach

The advantage of the smart meter-driven approach is that it does not require explicit electrical models, i.e., does not require power flow simulations, only historical smart meter data. This makes the smart meter-driven approach a very promising alternative that can save time and effort in the assessment of new connection requests.

As shown in Deliverable 2 [6], using hybrid smart meter data it was possible to demonstrate that a very strong linear correlation exists between the maximum customer voltage on a given day for a given LV network (distribution transformer) and the aggregated net active power demand of the corresponding customers (at the time of the maximum voltage). These two features can be used to estimate the solar PV hosting capacity in any given LV network using historical smart meter data and simple yet practical machine learning algorithm to produce a regression model. No electrical models are required.

The supervised (i.e., gradient decent) univariate regression model, in effect, estimates (very quickly) the aggregated net active power demand (that can be negative due to PV systems) that can lead to voltages rise issues (i.e., above 1.1 p.u.). This value, in turn, can be used to calculate the additional PV capacity that can be hosted by the LV network. Prediction limits to cater for uncertainties can also be considered.

The main steps of the methodology, as if implemented by a DNSP, are presented below:

1. Smart meter database. For a given number of days (ideally covering most of the evolution of PV penetrations to date), the daily smart meter data (i.e., P, Q, V) from all customers in a given LV network (distribution transformer) are extracted from the smart meter database.
2. Data Processing. The smart meter data are analysed and cleaned from missing and inconsistent values. Then, the maximum voltage recorded for each day is identified and the corresponding (same timestamp) active powers are added up. Finally, a new dataset is produced containing the maximum voltage and the corresponding aggregated power for each day.
3. PV Hosting Capacity Estimation. The new dataset is used to train a supervised (i.e., gradient decent) univariate regression model which corresponds to the PV hosting capacity estimation model for the analysed LV network.

In terms of the accuracy of the model, it is important to highlight that the volume of smart meter data used to produce the hosting capacity estimation model plays an important role. More data helps to capture the variance of a larger sample of network conditions (i.e., voltage vs active power), thus increasing the model's estimation accuracy.

Despite the encouraging results reported in Deliverable 2 [6], this approach is not suitable for planning studies that involve testing various network solutions that change the fundamentals of the feeder. This is because the smart-meter driven approach cannot predict actions for data it has not yet been accounted for in the regression model.

3.3 Realistic Integrated HV-LV Feeders

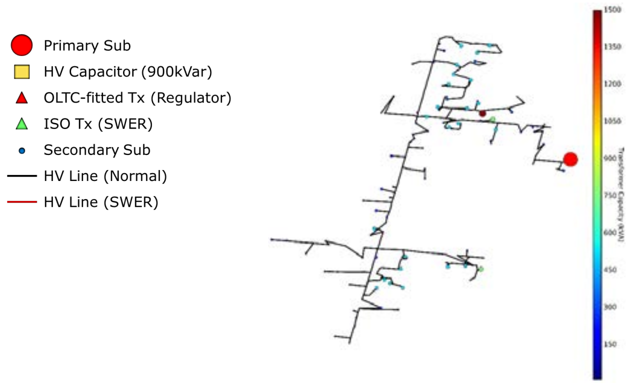
The project considered four fully-modelled HV-LV feeders, each with significantly different characteristics (i.e., urban, short rural, long rural etc.). These feeder types exhibit very different physical properties depending on their location (feeder length, substations per number of customers, etc.). This allows demonstrating that the adopted solutions can be applied, to the extent that is possible, across the wide spectrum of HV feeders in the area of AusNet Services.

As mentioned previously, LV feeder models are critical to fully capture the effectiveness of any potential solution to increase residential PV hosting capacity. Whilst these models are derived from real Victorian HV feeders, the LV feeders are modelled on modern design principles, described in Deliverable 1 [5].

All analyses were performed considering all four (4) fully-modelled HV-LV Feeders presented and detailed in Deliverable 1 "HV-LV modelling of selected HV feeders" [5]. These correspond to:

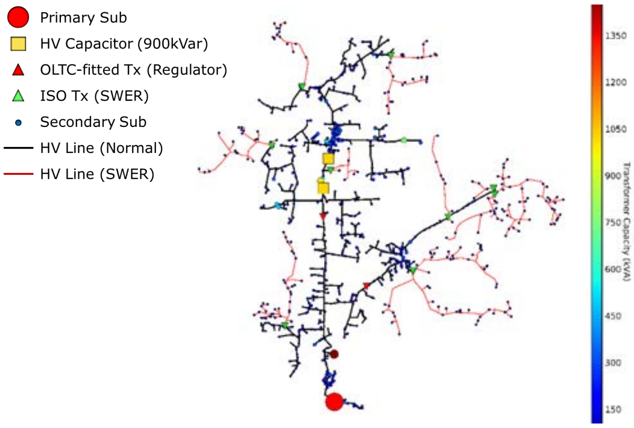
1. HV Feeder CRE21, urban, Figure 3-5
2. HV Feeder SMR8, long rural, Figure 3-6
3. HV Feeder HPK11, urban, Figure 3-7
4. HV Feeder KLO14, short rural Figure 3-8

The topology and general characteristics of each HV feeder are provided on the corresponding figures. These figures only show the HV portion of the feeder that comes from real Victorian data, whilst the modelled LV feeders using modern design principles are not shown (but are modelled electrically connected). Each of the feeders has a fully-modelled LV network attached to each of the HV/LV substations (blue circles or green triangles).



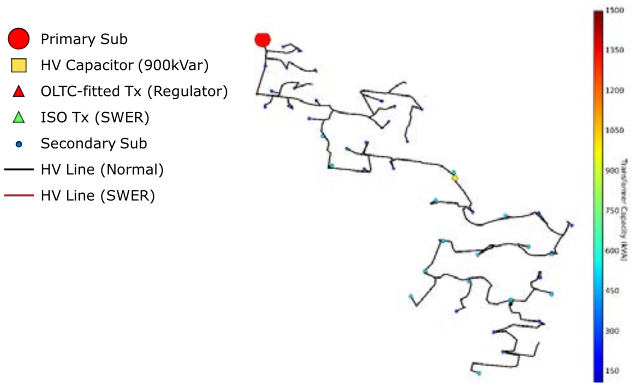
# of LV Residential Substations:	71
# of LV Residential Customers:	3,374
# of LV Non-Residential Substations:	9
# of LV Non-Residential Customers:	9
Distance of Farthest Transformer (km):	9
# of HV Capacitors (900kVar each):	0
# of SWER Transformers:	0
# of REGULATOR Transformers:	0
Total HV Conductors (km):	30
Total HV SWER Conductors (km)	0

Figure 3-5 Feeder CRE21, Urban – Topology and General Characteristics



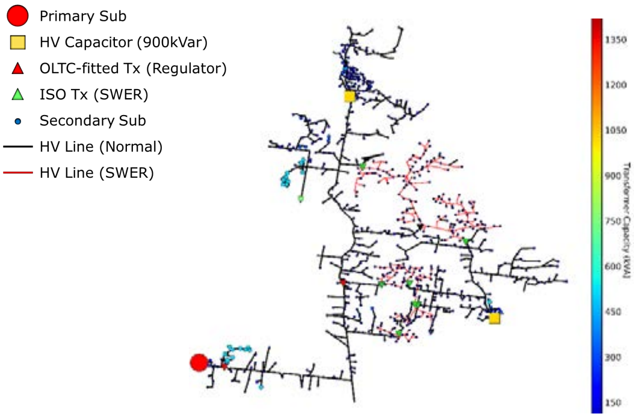
# of LV Residential Substations:	704
# of LV Residential Customers:	3,608
# of LV Non-Residential Substations:	61
# of LV Non-Residential Customers:	61
Distance of Farthest Transformer (km):	52
# of HV Capacitors (900kVar each):	2
# of SWER Transformers:	10
# of REGULATOR Transformers:	2
Total HV Conductors (km):	486
Total HV SWER Conductors (km)	194

Figure 3-6 Feeder SMR8, Long Rural – Topology and General Characteristics



# of LV Residential Substations:	44
# of LV Residential Customers:	5,274
# of LV Non-Residential Substations:	1
# of LV Non-Residential Customers:	1
Distance of Farthest Transformer (km):	12
# of HV Capacitors (900kVar each):	0
# of SWER Transformers:	0
# of REGULATOR Transformers:	0
Total HV Conductors (km):	70
Total HV SWER Conductors (km)	0

Figure 3-7 Feeder HPK11, Urban – Topology and General Characteristics



# of LV Residential Substations:	700
# of LV Residential Customers:	4,691
# of LV Non-Residential Substations:	24
# of LV Non-Residential Customers:	24
Distance of Farthest Transformer (km):	36
# of HV Capacitors (900kVar each):	2
# of SWER Transformers:	7
# of REGULATOR Transformers:	2
Total HV Conductors (km):	275
Total HV SWER Conductors (km)	54

Figure 3-8 Feeder KLO14, Short Rural – Topology and General Characteristics

3.4 Solutions to Increase PV Hosting Capacity

To increase PV hosting capacity, voltage and asset congestion problems need to be managed in an effective manner. Whilst augmentation of the whole or large parts of the distribution network are possible and can in some instances help with voltage problems (and other instances has minimal improvements), this is a very costly approach. Fortunately, there are several solutions that exist that can make better use of existing assets with a much lower rate of asset replacement required.

This project identified multiple potential solutions to increase PV hosting capacity and divided them into traditional and non-traditional. The analyses carried out in Task 3 [1] and Task 4 [2], traditional and non-traditional solutions, respectively, helped quantifying the technical advantages of those solutions across the four types of HV-LV feeders. Most of the solutions that mitigated voltage rise problems were found not to address asset congestion problems. Network augmentation, the only solution that directly tackles asset congestion, was found not to affect voltages. Based on these findings, in Task 5 [3], the combination of solutions was used to ensure both voltage and asset congestion problems are mitigated to enable a given PV hosting capacity. These combinations are hereafter referred to as *Complete* solutions and are listed below. Since different complete solutions can be used to achieve a desired PV hosting capacity, cost comparisons can be carried out to determine the cheapest option.

The traditional, non-traditional and complete solutions are briefly described in the following subsections.

3.4.1 Traditional Solutions

The term "Traditional Solutions" refers, in this project, to the commonly adopted solutions by DNSPs in Australia and around the world in order to alleviate technical issues related to voltage and asset congestion. Such traditional solutions leverage existing network owned controllable assets (e.g., off-load and on-load tap changers, capacitors, in-line voltage regulators, etc.) as well as consider the replacement or upgrade of conductors and/or transformers.

Adjustment of Off-Load Tap Changers

This solution considers the adjustment of the tap positions of the Off-Load Tap Changer located in each LV distribution transformer. The main idea of this approach is that the current adopted off-load tap positions are adjusted (i.e., reduced) in such a way so that the voltage is reduced to the lowest point possible (i.e., the minimum voltage across all supplied customers is within the statutory limit). This approach allows unlocking additional voltage headroom, hence reduce amplitude of the maximum voltage (across all supplied customers) due to the increasing penetration of solar PV and ultimately increase the corresponding hosting capacity.

- ✓ Creates voltage headroom for LV customers, thus reducing overvoltage issues.
- × Limited effectiveness at high PV penetrations.
- × Fixed tap position makes it unsuitable to deal with future voltage drops (e.g., EV charging).
- × Adjustment off-load taps are unable to manage asset congestion.

Adjustment of Zone Substation OLTC

This solution considers the adjustment of the fixed voltage target at the Zone Substation OLTC. The main idea of this approach is that the current adopted voltage target is adjusted (i.e., reduced) in such a way so that the source voltage is reduced hence unlocking additional voltage headroom. This is expected to reduce the amplitude of the maximum voltage (across all supplied customers) due to the increasing penetration of solar PV and ultimately increase the corresponding hosting capacity. This solution affects thousands of customers and needs to be performed only for the OLTC.

- ✓ Creates a slight voltage headroom for overvoltage issues when also using off-load tap changers.
- × Limited effectiveness at higher PV penetrations.
- × Voltage-drops at night would remain a potential issue in the LV feeders due to off-tap change.
- × Adjustment of zone substation's OLTC fixed voltage target is unable to manage asset congestion.

Network Augmentation

This solution considers the replacement of conductors and transformers with larger ampacity and rating, respectively, with the aim of mitigating congestion issues as larger amounts of current flow can be supported as well as reducing the effect of voltage rise/drop due to the smaller impedances of larger conductors. Adopting such an approach, however, can be considered costly and time consuming (i.e., significant labour, expensive assets, etc.).

- ✓ Network augmentation is effective at managing asset congestion related problems.
- × Ineffective in tackling voltage issues even at low PV penetrations given that new conductors have similar impedances to old ones (minimal effect on customer voltages).

3.4.2 Non-Traditional Solutions

The term "Non-Traditional Solutions" refers, in this project, to solutions not commonly adopted (today) by DNSPs in Australia (and internationally) to alleviate technical issues related to voltage and asset congestion. Such non-traditional solutions consider new network-owned controllable assets (e.g., LV on-load tap changer-fitted transformers) as well as customer-owned assets (e.g., solar PV, battery energy storage systems). Such non-traditional solutions can also be combined with traditional solutions, i.e., leveraging existing controllable elements and replacing or upgrading assets.

Tailored Volt-Watt and Volt-var PV Inverter Settings
Tailored settings are aimed to fully mitigate voltage rise issues and help further increase the hosting capacity. These settings aim at absorbing as much reactive power as possible just before the maximum voltage limit is reached, i.e., 1.09 p.u. (251V) where after that point a curtailment of the generated power is triggered. Then the generation is linearly dropping down until the maximum voltage limit is reached, i.e., 1.10 p.u. (253V) where the PV system is forced to stop generating power (i.e., 0% of rated power). These settings are expected to limit the voltage of all customers with solar PV up to 1.10 p.u. While these settings are likely to lead to higher volumes of PV curtailment, they are much better at manage voltage problems

- ✓ Prevents any voltage rise violation, i.e., is more effective than VicSet.
- ✓ Although average annual curtailment increases compared VicSet, it is only 1% more.
- × Tailored VW and VV settings are unable to manage asset congestion issues on their own.

LV OLTC-fitted Transformers
The last point of voltage regulation in distribution networks is traditionally performed at the zone substations (e.g., 66/22kV) which are equipped with OLTC-fitted transformers. The principle of voltage regulation on distribution networks is to maintain the voltage at the secondary side close to a predefined voltage target (commonly above the nominal) within the statutory limits during maximum load. Crucially, the degree to which voltages can be reduced or increased is constrained due to the voltage compliance of HV customers and the thousands of customers connected in the LV networks. Thus, to increase the 'on-load' flexibility in LV networks the use of LV OLTC-fitted transformers can be considered as a potential solution to manage voltages closer to LV customers and increasing PV hosting capacity.

- ✓ Prevents any voltage rise violation of customers in the corresponding LV feeders.
- ✓ Future demand (larger voltage drops) can be managed effectively.
- × LV OLTC-fitted transformers are unable to manage asset congestion issues on their own.

Off-the-shelf residential battery energy storage (BES) systems
This solution considers the case where households with solar PV adopt residential "off-the-shelf" (OTS) battery energy storage (BES) systems. The OTS control is based on what manufacturers provide as general description of the basic operating principles and corresponds to the following: when generation exceeds demand, the BES system charges from all the surplus PV generation. When PV generation falls below the household demand, the BES discharges to meet the local demand [17].

- ✓ Minor improvements in voltage and asset congestion performance.
- ✓ Good for customers (significantly reduced energy imports).
- × OTS BES systems do not adequately discharge at night and can reach full SOC during the day.
- × Ineffective at managing voltage and asset congestion to achieve higher PV hosting capacities.

Network smart residential battery energy storage (BES) systems
Given the flexible controllability of BES systems, there is an opportunity to adopt advanced battery management strategies that not only provide benefits to their owners (lowering electricity bills) but also to electricity distribution companies, reducing power exports from households with solar PV and, thus, mitigating network impacts. A Network Smart controller aimed at reducing high PV exports by adapting the BES charging power proportionally to the PV generation, and ensuring available capacity by discharging overnight can be used. Household behaviour when adopting a NS BES system can mean that PV exports can be significantly reduced while meeting the local needs of the household. This can lead to reduced peak reverse power flows and potentially maintain network integrity.

- ✓ Highly effective in managing both asset congestion and voltage related issues to achieve high PV hosting capacities.
- × Slightly increased energy imports (2-5% more than the OTS BES system).

Dynamic Voltage Target at Zone Substation OLTC
This solution considers the adoption of a dynamic voltage target (particularly, a reduction in voltage target) at the zone substation OLTC. The main idea is that the power flow measured at the zone substation can be used as a proxy to estimate the volume of PV generation as a proxy of the voltage rise in downstream networks. Therefore, this measurement can be used to calculate the desired voltage target so as to increase the available voltage headroom in downstream networks.

- ✓ Highly effective in managing voltage in the LV despite the control at the zone substation.
- × Dynamic Voltage Target at the Zone Substations OLTC is unable to solve asset congestion related issues.
- × Other HV feeders supplied by the same zone substation might impose constraints.

3.4.3 Complete Solutions

The *Complete* solutions are the combination of traditional and non-traditional solutions that ensure both voltage and asset congestion problems are mitigated to enable a given PV hosting capacity. The seven complete solutions investigated in this project (Task 5 [3]) are listed below.

(1) Off-Load Tap Changers + Augmentation + VicSet
(2) Zone Sub OLTC + Off-Load Tap Changers + Augmentation + VicSet
(3) Tailored Volt-Watt and Volt-var Settings + Off-Load Tap Changers + Augmentation
(4) LV OLTC + Augmentation + Off-Load Tap Changers + VicSet
(5) Off-The-Shelf Batteries + Off-Load Tap Changers + Augmentation + VicSet
(6) Network Smart Batteries + Off-Load Tap Changers + Augmentation + VicSet
(7) Dynamic Voltage at Zone Sub OLTC + Off-Load Tap Changers + Augmentation + VicSet[5]

A summary comparison of complete solutions is presented in Table 3-1 considering the four fully-modelled HV-LV feeders. Table 3-1 shows that complete solutions (3), (4) and (6), involving the tailored Volt-Watt and Volt-var settings, LV OLTC-fitted transformers and Network Smart residential BES systems, respectively, can increase the hosting capacity to 100% for all HV feeder types. However, other complete solutions effectiveness varies significantly on the type of the feeder and its corresponding characteristics. It should be noted that (7) was simulated only for CRE21 and, therefore, the findings cannot be extrapolated to the other feeders; however, it is likely to perform well.

The other complete solutions (1), (2) and (5) are able to achieve lower hosting capacities, but not for all feeder types. It is evident that long lines with high impedances in long rural SMR8 can be problematic for increasing hosting capacity and managing voltage rise. For SMR8, complete solutions (1), (2) and (5) are unable to even meet 20% hosting capacity. Furthermore, short rural KLO14 follows close behind in being problematic for these complete solutions, only achieving a maximum of 20% hosting capacity. The urban feeder HPK11 is only able to reach 40% hosting capacity using these solutions but for the stronger urban feeder CRE21 the same solutions reach 80% hosting capacity. In general, rural networks present a challenge for increasing hosting capacity with a reduced selection of complete solutions available.

Given this summary of the effectiveness of different complete solutions at different penetrations (years) across many types of distribution feeders (i.e., urban and rural), a cost comparison among complete solutions is required to determine cost effectiveness. This is presented in the next Chapter.

[5] Analysis done only for CRE21 (Urban HV Feeder)

Table 3-1 Summary of Performance for Complete Solutions

Key: ✗ **No HV Feeder** ✓ **1 Network** ✓ **2 Networks** ✓ **3 Networks** ✓ **4 Networks** ✓ **CRE21 only**
U Urban **SR Short Rural** **LR Long Rural**

Complete Solutions	Residential PV Hosting Capacity (HC)				
	20%	40%	60%	80%	100%
(1) **Off-Load Tap Changers** + Augmentation + VicSet	✓ (3 Networks) U CRE21 U HPK11 SR KLO14	✓ (2 Networks) U CRE21 U HPK11	✓ (1 Network) U CRE21	✓ (1 Network) U CRE21	✗
(2) **Zone Sub OLTC** + Off-Load Tap Changers + Augmentation + VicSet	✓ (3 Networks) U CRE21 U HPK11 SR KLO14	✓ (2 Networks) U CRE21 U HPK11	✓ (1 Network) U CRE21	✓ (1 Network) U CRE21	✗
(3) **Tailored Volt-Watt and Volt-var Settings** + Off-Load Tap Changers + Augmentation	✓ (4 Networks) U CRE21 LR SMR8 U HPK11 SR KLO14	✓ (4 Networks) U CRE21 LR SMR8 U HPK11 SR KLO14	✓ (4 Networks) U CRE21 LR SMR8 U HPK11 SR KLO14	✓ (4 Networks) U CRE21 LR SMR8 U HPK11 SR KLO14	✓ (4 Networks) U CRE21 LR SMR8 U HPK11 SR KLO14
(4) **LV OLTC** + Off-Load Tap Changers + Augmentation + VicSet	✓ (4 Networks) U CRE21 LR SMR8 U HPK11 SR KLO14	✓ (4 Networks) U CRE21 LR SMR8 U HPK11 SR KLO14	✓ (4 Networks) U CRE21 LR SMR8 U HPK11 SR KLO14	✓ (4 Networks) U CRE21 LR SMR8 U HPK11 SR KLO14	✓ (4 Networks) U CRE21 LR SMR8 U HPK11 SR KLO14
(5) **Off-The-Shelf Batteries** + Off-Load Tap Changers + Augmentation + VicSet	✓ (3 Networks) U CRE21 U HPK11 SR KLO14	✓ (2 Networks) U CRE21 U HPK11	✓ (1 Network) U CRE21	✓ (1 Network) U CRE21	✗
(6) **Network Smart Batteries** + Off-Load Tap Changers + Augmentation + VicSet	✓ (4 Networks) U CRE21 LR SMR8 U HPK11 SR KLO14	✓ (4 Networks) U CRE21 LR SMR8 U HPK11 SR KLO14	✓ (4 Networks) U CRE21 LR SMR8 U HPK11 SR KLO14	✓ (4 Networks) U CRE21 LR SMR8 U HPK11 SR KLO14	✓ (4 Networks) U CRE21 LR SMR8 U HPK11 SR KLO14
(7) **Dynamic Voltage at Zone Sub OLTC** + Off-Load Tap Changers + Augmentation + VicSet	✓ (CRE21 only) U CRE21	✓ (CRE21 only) U CRE21	✓ (CRE21 only) U CRE21	✓ (CRE21 only) U CRE21	✓ (CRE21 only) U CRE21

4 Techno-Economic Performance of Complete Solutions

This chapter presents the techno-economic considerations of potential solutions to increase hosting capacity. Section 4.1 summarises cost considerations, such as net present value, cost of assets, year of installation and time-frame of analysis for each HV feeder. Analysis of the cost-effectiveness of complete solutions is presented in section 4.2 in terms of total cost to increase PV hosting capacity and in terms of cost per MWh of PV generation is presented in section 4.3.

4.1 Economic Considerations

Net Present Value (NPV)

NPV is typically used to value future cashflows over the life of an investment that is discounted to the present. If investments are done across multiple years for a given horizon, NPV helps bringing the multiple investments to a single present-day equivalent, to enable like-for-like comparisons. NPV accounts for capital expenses, operational expenses, PV curtailment costs, a discount rate for the passage of time and a rate of inflation.

Cost of Assets

The necessary assets of complete solutions are quantified considering superposition of the results from Task 3 [1] and Task 4 [2], i.e., any remaining asset congestion problems are solved through augmentation (e.g., replacing overloaded LV transformers).

Cost of increasing hosting capacity are considered with the capital expenditure (CapEx) and operational expenditure (OpEx) of assets, as well as the cost of PV curtailment within a complete solution. Full details of these cost considerations can be found within Deliverable 5 [3], with a summary outlined below:

- CapEx:
  - LV transformer cost
  - LV OLTC-Fitted transformer cost
  - HV or LV conductor replacement
  - Dynamic Voltage Target in Zone Substation
- OpEx:
  - Changing off-load tap position in LV distribution transformer
  - Potential maintenance of LV OLTC-fitted transformers
- PV Curtailment:
  - Cost of PV curtailment considering Victorian minimum feed-in-tariff

Residential batteries are considered in this project to be bought and installed by residential customers alongside their PV systems to reduce their electricity bills. Consequently, for the DNSP, there is not cost associated with the residential batteries. Nonetheless, the distribution networks can still benefit from the effects on reverse power flows due to the presence of residential batteries (either 'Off-the-Shelf Batteries' or using network-friendly connection requirements such as the 'Network Smart Batteries').

Year of Installation

The calculation of CapEx and OpEx considers the number of assets and the year of asset installation. Any OpEx also accounts for any per-year costs up until the end of assessment.

The analyses carried out in Task 3 and Task 4 identified the solutions required to achieve different PV hosting capacities for different time windows (involving multiple years). Because of this, the quantification of the associated costs considers the installation of the assets at the start of the corresponding window (e.g., for a 2031-2042 window, assets are installed in 2031), ensuring its effectiveness throughout whilst still adequately discounted compared to an unnecessarily early installation. PV curtailment cost uses annual curtailment figures from Task 3 and Task 4, with a linear approximation of curtailment for years between the time windows, thereby creating a per year annual PV curtailment cost.

Timeframes of Analysis

Two PV hosting capacity scenarios were considered for cost comparisons: 60% and 100%. These timeframes are also used as two planning horizons for recommendations in Chapter 5: short-to-medium term (10-20 years from 2021) and long term (20-40 years from 2021), which are expected to reach around 40-60% of PV penetration and beyond 60%, respectively (depending on HV feeder).

Because of this, 60% of PV hosting capacity can be considered as a milestone beyond which there is too much uncertainty about technologies as new solutions and challenges might emerge. The 100% PV hosting capacity scenario, despite being much further in the future (31 years for CRE21 and 49 for the others), is considered for completeness and to understand the theoretical total cost of complete solutions. A table summarising the time horizon for economic analysis is shown in Table 4-1.

Table 4-1 PV Hosting Capacity Forecasts for Different Feeders

Hosting Capacity	CRE21 (urban)	SMR8 (long rural)	HPK11 (urban)	KLO14 (short rural)
60%	2011-2030	2011-2040	2011-2040	2011-2040
100%	2011-2042	2011-2060	2011-2060	2011-2060

Cost Sensitivity

The cost of PV curtailment and cost of OLTCs presented were subjected to a sensitivity. The OLTC costs were variations around the cost increase of an OLTC relative to a normal LV transformer, shown in Table 4-2. The PV curtailment cost sensitivity considered the effect of if in the future the Victorian feed-in-tariff half its current value, shown in Table 4-3. Results of these sensitives on cost of complete solutions can be found within in Deliverable 5 [3].

Table 4-2 OLTC Cost Sensitivity Values

Transformer Size	Lowest Cost	Low cost	Base Cost	Highest Cost
Less than 300kVA	1.125	1.5	2	3
300-500kVA	1.125	1.5	2	3
Greater than 500kVA	1.05	1.2	1.5	2

Table 4-3 PV Curtailment Cost Sensitivity Values

Current Feed-in-Tariff	Half of current Feed-in-Tariff
10.2c per kWh	5.1c per kWh

4.2 Summary of Complete Solutions Costs to Increase PV Hosting Capacity

This section presents a summary of complete solution costs to achieve both 60% (i.e., short-to-medium term) and 100% (i.e., long term) hosting capacity. A full breakdown of cost results, including cost sensitivity results not presented, can be found in Deliverable 5 [3]. Any solution and feeder combination that violates voltage limits is because the solution cannot manage customer voltage rise adequately.

4.2.1 Complete Solution Summary to Achieve 60% Residential PV Hosting Capacity

A summary is seen in Table 4-4 for a comparison of complete solution costs to achieve 60% hosting capacity (HC) across four HV feeders.

Table 4-4 Summary of Techno-Economic Performance of Complete Solutions for 60% HC

Key: Low Cost ⟷ High Cost, Not Simulated, Unsuitable for HC

Complete Solutions	CRE21 (Urban) 2011-2030	SMR8 (Long Rural) 2011-2040	HPK11 (Urban) 2011-2040	KLO14 (Short Rural) 2011-2040
(1) **Off-Load Tap Changers** + Augmentation + VicSet	$160,899	*Network violates voltage limits*		
(2) **Zone Sub OLTC** + Off-Load Tap Changers + Augmentation + VicSet	$160,899	*Network violates voltage limits*		
(3) **Tailored Volt-Watt and Volt-var Settings** + Off-Load Tap Changers + Augmentation	$322,194	$737,490	$780,243	$3,725,982
(4) **LV OLTC** + Off-Load Tap Changers + Augmentation + VicSet	$2,717,533	$64,178,251	$6,793,143	$107,239,472
(5) **Off-The-Shelf Batteries** + Off-Load Tap Changers + Augmentation + VicSet	$161,489	*Network violates voltage limits*		
(6) **Network Smart Batteries** + Off-Load Tap Changers + Augmentation + VicSet	$59,250	$1,002,192	$45,738	$3,807,738
(7) **Dynamic Voltage at Zone Sub OLTC** + Off-Load Tap Changers + Augmentation + VicSet	$475,554	*Not simulated on this feeder*		

For urban feeders, complete solution (6) Network Smart Batteries, is the cheapest by a considerable margin. These low costs are due to minimal augmentation costs combined with very little curtailment (as voltages are kept well within limits). The only significant cost is associated with off-load tap changes which is applicable to all solutions.

The adjustment of off-load taps in LV transformers (1) and the zone substation OLTC's voltage target (2), combined with augmentation and VicSet inverter settings, can only achieve 60% hosting capacity in CRE21. Although very cheap, they are not suitable for rural feeders, whilst the other urban feeder (HPK11) could achieve only 40% hosting capacity. This affirms the current practice of DNSPs as they are cost-effective solutions in the short term for urban HV feeders. However, other solutions need to be investigated, particularly for rural feeders.

For rural feeders, complete solution (3) Tailored Volt-Watt and Volt-var settings is the cheapest complete solution, requiring reduced asset augmentation costs compared with (6) despite higher PV curtailment. It is worth mentioning that complete solution (3) does not require off-load tap changers to work (although can result in higher curtailment due to higher voltages). For example, in SMR8 with hundreds of LV transformers, such tailored settings would reduce the cost from $737,490 to $209,490, a significant cost saving. In general, rural feeders are more expensive compared with urban feeders given the number of distribution transformers that still need replacing due to congestion.

Complete solution (7) Dynamic Voltage Target at Zone Substation with combined with VicSet and augmentation was only tested with the dense urban feeder CRE21, and despite its relatively high costs, shows great promise for working on all types of feeder. Whilst it is more expensive than tailored inverter settings, it is a good cost-effective alternative where tougher inverter standards cannot be introduced, or network smart batteries are not feasible.

Complete solution (5) off-the-shelf batteries combined with VicSet inverter settings and augmentation for congested assets only worked with dense urban feeder CRE21. For the other feeders at 60% PV, the batteries get full late morning, resulting in reverse power flows and the corresponding problems due to PV generation. Complete solution (4) LV OLTC-fitted transformers with augmentation and VicSet inverter standards is very expensive due to the higher number of LV transformers per customer in rural feeders. This means many more OLTCs need to be installed per customer compared with urban feeders.

Overall, the cost of achieving 60% PV hosting capacity in urban feeders is lower than the cost for rural feeders. This is because of the greater number of assets that need to be replaced in rural feeders (more LV transformers per customer) due to congestion. KLO14 was by far the most expensive feeder due to also requiring some HV reconductoring.

4.2.2 Complete Solution Summary to Achieve 100% Residential PV Hosting Capacity

A summary is seen in Table 4-5 for a comparison of complete solution costs to achieve 100% hosting capacity across four HV feeders.

Table 4-5 Summary of Techno-Economic Performance of Complete Solutions for 100% HC

Key: Low Cost ⟵⟶ High Cost , Not Simulated , Unsuitable for HC

Complete Solutions	CRE21 (Urban) 2011-2040	SMR8 (Long Rural) *2011-2060*	HPK11 (Urban) *2011-2060*	KLO14 (Short Rural) *2011-2060*
(1) **Off-Load Tap Changers** + Augmentation + VicSet	*Network violates voltage limits*			
(2) **Zone Sub OLTC** + Off-Load Tap Changers + Augmentation + VicSet	*Network violates voltage limits*			
(3) **Tailored Volt-Watt and Volt-var Settings** + Off-Load Tap Changers + Augmentation	$798,542	$1,061,895	$1,851,441	$3,980,223
(4) **LV OLTC** + Off-Load Tap Changers + Augmentation + VicSet	$4,845,184	$72,139,695	$9,171,567	$121,205,528
(5) **Off-The-Shelf Batteries** + Off-Load Tap Changers + Augmentation + VicSet	*Network violates voltage limits*			
(6) **Network Smart Batteries** + Off-Load Tap Changers + Augmentation + VicSet	$59,250	$1,014,580	$91,984	$3,810,097
(7) **Dynamic Voltage at Zone Sub OLTC** + Off-Load Tap Changers + Augmentation + VicSet	$969,099	*Not simulated on this feeder*		

For both urban and rural feeders, complete solution (6) Network Smart Batteries is the cheapest complete solution to achieve 100% hosting capacity across all four feeders. For urban feeders, the voltages are kept within limits which means that the inverters with VicSet do not need to curtail much active power. Furthermore, there is little to no augmentation costs, leaving the only cost due to off-load tap changes of the LV transformers. This makes (6) an extremely cost-effective solution in urban feeders. In rural feeders, it can be seen that whilst (6) is still the cheapest, it is much closer to complete solution (3) Tailored Volt-Watt and Volt-var settings (which was the cheapest solution for rural feeders at 60%).

Complete solution (3) can still achieve 100% without the off-load tap changes in LV transformers, and if that cost reduction is accounted for relative to (6) (which does need off-load tap adjustment), then (3) is significantly cheaper by nearly half a million dollars. This is because of the hundreds of LV transformers that need to be adjusted in rural feeders which leads to costs relating to LV transformers adds up quicky (as is seen in the (4) LV OLTC costs replacing transformers). This means that if (3) were to be implemented without the current practice of adjust off-load tap settings, in the short-term, it is a very cost-effective solution and is the cheapest for rural feeders at 100% hosting capacity. Nonetheless, this is at the expense of higher curtailment.

Complete solution (7) Dynamic Voltage at Zone Sub OLTC is the third most cost-effective solution to achieve 100% hosting capacity, with the cost of the zone substation modification responsible for most of the increase in cost relative to (3). However, like (3), this solution can also work effectively without off-load tap changes in the LV transformers, which reduces the cost by approximately $50,000 for CRE21. Whilst this makes it cheaper, the next complete solution (3) also can operate effectively without off-load tap changing transformers, making (3) still significantly cheaper in CRE21. However, where (6) and (3) is not an option, (7) is still cost-effective when compared with (4) and the other solutions that cannot achieve 100% hosting capacity.

It can be seen that the current approaches of increasing hosting capacity with (1) and (2) using mostly off-load tap changers (or with the addition of the zone substation fixed voltage target adjustment), is not suitable for 100% hosting capacity on any type of feeder. Furthermore, (5) off-the-shelf batteries do nothing to help achieve 100% hosting capacities in all feeders and require network-friendly settings such as (6) if they are to help with volage issues.

As before for 60% hosting capacity, (4) LV OLTC-fitted transformers are expensive in urban feeders but is extremely expensive in rural feeders due to the much greater number of LV transformers that would need replacement. This means that (4) is only viable in urban feeders, where flexibility of voltages is required and the dynamic voltage target at the zone substation is not an option. In rural feeders, (4) it is prohibitively expensive but is technically still effective.

Overall, it can be observed that the cost of achieving 100% PV hosting capacities in urban feeders is lower than the cost for rural feeders (as was the case for 60%). This is due to the greater number of assets that need to be replaced per customer in rural feeders (more LV transformers per customer that will otherwise overload). KLO14 was by far the most expensive feeder due also requiring some HV reconductoring, combined with the high number of LV transformers that required augmentation, but most of this cost occurred for 60% hosting capacity and the cost increase for 100% is not as significant.

4.2.3 Other Considerations

The pseudo LV feeders used in this study were modelled following modern design principles based on the number of customers connected to the distribution transformer. This means that, from a thermal perspective, since the LV conductors are large enough to deal with average peak loads of 3 to 5kW (after diversity maximum demands commonly used by DNSPs for single-phase customers), they can also cope with the reverse power flows from PV systems. Therefore, in the study, the augmentation of LV conductors was not needed. In practice, older LV feeders will need to be augmented to manage higher reverse power flows. However, since houses with PV systems are likely to have high-load devices such as air-conditioning units, it can be argued that older LV feeders may be upgraded due to the new loads before it is needed for the PV systems. From a voltage perspective, despite larger cross sections of newer LV conductors mean a lower impedance, improvements on voltage can occur but were found to be limited in the context of increasing PV hosting capacity. Thus, the findings of the study might still be applicable for older LV feeders.

4.3 Summary of Total Complete Solution Cost per MWh of PV Generation

While the costs presented in the previous section provide valuable insights into the future potential costs DNSPs need to face if they want to increase hosting capacity, the cost per MWh generated ($/MWh) enables comparison between complete solutions in the context of generation. This section presents a summary of complete solution $/MWh generated from residential PV systems, to achieve both 60% PV (short-to-medium term) and 100% PV (long term) hosting capacity.

The costs per total MWh of generation for the corresponding period of interest (e.g., 2011-2042 for CRE21) are presented in section 4.3.1 and 4.3.2. Annual energy for each PV penetration was extracted from the simulation data with linear interpolation used to estimate energy between each year of simulation. This gives a PV energy generated figure for the period of assessment per feeder, per solution, which is ultimately divided by each solution cost. Further information related to the energy production for each feeder can be found in the appendix section 7.1 for 60% hosting capacity and section 7.2 for 100% hosting capacity.

4.3.1 Total $/MWh for 60% hosting Capacity

A summary is seen in Table 4-6 for a comparison of complete solution costs per MWh over the period of assessment for each feeder to achieve 60% hosting capacity across four HV feeders.

Table 4-6 Cost per MWh Over Period of Assessment for Complete Solutions at 60% HC

Key: Low Cost ⟷ High Cost, Not Simulated, Unsuitable for HC

Complete Solutions	CRE21 (Urban) *2011-2030*	SMR8 (Long Rural) *2011-2040*	HPK11 (Urban) *2011-2040*	KLO14 (Short Rural) *2011-2040*
(1) **Off-Load Tap Changers** + Augmentation + VicSet	1.13 $/MWh	*Network violates customer voltage limits*		
(2) **Zone Sub OLTC** + Off-Load Tap Changers + Augmentation + VicSet	1.13 $/MWh	*Network violates customer voltage limits*		
(3) **Tailored Volt-Watt and Volt-var Settings** + Off-Load Tap Changers + Augmentation	2.27 $/MWh	4.42 $/MWh	2.20 $/MWh	16.78 $/MWh
(4) **LV OLTC** + Off-Load Tap Changers + Augmentation + VicSet	19.05 $/MWh	377.58 $/MWh	19.01 $/MWh	479.56 $/MWh
(5) **Off-The-Shelf Batteries** + Off-Load Tap Changers + Augmentation + VicSet	1.13 $/MWh	*Network violates customer voltage limits*		
(6) **Network Smart Batteries** + Off-Load Tap Changers + Augmentation + VicSet	0.42 $/MWh	5.90 $/MWh	0.13 $/MWh	17.03 $/MWh
(7) **Dynamic Voltage at Zone Sub OLTC** + Off-Load Tap Changers + Augmentation + VicSet	3.33 $/MWh	*Not simulated on this feeder*		

The $/MWh does not fundamentally change the order of least-cost solutions for 60% hosting capacity. For urban feeders at 60% hosting capacity, the cheapest solution in terms of $/MWh of PV generation is still (6) Network Smart Batteries. This is because of the very low augmentation costs due to little asset congestion, as well as excellent performance in managing voltages which keep curtailment to a minimum. The main costs are due to off-load tap changes of LV transformers.

For rural feeders at 60%, the cheapest complete solution in terms of $/MWh is still (3) Tailored Volt-Watt and Volt-var settings. (3) can work without off-load tap changes in the LV transformers, which would further lower the $/MWh of PV generation.

It can be seen that when rounded to the nearest cent, (1), (2) and (5) all have an equivalent $/MWh of PV generated in CRE21. This is due to largely similar augmentation costs, the same off-load tap changing costs and very similar PV generation.

Complete solution (7) is still a cost-effective solution where (3) and (6) are not possible. The higher cost is mainly due to the zone substation modification, and not to do with PV curtailment. Finally, it can be seen that urban feeders make more sense in a $/MWh for (4) LV OLTC transformers. This is because of the much lower number of devices required to be installed.

Whilst PV generation does differ from solution to solution, it remains reasonably similar across solutions. However, it does differ considerably between feeders due to the number of customers, as shown in the Appendix (section 7.1). In general, the $/MWh is cheaper for urban feeders thanks to lower augmentation costs. For HPK11(urban), this further helped by having the greatest number of customers (and therefore the greatest amount of energy). CRE21 (the other urban feeder) has the fewest number of customers (as shown in section 4.2.1). This is why, when comparing any solution for CRE21 and HPK11 in $/MWh, the greater number of customers makes any investment in HPK11 more effective in terms of MWh.

Rural feeders on the other hand are more expensive compared with urban feeders in $/MWh for 60% hosting capacity. This is because of the much greater cost of augmentation in rural feeders, reflected in the higher total cost as well. However, when comparing KLO14 and SRM8, despite the higher number of customers in KLO14, it can be argued that the number of customers per feeder is not a clear indication on the $/MWh and that the specific characteristics of the feeders should be considered.

4.3.2 Total $/MWh for 100% hosting Capacity

A summary is seen in Table 4-7 with a comparison of complete solution in $/MWh over the period of assessment for each feeder to achieve 100% hosting capacity across four HV feeders.

As was for 60%, using $/MWh does not change the cost order of solutions. The findings in section 4.2.2 are still applicable.

Compared with 60% hosting capacity, it can be observed that the $/MWh for all solutions has decreased for 100% hosting capacity. This is primarily because the amount of PV energy generated has increased in this period, both overall (more years) and on a year-to-year basis (more PV systems). Whilst costs have increased to meet a 100% PV hosting capacity, the cost increase does not outweigh the benefits in additional PV generation between these years, leading to a lower $/MWh. For urban feeders, the relative $/MWh decrease between 60% to 100% is worse than it is for rural feeders. This is because rural feeders reach their asset capacity much sooner and require augmentation sooner, meaning rural feeder augmentation costs between 60%-100% is much lower than 0%-60% (versus urban feeders).

In general, as was reflected with the total cost of hosting capacity (section 4.2.2), rural feeders are more expensive per MWh of PV generation than urban feeders (CRE21 20 fewer years of energy and the least number of customers). This is mostly because of the extra cost of augmentation in rural feeders relative to urban feeders, in particular replacing overloaded LV transformers (for which they are more LV transformers per customer in rural feeders).

As was the case for 60%, HPK11 with a higher number of customers leads to it being cheaper in $/MWh compared with CRE21. On the other hand, KLO14 despite having more customers than SMR8, is more expensive in $/MWh. This highlights that the number of customers per feeder is not a clear indication on the $/MWh and that the specific characteristics of the feeders should be considered.

Table 4-7 Cost per MWh Over Period of Assessment for Complete Solutions at 100% HC

Key: Low Cost ⟷ High Cost , Not Simulated , Unsuitable for HC

Complete Solutions	CRE21 (Urban) *2011-2040*	SMR8 (Long Rural) *2011-2060*	HPK11 (Urban) *2011-2060*	KLO14 (Short Rural) *2011-2060*
(1) **Off-Load Tap Changers** + Augmentation + VicSet	*Network violates customer voltage limits*			
(2) **Zone Sub OLTC** + Off-Load Tap Changers + Augmentation + VicSet	*Network violates customer voltage limits*			
(3) **Tailored Volt-Watt and Volt-var Settings** + Off-Load Tap Changers + Augmentation	2.15 $/MWh	2.13 $/MWh	1.97 $/MWh	6.06 $/MWh
(4) **LV OLTC** + Off-Load Tap Changers + Augmentation + VicSet	12.93 $/MWh	141.67 $/MWh	9.61 $/MWh	182.23 $/MWh
(5) **Off-The-Shelf Batteries** + Off-Load Tap Changers + Augmentation + VicSet	*Network violates customer voltage limits*			
(6) **Network Smart Batteries** + Off-Load Tap Changers + Augmentation + VicSet	0.16 $/MWh	1.99 $/MWh	0.10 $/MWh	5.73 $/MWh
(7) **Dynamic Voltage at Zone Sub OLTC** + Off-Load Tap Changers + Augmentation + VicSet	2.59 $/MWh	*Not simulated on this feeder*		

5 Recommendations

The modelling and analysis tasks carried out within this project have allowed the detailed quantification of the effects that different penetrations of residential PV can have on the studied urban and rural HV-LV feeders when considering a range of potential solutions. This, in turn, has made it possible to estimate not only the increase in PV hosting capacity that each solution can achieve per HV-LV feeder type but also the associated cost.

To help Distribution Network Service Providers (DNSPs) in Australia, and internationally, take adequate planning actions that facilitate the adoption of residential PV in a cost-effective and practical manner, this chapter presents a series of recommendations based on the findings from Tasks 3 to 5 (reported in Deliverables 3 to 5 [1-3]). These planning recommendations are divided into two planning horizons: short-to-medium term (10-20 years from 2021) and long term (20-40 years from 2021), which are expected to reach around 40-60% of PV penetration and beyond 60%, respectively[6].

Furthermore, to provide guidance for DNSPs to carry out advanced PV hosting capacity calculations that will enable the assessment of connection requests and/or potential solutions, this chapter presents both model-based and smart meter-driven (data analytics) recommendations derived from the techniques developed in Tasks 1 to 4 (reported in Deliverables 1 to 4 [1, 2, 5, 6]).

5.1 Planning Recommendations for PV-Rich Distribution Networks

The following planning recommendations consider the *complete* solutions investigated in this project (listed below and discussed in sections 3.4.3 and 3.4.4), their cost-effectiveness with respect to the short-to-medium and long terms (discussed in chapter 4 and Task 5 [3]), and the practicalities surrounding their potential adoption by DNSPs.

(1) Off-Load Tap Changers + Augmentation + VicSet
(2) Zone Sub OLTC + Off-Load Tap Changers + Augmentation + VicSet
(3) Tailored Volt-Watt and Volt-var Settings + Off-Load Tap Changers + Augmentation
(4) LV OLTC + Augmentation + Off-Load Tap Changers + VicSet
(5) Off-The-Shelf Batteries + Off-Load Tap Changers + Augmentation + VicSet
(6) Network Smart Batteries + Off-Load Tap Changers + Augmentation + VicSet
(7) Dynamic Voltage at Zone Sub OLTC + Off-Load Tap Changers + Augmentation + VicSet

It is worth highlighting that there is a myriad of innovative solutions that involve the orchestration of PV systems (e.g., using dynamic settings or export limits) to increase hosting capacity. In fact, many of these solutions have been or are being trialled in Australia [18-20]. However, the cost and technical aspects associated with them are not clear enough (or known) to be compared with the above complete solutions and, hence, have been excluded from this project. In the next few years, with a better understanding of the cost-effectiveness of solutions that involve PV orchestration, similar comparisons can be carried out to update these planning recommendations.

These planning recommendations are made from the point of view of DNSPs to increase PV hosting capacity, i.e., focusing on the necessary DNSP-related investments and the effects on customers but excluding potential externalities (e.g., system-level effects on energy prices due to PV).

5.1.1 In the Short-to-Medium Term (40-60% PV Penetration)

This considers the short term as 2030 and medium term as 2040. Although Deliverable 5 [3] showed that the adoption of advanced battery controllers (such as the Network Smart controller) combined with augmentation was one of the most cost-effective complete solutions, its usefulness depends on all PV

[6] These expected PV penetrations are based on the forecasts produced by AusNet for the analysed HV feeders [1, 2] in combination with the current PV penetration in Australia (more than 1 in 5 houses in Australia have a PV installation, i.e., approximately 20% PV penetration) [4]. These expected PV penetrations are, however, indicative as, ultimately, they depend on the type of HV feeder and the corresponding socio-economic characteristics. Some HV feeders might achieve very high PV penetrations much sooner.

installations to have a battery. Since in this timeframe, residential battery uptake is unlikely to match the number of PV installations, battery-based solutions may not bring significant benefits.

Consequently, DNSPs need to focus their efforts on exploiting the capabilities of existing assets, from residential PV inverters (through standards/requirements) to on-load tap changers at zone substations (adapting tap positions to downstream network conditions).

1) *Continue Enabling Volt-Watt & Volt-var Settings*

- The Victorian PV inverter requirements (VicSet) established in 2019 should be emulated by DNSPs outside Victoria not yet doing something similar. Crucially, the amount of PV curtailment required by the VicSet is a small fraction of that required by the Australian standard, thereby also bringing benefits to customers.

By enabling both Volt-Watt and Volt-var functions, these requirements help any type of HV feeder (urban or rural) further mitigate voltage issues when compared with the current Australian standard (where only Volt-Watt is enabled). It was found that the VicSet curtails, in average across all customers within a HV feeder, approximately only 1% of the potential PV generation; which is a fraction of the curtailment resulting from using the Australian standard.

Despite the benefits from VicSet, given that the Volt-Watt settings allow voltages above 1.10pu (253V), voltage issues remain even at modest PV penetrations. Furthermore, as PV penetrations increase, congestion issues also occur, thus, needing augmentation to mainly replace distribution transformers and, where required, HV conductors.

While the VicSet do not entirely solve voltage issues, the number of customers affected by voltage issues and the magnitude of those voltages is much lower than with the Australian standard. Consequently, when combined with augmentation, this solution becomes a low-cost interim alternative for DNSPs. For most HV feeders[7], the only direct cost for DNSPs corresponds mainly to the augmentation of congested distribution transformers.

The study considered a homogenous approach to PV installations, i.e., all PV inverters were considered to have the VicSet in all penetrations. In practice, in the short term, there will be PV inverters with old settings and, therefore, the overall benefits are likely to be less. However, as time goes on, old installations also get updated/upgraded, eventually using the new VicSet and increasing the corresponding benefits.

2) *Continue Exploiting Existing Assets*

- DNSPs should adjust the off-load tap changer position of distribution transformer and/or the voltage target at zone substations to lower customer voltages and, hence, reduce voltage rise issues due to PV.

Voltage regulation has historically been done conservatively to compensate for voltage drops due to peak load. By reducing the amount of compensation through the adjustment of off-load tap changer position of distribution transformer and/or the voltage target at zone substations, voltage rise issues during times of PV generation can be reduced. In fact, these are actions already implemented -although to different extents- by DNSPs.

When these adjustments are done in combination with VicSet and augmentation, they can increase hosting capacity to 40-60% in urban HV feeders, i.e., fully mitigating voltage and thermal issues in the medium term. Despite the cost involved in the adjustments (on top of the cost due to augmentation mainly because of congested transformers), exploiting existing assets is the lowest-

[7] For the short rural HV feeder, the augmentation cost corresponding to HV conductors was more significant than that for distribution transformers. This could be related to the age/spare capacity of the existing HV conductors.

cost solution. This affirms that the current practices of DNSPs are adequate and on the right track. However, for rural feeders, these adjustments bring limited benefits and are only useful for low PV penetrations (up to 20%). Furthermore, these adjustments will also provide a much better starting point for more advanced techniques, such as stricter inverter settings of dynamic voltage targets at the zone substation. This makes off-load tap adjustment an excellent short-term measure that does not hinder further techniques to increase PV hosting capacity.

The LV feeders used in this study were modelled following modern design principles based on the number of customers connected to the distribution transformer. This means that, from a thermal perspective, since the LV conductors are large enough to deal with average peak loads of 3 to 5kW (after diversity maximum demands commonly used by DNSPs for single-phase customers), they can also cope with the reverse power flows from PV systems (as DNSPs typically limit exports to 5kW per phase). Therefore, in the study, the augmentation of LV conductors was not needed. In practice, older LV feeders will need to be augmented to manage higher reverse power flows. However, since houses with PV systems are likely to have high-load devices such as air-conditioning units, it can be argued that older LV feeders may be upgraded due to the new loads before it is needed for the PV systems. From a voltage perspective, despite larger cross sections of newer LV conductors mean a lower impedance, improvements on voltage can occur but were found to be limited in the context of increasing PV hosting capacity. Thus, the findings of the study might still be applicable for older LV feeders.

Finally, for HV feeders with rapid adoption of PV systems (e.g., beyond 60% PV penetration by 2040), the exploitation of existing assets will not be enough to manage voltage issues. In those cases, additional measures (such as the next recommendations) will be needed.

3) Adopt Stricter Volt-Watt & Volt-var Settings

- DNSPs should pursue the further improvement of the Victorian inverter settings (VicSet[8]) that are stricter when dealing with voltage rise. This can be done by adopting Volt-Watt settings that start curtailing at 1.09 p.u. (250.7V) and do not allow PV generation beyond 1.10 p.u. (253V), and Volt-var settings that absorb reactive power up to 1.09 p.u. (250.7V). Whilst, in average, curtailment does increase compared to VicSet, it is only marginal; hence, bringing benefits to both networks and customers.

DNSPs and other stakeholders should not be afraid of pursing stricter Volt-Watt and Volt-var inverter settings as no investment is required to manage voltage issues. These stricter settings lead to only a 1-2% increase in the average curtailment across all customers compared to the VicSet business-as-usual case.

By using stricter inverter requirements, with adjustments to off-load tap settings and augmentation (to deal mostly with congested transformers), PV hosting capacity can be increased regardless of feeder type (urban and rural). When all PV installations adopt the stricter settings, all voltage issues are eliminated. If off-load tap settings are not adjusted, the stricter inverter requirements will keep voltages within limits but at the expense of more curtailment. Asset congestion issues still exist but are slightly lower when compared with VicSet business as usual.

This solution will be less effective when considering a non-homogenous implementation of inverter requirements but will continuously improve as time passes and more PV systems use the updated requirements. A mismatch of inverter requirements will lead to greater curtailment placed on customers with the stricter requirements versus older ones. The earlier stricter settings are implemented, the more effective it will be.

[8] VicSet settings are defined as Volt-Watt settings that start curtailing at 1.10 p.u. (253V) and do not allow PV generation beyond 1.12 p.u. (259V), and Volt-var settings that inject reactive power from 0.90 p.u.(208v) to 0.95 p.u. (220V) and absorb reactive power from 1.04 p.u. (241V) up to 1.10 p.u. (253V). Priority is given to active power, so PV inverter reactive response is limited at peak generation periods. The reactive power settings also apply to stricter Volt-Watt and Volt-var settings except absorption stops at 1.09pu (250.7V).

Overall, this is a very cost-effective method to increase PV hosting capacity being one of the cheapest to achieve 60% PV in urban feeders and the cheapest for rural feeders. Being suitable for every type of feeder (urban and rural) makes it a very scalable solution. However, its practicality will depend on the ability of DNSPs to champion the stricter inverter requirements.

4) ***Implement Intelligent Voltage Control at Zone Substations***

- DNSPs should adopt intelligent approaches that exploit the existing flexibility provided by OLTCs at zone substations. By using intelligent voltage control that can estimate PV generation downstream (or its effects on customer voltages) and adjust the OLTC voltage target accordingly, voltage issues in LV feeders can be alleviated.

Voltage regulation at zone substations (e.g., 66kV/22kV) has historically been done considering a conservative fixed voltage target at the secondary side (e.g., 22kV) that compensates for voltage drops due to peak load. By dynamically changing the voltage target based on an estimated PV generation downstream (or its effects on customer voltages), voltage rise issues during times of PV generation can be reduced. In fact, these are actions already being tested -although to different extents- by DNSPs.

If stricter inverter settings are not possible for a DNSP that is already using VicSet, then the implementation of an intelligent voltage control at the zone substation is a great alternative to mitigate voltage issues. Significant voltage benefits are expected for all type of networks (rural and urban) as well as in cases where only the Australian inverter standard is used.

When combined with adjustment of off-load tap positions as well as augmentation of congested assets (mainly distribution transformers), it is a highly effective method to increase PV hosting capacity. Depending on the HV feeder, off-load tap settings might not need to be adjusted as the intelligent voltage control might be able to keep voltages within limits (but, potentially, at the expense of more tap actions). While it is a bit more expensive than stricter Volt-Watt & Volt-var inverter settings (even when accounting for the cost of PV curtailment), the use of intelligent voltage control is a practical solution for DNSPs as it can be implemented on their existing assets and with existing technology.

The suitability of this solution, however, depends on the design of the zone substation (taps available), the requirements from the sub-transmission network (which affects the operational tap availability), and the demand characteristics of the other HV feeders supplied by the same zone substation.

Finally, for HV feeders with rapid adoption of PV systems (e.g., beyond 60% PV penetration by 2040), the use of intelligent voltage control at zone substations combined with augmentation can also be an effective alternative.

5) ***Implement Network-Friendly Battery Connection Requirements***

- DNSPs should seize the opportunity and champion adequate battery connection requirements (or standards) for the long term. These requirements (like the investigated ‘Network Smart’) need to be enacted in the short to medium term so that, in the long term, most residential batteries can reduce grid exports due to PV generation, hence, mitigating voltage and congestion issues.

Whilst commercially available residential batteries today can significantly reduce electricity bills for customers with PV systems, their control strategy does not reduce grid exports. Batteries today can get full even before high PV generation times, resulting in grid exports and the corresponding network issues. A new requirement can mandate a more network-friendly approach that can also provide benefits to the customer (reducing electricity bills).

Network-friendly approaches (like the 'Network Smart') have been shown to be very effective in mitigating both voltage and asset congestion issues, with a much lower rate of augmentation especially for urban feeders (costing substantially less than other solutions). However, in the short to medium term, batteries are not yet in volumes that can help with these issues.

6) <u>Other Considerations</u>

Despite the flexibility provided by LV OLTC-fitted transformers (effectively enabling high PV hosting capacities for all types of HV feeders), it is much more expensive than the other investigated solutions. This is because old transformers cannot be retrofitted with OLTCs, thus needing a brand new one. Even if the cost of an OLTC-fitted transformer were equal to a normal transformer, many devices would need to be replaced to manage voltage issues. Augmentation will still be required due to congestion issues, but the corresponding cost is minor in comparison to that due to voltage issues.

Phase switching (to improve unbalance) might be a promising alternative [21] as it can help reducing voltage rise due to unbalance. However, the effectiveness of this method on a wide variety of feeders across PV penetrations is still yet to be assessed. Furthermore, congestion issues will remain, and augmentation will still be needed.

DNSP-operated batteries might also be a promising solution [22, 23]. Depending on their location and size, they can reduce or eliminate reverse power flows, mitigating voltage and congestion problems. At distribution transformers, it means they can deal with reverse power flows to the HV feeder but not necessarily manage voltages at the end of the LV feeder.

5.1.2 In the Long Term (Beyond 60% PV Penetration)

This considers the long term as up to 2060 where most feeders could potentially reach very high PV penetrations (theoretically, up to 100%). However, the long-term view of this means there are significant technological uncertainties between 2021 and 2060, such as increased uptake of EVs, new forms of distributed energy resources (DER), new forms of DER orchestration, and potential new forms of cost-effective bulk energy generation (e.g., nuclear fusion).

Considering the solutions investigated in this project, in the long term, DNSPs can benefit from exploiting the flexibility of PV inverters (using stricter settings), batteries (using network-friendly requirements) and zone substations (using intelligent voltage control) in combination with augmentation to achieve up to 100% PV hosting capacity in a cost-effective manner, regardless of the type of HV feeder.

1) <u>Adopt Stricter Volt-Watt & Volt-var Settings</u>

- DNSPs should pursue stricter Volt-Watt and Volt-var settings as they can manage voltage problems due to reverse power flows for all feeder types and PV penetrations. Augmentation should be used in combination to solve asset congestion issues which, at high PV penetrations, involves not only distribution transformers but can also involve HV conductors.

If stricter settings are adopted in the short-to-medium term, their benefits in eliminating voltage problems will continue to be seen at very high PV penetrations (long term). Adopting these settings at early stage is preferable to ensure that most PV systems tackle voltage issues effectively. Nevertheless, the adoption of strict settings at any point in time will still help (but may not completely solve voltage problems). The use of stricter Volt-Watt & Volt-var settings is especially effective because as the number of PV systems increase with the new settings, the greater the number of devices that can manage the voltage issues.

When combined with off-load tap adjustment and network augmentation, this solution can achieve 100% PV hosting capacity on all types of feeders, whilst being one of the cheapest solutions investigated.

2) Implement Intelligent Voltage Control at Zone Substations

- DNSPs should adopt intelligent voltage control at zone substations that can estimate the effect of PV generation downstream and adjust the OLTC voltage target accordingly, thus alleviating voltage issues in LV feeders. Augmentation should be used in combination to solve asset congestion issues.

If stricter inverter settings are not possible for a DNSP that is already using VicSet and has adjusted off-load tap positions on LV transformers, then this is a great alternative that has the potential to achieve high PV penetrations; at the very least for urban HV feeders. Asset congestion will still exist, so augmentation is required but is similar to that when using stricter settings. Although the cost of the required zone substation modifications makes it more expensive, it is one of the cheapest solutions in the long term.

Finally, this solution can also help manage voltage drops that might occur due to EVs later in the day. A traditional solution such as the adjustment of off-load taps is inflexible and can only manage either voltage rise or drop issues independently. An intelligently controlled zone substation can manage both conditions and help alleviate voltage problems.

3) Implement Network-Friendly Battery Connection Requirements

- DNSPs should exploit the flexibility of residential batteries by mandating network-friendly connection requirements. Network-friendly control strategies, such as the investigated 'Network Smart', can be cost-effective in achieving high to full PV penetrations on all HV feeder types, mitigating both voltage and congestion issues. If actions are taken in the short-medium term to ensure that, in the long term, enough batteries have the updated requirements, then it will be highly effective. In urban feeders it can considerably reduce, or eliminate, augmentation costs, making it a much cheaper alternative while achieving high PV penetrations.

As more residential customers buy and install batteries alongside their PV systems to reduce their electricity bills, there is an opportunity for DNSPs to mandate network-friendly battery control strategies (as PV requirements/standards are already mandated). Such strategies, working alongside VicSet and adjustment of off-load tap settings of LV transformers, can significantly reduce the magnitude of reverse power flows due to PV generation which in turn keeps voltages well within limits and minimises the need for augmentation. Crucially, network-friendly control strategies, when adequately designed, can still benefit customers, reducing their electricity bills.

When compared with off-the-shelf batteries which get full by late morning/early afternoon, thus allowing PV exports (and the corresponding network issues), the investigated Network Smart control strategy tackles this issue by adjusting charging proportionally to PV generation, making sure that PV exports are always a fraction of normal PV exports. Furthermore, it ensures adequate battery storage capacity in the morning by discharging the battery overnight (whilst covering the household demand). In this way, network issues due to reverse power flows are mitigated or avoided (minimising curtailment) and customers continue benefiting from reduced electricity bills.

For all types of HV feeders, network-friendly batteries can keep voltages within limits. In rural networks, augmentation is still needed but in a similar way as when using stricter settings. In urban HV feeders, however, network-friendly batteries can almost eliminate the need for augmentation, making the solution incredibly cheap for the DNSP to increase PV hosting capacity.

Finally, the effectiveness of this solution was on the assumption every customer has a battery. Scenarios with a mix of PV-no battery and PV-battery installations were not tested. In practice, such a mix will exist and, therefore, although network-friendly batteries will reduce the PV exports of the corresponding customers, the overall benefits will be less. Furthermore, although the analysis was done with VicSet, Network Smart batteries will likely be as effective with the current Australian standard as well as the strict Volt-Watt & Volt-var inverter settings.

4) Other Considerations

The flexibility provided by LV OLTC-fitted transformers can be used to effectively manage voltage rise issues across all PV penetrations and feeders. Furthermore, this flexibility could also be applied to deal with voltage drop issues due to the future demand from electric vehicles (EVs) in the long term (e.g., at night) whilst also managing voltage rise issues due to high penetrations of PV systems (e.g., midday). However, LV OLTCs are inherently an expensive solution due to the large number of devices that need to be installed (one per LV feeder that requires voltage management) and the higher cost of an OLTC-fitted transformer versus a normal transformer (since OLTCs cannot be retrofitted). Another solution that can both increase PV hosting capacity and help with voltage drops due to the future EV uptake is the intelligent voltage control of the zone substation. However, in either case, it should be noted that any adjustment of off-load taps made in the short term could require re-adjustment for voltage drops at night.

5.2 Recommendation for Advanced PV Hosting Capacity Calculations

Based on the approaches and techniques adopted in this project, explained and demonstrated in Tasks 1 to 4 (reported in Deliverables 1 to 4 [1, 2, 5, 6]), this section presents recommendations to DNSPs and others who wish to carry out similar advanced PV hosting capacity calculations to assess connection requests and/or potential solutions. The recommendations are presented for each of the two approaches used in this project:

- Model-Based Approach (Tasks 1, 3 and 4 [1, 2, 5]); and,
- Smart Meter-Driven Approach (Task 2 [6]).

A model-based approach uses an explicit electrical model of the corresponding distribution network (including its topology, elements, parameters, etc.) that in turn allows to run power flow simulations (using specialised software packages) for different demand/generation scenarios. This is a well-known approach used routinely by DNSPs in Australia and around the world to design, plan and improve their networks. However, it is typically limited to HV feeders and to critical demand/generation scenarios.

On the other hand, a smart meter-driven approach exploits historical smart meter data to find correlations that can be used to estimate, in this case, the PV hosting capacity of a given HV feeder or LV network. This type of approach has the inherent advantage of not requiring explicit electrical models and, while promising, is still new to most DNSPs, even to those with smart meter data.

5.2.1 Model-Based Recommendations

The advantage of the model-based approach is that it is adaptable, network elements and participants can be added, removed or changed and control techniques can be implemented and tested through simulations. This makes the model-based approach highly effective if used to investigate the effectiveness of various solutions to various problems such as those related to the increase of PV hosting capacity.

However, for DNSPs to achieve accurate and meaningful results, the corresponding modelling needs to be as realistic as possible, which means that it needs to include –to the extent that is possible– LV feeders, consider time-series simulations and account for uncertainties.

1) Explicitly Model LV Feeders

- DNSPs should consider the use of integrated HV-LV feeder models, i.e., explicitly modelling LV feeders (or pseudo LV feeders) down to customer connection points. This is necessary to fully capture the response of voltage-related control actions from residential PV systems as well as network elements and, hence, correctly quantify voltage rise issues and benefits from potential solutions.

Because customer voltage rise issues occur mostly at the ends of LV feeders, carrying out studies that only model the HV feeder and aggregate customers and PV systems at the distribution transformer might result in over or underestimations as the voltages at the customer connection point are not explicitly considered [24]. Furthermore, congestion can occur within LV feeders beyond just distribution transformers. This makes proper LV feeder modelling essential in advanced planning studies to increase residential PV hosting capacity.

In practice, despite the efforts of many DNSPs to map LV feeders with Geographical Information Systems (GIS), the corresponding electrical models are still non-existent due to data limitations (e.g., customer phase group connectivity, service cable impedances, etc.). An interim solution is to construct pseudo LV feeder models as done in this project by using LV design principles [11-15]. Further information can be found in Deliverable 2 [6] on number of feeders, length of feeders and number of customers per feeder and per phase. Once the unbalanced (three-phase) pseudo LV feeders are produced they can be incorporated to the corresponding HV feeder model resulting in an integrated HV-LV feeder model ready for power flow simulations that adequately capture the voltages at the customer connection points.

2) Perform Time-Series Simulations

- Time-series simulations should be conducted by DNSPs to adequately capture time-dependent aspects of demand, PV irradiance and controllable elements in the network including those on the customer side. This enables a more accurate assessment of voltages and power flows in time and the corresponding effects on PV curtailment and asset congestion.

While the snapshot assessment of worst-case scenarios, such as minimum demand and maximum PV generation, can provide insights on hosting capacity, it does not capture the true performance of PV systems, in particular the amount of PV curtailment triggered by different solutions. Consequently, to better understand the customer benefits of any potential solution, the time component needs to be incorporated in the analysis whenever possible.

Time-series simulations require time-series data (i.e., demand profiles, PV irradiance profiles) with adequate granularity. A granularity of at least 30-minute resolution was found to be an adequate trade-off between capturing time-dependent aspects, the corresponding computation time and the available historical data. In fact, this minimum resolution is aligned with what is typically available from historical smart meter data, SCADA measurements and meteorological data.

Given that demand and PV generation can vary significantly between seasons and, hence, the corresponding voltage effects, PV curtailment, etc., time-series data needs to cover –to some extent– the whole year. Considering at least 14 consecutive days in each season was found to be an adequate trade-off between capturing seasonality and the corresponding computation time. Based on supplementary analyses performed, it was found that two weeks (i.e., 14 days) analysis per season results in almost the same levels of energy curtailment (in %) when compared to a full year (i.e., 365 days) analysis.

3) Cater for Uncertainties

- DNSPs should account, to the extent that is possible, for uncertainties related to PV location, PV size, irradiance profiles and demand profiles.

While deterministic time-series analyses can provide adequate insights related to PV hosting capacity, they are limited to the very specific characteristics of the chosen PV locations, PV sizes, and profiles. This can result in over or underestimations since, in practice, the actual characteristics of a given PV penetration can differ significantly.

One alternative is to adopt realistic PV allocations by allowing uneven penetrations per LV networks and per LV feeder (as it can happen in practice). Furthermore, multiple PV installed capacities can also be used (e.g., based on Australian PV installation statistics). These considerations can, of course, be tuned accordingly to the local PV adoption characteristics.

Another more advanced alternative, although with added complexity and computation time, is the implementation of Monte Carlo simulations (multiple cases with different PV locations, etc. being analysed). Such approach can better account for these uncertainties and provide results that cover the potential spectrum of scenarios [25].

4) Other Considerations

Although HV feeders can have significantly different characteristics, the investigation of potential solutions can be done on a limited number to reduce the required modelling effort and time. The selection of HV feeders should consider several characteristics such as general type (e.g., rural, urban), length, number of customers, number of PV system installations, etc. that can be used to map the corresponding population and identify the most extreme cases (as explained in Deliverable 1 [5]). Using extreme cases demonstrates the viability of a potential solution and, therefore, that solution is likely to also work (and perform even better) in milder cases. In practice, however, the selection of HV feeders will be a trade-off between the quality and availability of data (network, smart meter, GIS, etc.), existing PV system installations (critical for validation of the analytical techniques), as well as the corresponding data extraction complexity.

Given the large number of simulations required when assessing PV hosting capacity, it is crucial that all simulations are consistent and coherent. When assessing different PV penetrations, continuity must be respected in the subsequent simulations. In other words, the locations and sizes of PV systems, batteries as well as demand profiles considered for a given PV penetration must remain consistent (the same) so the subsequent PV penetration will be ‘on top’ of the previous one. This includes any technical requirement/standard being implemented (such as inverter or battery settings). When comparing solutions for a given PV penetration, the conditions (PV location/size, demand, etc.) should also be consistent (the same).

5.2.2 Smart Meter-Driven Recommendations

The advantage of the smart meter-driven approach is that it does not require explicit electrical models, i.e., does not require power flow simulations, only historical smart meter data. This makes the smart meter-driven approach a very promising alternative that can save time and effort in the assessment of new connection requests.

As shown in Deliverable 2 [6], using hybrid smart meter data it was possible to demonstrate that a very strong linear correlation exists between the maximum customer voltage on a given day for a given LV network (distribution transformer) and the aggregated net active power demand of the corresponding customers (at the time of the maximum voltage). These two features can be used to estimate the solar PV hosting capacity in any given LV network using historical smart meter data and a simple yet practical machine learning algorithm to produce a regression model. No electrical models are required.

The supervised (i.e., gradient decent) univariate regression model, in effect, estimates (very quickly) the aggregated net active power demand (that can be negative due to PV systems) that can lead to voltages rise issues (i.e., above 1.1 p.u.). This value, in turn, can be used to calculate the additional PV capacity that can be hosted by the LV network. Prediction limits to cater for uncertainties can also be considered.

However, this approach is not suitable for planning studies that involve testing various network solutions that change the fundamentals of the feeder. This is because the smart-meter driven approach cannot predict actions for data it has not yet been accounted for in the regression model.

1) Run Trials on Actual Distribution Transformers

- DNSPs with smart meter data should run trials of the proposed smart-meter driven approach and compare the results with their existing PV hosting capacity assessments.

Despite the promising results shown in Deliverable 2 [6], further tests are needed to ensure the effectiveness of the proposed smart meter-driven approach. DNSPs can select a few distribution transformers that have already reached their PV hosting capacity (e.g., voltages are already high enough not to allow further installations), extract the corresponding historical smart meter data and apply the regression model to periods with lower PV penetrations (and, thus, check the accuracy of the PV hosting capacity estimation). These tests can also be compared with PV hosting capacity assessments already in use by the DNSP to compare their effectiveness, practicality and speed.

2) Use Data that Covers a Minimum PV Penetration Increase

- For DNSPs to successfully use the proposed smart meter-driven approach, the historical data must cover a period where a minimum increase of PV penetration occurs: 30% for distribution transformers in urban HV feeders and 20% for those in rural HV feeders.

The volume of smart meter data used to estimate the PV hosting capacity plays an important role. More data helps to capture the variance of a larger sample of network conditions (i.e., voltage vs active power), thus increasing the estimation accuracy.

It was found that very modest PV penetrations (that do not result in voltage rise) can result in hosting capacity over or underestimations. For distribution transformers in urban HV feeders, it was found that when PV installations appear in different places (randomly), at least a 30% increase in PV penetration is required to have more accurate hosting capacity estimations. For transformers in rural HV feeders, at least 20% is required.

The need for a minimum PV penetration increase to be covered by the historical smart meter data also means that DNSPs need to track PV installations and use that information to adequately select the most suitable data.

3) Other Considerations

Further analysis using SCADA data to represent the zone substation's OLTC actions was carried out. It was found that the resulting changes in voltages (due to tap changes) can slightly reduce the accuracy of the PV hosting capacity estimations. Furthermore, because the OLTC actions can create voltage spikes (and become outliers), the accuracy of the prediction limits also reduces.

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7 Appendix

7.1 Energy Information for 60% Hosting Capacity

A summary is seen in Table 7-1 showing the total number of residential customers per feeder alongside the residential PV energy generated per solution per feeder for 60% hosting capacity.

Table 7-1 PV Generation of Complete Solutions at 60% and Total Number of Customers

Complete Solutions	**CRE21 (Urban) *2011-2030***	**SMR8 (Long Rural) *2011-2040***	**HPK11 (Urban) *2011-2040***	**KLO14 (Short Rural) *2011-2040***
Total Number of Residential Customers per Feeder	3,374	3,608	5,274	4,691
(1) **Off-Load Tap Changers** + Augmentation + VicSet	142,673.3 MWh	*Network violates customer voltage limits*		
(2) **Zone Sub OLTC** + Off-Load Tap Changers + Augmentation + VicSet	142,675.7 MWh	*Network violates customer voltage limits*		
(3) **Tailored Volt-Watt and Volt-var Settings** + Off-Load Tap Changers + Augmentation	141,888.2 MWh	167,020.6 MWh	354,428 MWh	222,017.7 MWh
(4) **LV OLTC** +Off-Load Tap Changers + Augmentation + VicSet	142,661.5 MWh	169,974.7 MWh	357,296.6 MWh	223,622 MWh
(5) **Off-The-Shelf Batteries** + Off-Load Tap Changers + Augmentation + VicSet	142,659.7 MWh	*Network violates customer voltage issues*		
(6) **Network Smart Batteries** + Off-Load Tap Changers + Augmentation + VicSet	142,654.2 MWh	169,746.9 MWh	357,258.3 MWh	223,621.3 MWh
(7) **Dynamic Voltage at Zone Sub OLTC** + Off-Load Tap Changers + Augmentation + VicSet	142,646.7 MWh	*Not simulated on this feeder*	*Not simulated on this feeder*	*Not simulated on this feeder*

7.2 Energy Information for 100% Hosting Capacity

A summary is seen in Table 7-2 showing the total number of residential customers per feeder alongside the residential PV energy generated per solution per feeder for 100% hosting capacity.

Table 7-2 PV Generation of Complete Solutions at 100% and Total Number of Customers

Complete Solutions	CRE21 (Urban) 2042	SMR8 (Long Rural) 2060	HPK11 (Urban) 2060	KLO14 (Short Rural) 2060
Total Number of Residential Customers per Feeder	3,374	3,608	5,274	4,691
(1) **Off-Load Tap Changers** + Augmentation + VicSet	*Network violates customer voltage limits*			
(2) **Zone Sub OLTC** + Off-Load Tap Changers + Augmentation + VicSet	*Network violates customer voltage limits*			
(3) **Tailored Volt-Watt and Volt-var Settings** + Off-Load Tap Changers + Augmentation	371,570.8 MWh	499,266 MWh	941,738 MWh	657,035.4 MWh
(4) **LV OLTC** + Off-Load Tap Changers + Augmentation + VicSet	374,741.1 MWh	509,216.9 MWh	954,846.6 MWh	665,123 MWh
(5) **Off-The-Shelf Batteries** + Off-Load Tap Changers + Augmentation + VicSet	*Network violates customer voltage limits*			
(6) **Network Smart Batteries** + Off-Load Tap Changers + Augmentation + VicSet	374,713.8 MWh	508,910.5 MWh	954,712.2 MWh	665,106.3 MWh
(7) **Dynamic Voltage at Zone Sub OLTC** + Off-Load Tap Changers + Augmentation + VicSet	374,721.9 MWh	*Not simulated on this feeder*		