Title:

Advanced Planning of PV-Rich Distribution Networks – Deliverable 4: Non-Traditional Solutions

Synopsis: This document investigates the adoption of non-traditional solutions such as strict Volt-Watt and Volt-Var PV inverter settings, OLTC-fitted LV transformers, Battery Energy Storage (BES) systems with Off-the-Shelf (OTS) controllers, BES with smarter controllers, and dynamic voltage target at zone substation OLTC, in combination with traditional solutions aiming at increasing the solar PV hosting capacity (HC) of PV-rich Distribution Networks. Studies are performed on four fully modelled and significantly different HV feeders (i.e., urban and rural) 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 HC to 100%. OTS BES systems do not change the HC as they are unable to reduce peak PV exports (they become full early in the day). However, advanced BES controllers that do reduce exports (such as the investigated Network Smart controller), could help increase HC to 100% 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 HC.

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Executive Summary

This document corresponds to the *"Deliverable 4: Non-Traditional Solutions"* 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 led by the University of Melbourne in collaboration with AusNet Services. It focuses on the investigation of "non-traditional solutions" in combination with "traditional solutions" aiming at increasing the solar PV hosting capacity (HC) of Distribution Networks considering the new Victorian Volt-Watt and Volt-var settings which mandates that both power quality response modes are enabled.

This document first presents the non-traditional solutions investigated in this Task and details the methodologies adopted for the corresponding solutions. Chapter 3 presents the data and considerations used for the analyses and case studies performed in this Task. Chapters 4-7 present and discuss the results obtained from each case study. Finally, conclusions and next steps are presented in Chapter 8 and 9, respectively.

The key points summarising this report are listed below.

<u>Non-Traditional solutions</u>
The term "Non-Traditional Solutions", in this document, refers to solutions not commonly adopted (today) by DNSPs in Australia (and internationally) in order to alleviate technical issues related to voltage and asset congestion. Such non-traditional solutions are based on the combined use of 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 that leverage existing controllable elements such as off-load or on-load tap changers as well as replacing or upgrading conductors and/or transformers.

The non-traditional solutions investigated in this Task, with exception to the tailored Volt-Watt and Volt-var settings, are considered on top of the voltage regulation traditional solutions investigated in Task 3 "Traditional Solutions" [1], in particular, the use of existing off-load tap changers. This is to ensure that any investment associated with a non-traditional solution occurs only after the traditional alternatives have been exploited. As last resort, if the adoption of the non-traditional solutions cannot alleviate asset congestion issues, network augmentation is also considered.

The following five non-traditional solutions were considered in this Task. It is worth noting that the fifth solution has been added for completeness.

- <u>Tailored Volt-Watt and Volt-Var PV Inverter Settings</u>. This solution considers the adoption of tailored (stricter) Volt-Watt and Volt-Var PV inverter settings compared to the ones imposed by the Victorian DNSPs and investigated in Task 3 "Traditional Solutions" [1]. This will help understand the extent to which a tailored set of settings aiming at fully mitigating voltage rise issues can help further increase the HC as well as understand the corresponding effects on customers (i.e., solar PV curtailment). For this purpose, the adopted stricter set of PV inverter settings involve the full curtailment of PV generation when reaching the upper voltage limit (as detailed in section 2.1.1). To truly understand the corresponding effects and benefits when compared to the those imposed by the Victorian DNSPs, this solution will not consider any other traditional solution.
- <u>LV OLTC-fitted Transformers with Adaptive Control</u>. This solution considers the replacement of off-load tap changer-fitted LV transformers with OLTC-fitted LV transformers considering an adaptive control logic. The main idea of this approach is to leverage smart meter data to actively calculate a voltage target (at the busbar) that brings contrasting voltages issues (rise and drop) closer to a middle point, thus satisfying voltage limits. Crucially, this provides the significant benefit of easily adapting to network changes (i.e., additional PV system installations or loads) without the need of reconfiguring OLTC settings. This solution (installation of LV OLTC-fitted transformers) is adopted and combined with the traditional solutions (i.e., adjustment of off-load

tap changers and augmentation) and is only considered once the off-load capability of a LV transformers is fully utilised, i.e., available taps to reduce/increase are exhausted. Considering the congestion issues and given that the investigated solution does not manage any power flows, augmentation is considered for congested assets (i.e., conductors, transformers).

- Off-the-Shelf (OTS) Battery Energy Storage (BES) Systems. This solution considers the case where households with solar PV adopt residential "off-the-shelf" (OTS) BES systems and their corresponding effects on the solar PV HC. Such analysis allows to understand the extent to which the widespread adoption of this emerging commercially available technology can help reduce the household exports from excess solar PV generation, and, hence, reduce or alleviate network issues. It is important to highlight that this solution is investigated in combination with adjusted off-load tap changers as well as with network augmentation (for congested assets).
- Network Smart (NS) Battery Energy Storage (BES) Systems. This solution considers the adoption of commercially available residential-scale BES systems embedded with an advanced controller aiming at reducing high PV exports. In particular, the "Network Smart" (NS) controller proposed by The University of Melbourne is investigated. This controller adapts the BES charging power proportionally to the PV generation, while ensuring available capacity by discharging overnight. This analysis allows to understand the extent to which advanced BES controllers can provide benefits not only to their owners (lowering electricity bills) but also to the electricity infrastructure, reducing power exports from households with solar PV and, thus, mitigating network impacts. This solution is investigated in combination with adjusted off-load tap changers as well as network augmentation (for congested assets).
- Dynamic Voltage Target at Zone Substation OLTC. This solution is added for completeness, which also complements the current trials of 'Solar Ready Settings' by AusNet Services for in-line voltage regulators in rural networks. It considers a dynamic (and incremental) voltage reduction at the zone substation OLTC based on the volume of reverse power flow as a proxy of the voltage rise in downstream networks. Particularly, the volume of reverse flow is estimated using the net power flow through the zone substation. For simplicity, this solution will not consider other traditional solutions.

Data and Analysis Considerations

- Demand and Generation Profiles. A pool of 30,000 daily demand and 90 daily generation profiles (30-minutes resolution) per season are produced using anonymised smart meter data (covering different geographical areas) provided by AusNet Services. These profiles will be used to realistically model time-varying residential demand and generation.
- PV Penetration. PV penetration is defined in this Task as the percentage of residential customers (i.e., houses) that have a solar PV. Based on data provided by AusNet Services, residential customers of the four HV feeders started adopting solar PV around 2010. Hence, 2010 is the approximate year considered to have 0% of PV penetration.
- PV Forecasts. The year where each of the penetrations is expected to occur depends on data specific for each HV feeder considered in this Task. Solar PV data including installations from 2010 to 2017 and forecasts from 2018 to 2030 were provided by AusNet Services. The forecast was extended using linear regression up to the year were 100% of penetration is achieved.
- PV Panel Sizes. The size of the PV panels is based on Australian PV installation statistics, where the proportion of single-phase PV installations with 2.5, 3.5, 5.5, and 8kWp is 8, 24, 52 and 16%, respectively. A realistic PV uptake is adopted by allowing uneven penetrations per LV network and feeders as well as multiple PV installed capacities.
- PV Inverter Sizes. All single-phase solar PV installations less or equal than 5kWp are assumed to have inverters with a rated capacity matching the corresponding kWp (e.g., 3.5kVA for a 3.5kWp installation). For installations larger than 5kWp, inverters are assumed to have a rated

capacity of 5kVA. This assumption is adopted to model the 5kVA export limit (per phase) requirement imposed by AusNet Services.

- PV Inverter Settings. All PV inverters consider, as a default, the new Victorian Volt-Watt and Volt-var settings [2, 3] which mandates that both power quality response modes (each based on the standard AS/NZS 4777.2) are enabled[2][2][2][2][2][2].
- PV Inverter Power Priority. All PV inverters modelled in the analyses operate in an active power priority (i.e., Watt-priority) mode. Active power priority is the default mode in commercially available residential-scale inverters (if not otherwise specified). This means that the reactive capability of the corresponding PV inverter might be limited at peak generation periods.
- LV OLTC-fitted Transformers. All LV OLTC-fitted transformers consider a voltage regulation range of +/- 8% with 2% per tap, i.e., 9 tap positions in total.
- BES Systems. A widely popular residential-scale BES system, currently available in the market is considered in the analyses. The technical specifications correspond to a single-phase 5kW/13.5kWh system with 100% depth of discharge and 88% round-trip efficiency.
- Augmentation. Different types of HV and LV conductors as well as transformers typically used by many DNSPs in Australia are used for the network augmentation analyses.

Case Study Considerations

- HV Feeders. The four (4) HV Feeders modelled in Task 1, each with significantly different characteristics (i.e., urban, short rural, long rural etc.), are considered in this Task. 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 and, potentially, to other DNSP areas across Australia.
- Single-Day Analysis. For each feeder and solution, a single-day analysis is performed considering progressive solar PV penetration. This analysis provides a time-series demonstration of the network performance. This analysis represents the “worst-case” scenario of peak generation combined with low demand.
- Seasonal Analysis. For each feeder and solution, a seasonal analysis (multiple days per season) is performed considering progressive solar PV penetration. This analysis provides a more realistic representation of the network performance considering seasonality.
- Performance metrics. Voltage compliance, asset utilization and level of curtailment are used as performance metrics to quantify the technical impacts caused by different penetrations of solar PV as well as the effects and benefits (if any) of the investigated solutions.

Findings – Tailored Volt-Watt and Volt-Var PV Inverter Settings

- Highly effective in alleviating all voltage issues regardless the type of feeder (i.e., urban, rural).
- Regardless the PV penetration, the maximum voltage across all feeders is always up to 1.10pu. This is because the adopted (stricter) settings limit PV generation to 0% of their rated capacity when reaching 1.10 pu (in contrast to 20% used by the current Victorian settings).
- The curtailment of PV generation was found to increase by approximately 1% for each penetration when compared to the settings imposed by the Victorian DNSPs (BAU case, details shown in Task 3 – approximately 1% of curtailment). However, while the amount of curtailment is doubling, it can still be considered negligible given that it fully mitigates voltage issues. For example, with a 100% PV penetration, the total curtailment never exceeds 2% of the total solar PV generation, regardless the type of feeder.
- While a reduced utilisation level of all assets was observed when compared to the BAU case, almost the same performance is observed in terms of the number of congestion issues.
- The amount of reactive power being absorbed was found to be almost the same as with the BAU case leading to larger currents flowing through conductors and transformers. Most affected are the low-capacity LV transformers which become overloaded at relatively low penetration levels; much lower levels than without having the Volt-var function. This can be effectively solved by network augmentation which needs to be planned for.

- In the aggregate, the Volt-var function significantly increases the reactive power being imported at the head of the HV feeder. This could potentially create issues in maintaining the power factor at the transmission-distribution network interface within the allowed limits. Adequate planning of capacitor banks in the upstream network (i.e., sub-transmission) might be required to compensate for this increase.

Findings – LV OLTC-fitted transformers with Adaptive Control

The investigation of this solution which considers the combined use of LV OLTC-fitted transformers, adjusted off-load tap changers, and network augmentation, has the following observations:

- Highly effective in mitigating all voltage issues in both urban and rural feeders.
  a. Given the nature of the adaptive control, voltages are always well within the statutory limits. For instance, generally, maximum voltages do not exceed 1.09 p.u. (250V). The use of adjusted off-load tap changers only would lead to voltages close or above to 1.10 pu.
  b. For those LV transformers where off-load tap capability was not able to mitigate the voltage rise/drop issues, their replacement with an OLTC-fitted LV transformer with adaptive control proves to be highly effective in keeping all customer voltages within the statutory voltage limits, regardless the penetration and season.
  c. For long rural feeders with long SWER connections, while the adoption of LV OLTC-fitted transformers can keep voltages within the limits it should be noted that the magnitude of the maximum recorded voltages at high penetration levels (>60%) can be close to the statutory limit. This effect can be explained due to the fact that the level of voltage rise in SWER connected solar PV customers can be significantly higher than the corresponding voltage reduction of the tap step.
- Helps to increase the HC up to 100%.
- Leads to almost negligible curtailment when compared to the BAU case (shown in Task 3). This is the effect of significantly reducing voltage levels, hence, Volt-Watt is not triggered. The level of curtailment was similar to the one found when considering the adjustment of off-load tap changers alone (although with voltages closer to or above the 1.10 p.u.).
- A significant percentage of transformers had to be equipped with OLTCs. By 60% of penetration, at least 50% of the transformers will need to be equipped with OLTC.
  - For urban networks most capacities of the OLTCs correspond to relatively high rating transformers (>300kVA).
  - For rural networks the most capacities of the OLTCs correspond to relatively low rating transformers (<100kVA).
  - Regardless the type of feeder, penetration and season, the use of 30-min control cycles lead to an average daily number of tap changes of around 5. Although this number can increase with smaller control cycles, this relatively low number of tap changes can lead to a reduced wear and tear of the OLTC hence requiring less maintenance costs.

Findings – Off-the-Shelf BES Systems

The investigation of this solution, which considers the adoption of residential OTS BES systems for each household with solar PV, the adjustment of off-load tap changers as well as augmentation of assets has the following observation:

- Does not help increase the HC further to what it could be achieved with traditional solutions (off-load taps and augmentation) alone.
- While compared to the BAU case, HC can be increased by at least 20%, this is only achieved due to the adjustment of off-load tap changers (i.e., voltage) and the corresponding augmentations (i.e., congestion). The adoption of OTS BES offers limited to almost no benefits for either technical issue. This is due to the following limitations:
  - <u>OTS BES systems do not fully discharge overnight</u>. This is due to insufficient energy consumption of most customers. As a consequence, their ability to store surplus PV generation the following day is significantly reduced.

  - OTS BES systems reach full SOC very early. With a partially charged BES system, surplus PV generation that occurs early in the morning can lead to a full SOC before or during high PV generation, resulting in PV exports.
- Voltage levels during generation period were found to be almost the same as with the case of adjusting the off-load tap changers alone (Task 3). As such the adoption of OTS BES provides limited to no benefits on this aspect.
- Augmentation requirements were found to be almost the same as with those presented in Task 3. As such, the adoption of OTS BES provides limited to no benefits on this aspect.
- The curtailment of PV generation was found to be almost the same as with the case of adjusting the off-load tap changers alone (Task 3). This effect is primarily due to the adjustment of the off-load tap changers which reduces voltages hence the Volt-Watt function is not triggered. As such, the adoption of OTS BES has limited to no benefits on this effect.
- Although the OTS BES system do no bring significant benefits to the network, the results show they are an excellent investment for PV owners as it allows to significantly reduce grid energy imports by at least 80% and, as a consequence, reduce electricity bills.

Findings – Network Smart BES Systems

The investigation of this solution, which considers the adoption of residential BES systems with the Network Smart controller, the adjustment of off-load tap changers as well as augmentation of assets has the following observations:

- Helps increase HC to 100% regardless penetration and type of feeder.
- Compared to the results obtained when OTS BES systems are adopted, network performance in terms of voltage and asset utilization is significantly increased.
- Voltages significantly reduce during the peak PV generation period and are always kept below the maximum voltage statutory limit (<1.10p.u), regardless the penetration level and season. This is only achieved due to the Network Smart control logic that enables BES systems charge throughout the whole generation period, hence significantly reduce household exports.
- Highly effective in significantly reducing the utilization level of all assets and more importantly alleviate congestion issues for the majority of otherwise congested assets. It was found that the adoption of Network Smart BES systems considering all analyses can reduce augmentation requirements by at least 60% and, in some cases, by 100%.
- Curtailment of PV generation is almost negligible when adopting this solution. This effect is due to the ability to keep all customer voltages always below 1.10p.u, hence the Volt-Watt function does not trigger.
- From the households' perspective, the adoption of the Network Smart BES systems slightly affects customers' grid dependence (energy imports) when compared to the OTS BES systems. For example, the median yearly grid dependence of customers is 2-4% higher than that of the OTS BES systems. While the adoption of the Network Smart control might lead to slightly higher energy imports than with the OTS control, the aggregated value of the electricity bill increase can considerably lower than the capital investments required to provide the same network benefits with asset-intensive solutions, such as network augmentation.

Findings – Dynamic Voltage Target at Zone Substation OLTC

The investigation of this solution, which considers the adoption of a dynamic voltage target (particularly, a reduction in voltage target) at the zone substation OLTC, has the following observations:

- A dynamic voltage target is at the Zone Substation is shown to be effective in mitigating voltage violations in LV feeders.
- The main bottleneck in this case is the thermal capacity of LV distribution transformers, asset congestion occurred as early as 20% PV penetration. A main contributing factor is due to the extra PV generation as a result of the lower voltages across the network, and thus less curtailment from the Volt-Watt function in PV inverters.
- Thanks to the increased voltage headroom, total curtailment (due to the Volt-Watt function in inverters) is significantly reduced when compared with the BAU case.

Planning Recommendations Using Traditional and Non-Traditional Solutions

For completeness, the recommendations from the previous Task, Task 3 "Traditional Solutions", are presented first, followed by the recommendations drawn from Task 4 "Non-Traditional Solutions".

Business as Usual is 20% (as per Task 3)

- Without the implementation of traditional solutions, the HC of all HV feeders investigated is approximately 20% penetration of solar PV. Depending on the HV feeder, this HC is expected to have been reached between 2017 and 2019.
- The HC is primarily limited by voltage issues, which is experienced by all feeders.
- At the HC, a small number of transformers is expected to face congestion issues.
    - In particular, transformers with small capacities (<=50kVA).
    - More probable in rural feeders as larger number of small transformers exist.
- The analyses highlight that, for all HV feeders, enabling both Volt-Watt and Volt-var functions with the Victorian Volt-Watt and Volt-var settings set as default provides significant benefits to both DNSPs and customers. Voltage rise issues and curtailment are dramatically reduced compared to just having the Volt-Watt function enabled.
    - Regardless of the PV penetration, or solution adopted, the combination of the two functions helps keep the maximum voltage across all feeders up to 1.12pu. This effect can be explained due to the significant absorption of reactive power from multiple solar PV installations which helps reduce voltages.
    - Generation curtailment is always kept to significantly low levels (below 2%) regardless the type of feeder and penetration level. This finding demonstrates the significant value brought to customers (minimal curtailment).
        - Volt-Watt alone (Volt-var not enabled) leads to significant curtailment which can, in turn, affect the profitability of solar PV owners.
    - While significant benefits were found in terms of voltage issues and generation curtailment, the Volt-var function can exacerbate the thermal utilization of assets. The significant amount of reactive power being absorbed results in larger currents flowing through conductors and transformers. Most affected are the low-capacity LV transformers which become overloaded at relatively low penetration levels; at much lower levels than without having the Volt-var function. This can be effectively solved by network augmentation which needs to be planned for.
    - In the aggregate, the Volt-var function significantly increases the reactive power being imported at the head of the HV feeder. This could potentially create issues in maintaining the power factor at the transmission-distribution network interface within the allowed limits. Adequate planning of capacitor banks in the upstream network (i.e., sub-transmission) might be required to compensate for this increase.
- Based on the above, it is recommended that
    - DNSPs across Australia consider in their PV connection requirements that both inverter control functions (Volt-Watt and Volt-var) are enabled and with the same or similar settings to those defined by Victorian DNSPs [2, 3]; and,
    - customer voltages of HV feeders approaching 20% of solar PV penetration are monitored/analyzed, and that further connection requests are approved upon more detailed network studies.

Increasing HC with traditional solutions to 40% (extra 20%, as per Task 3)

- The HC of all urban and short rural HV feeders can be shifted to 40% (to be reached between 2021 and 2030 depending on the HV feeder) by adjusting the off-load taps of the LV transformers as it significantly reduces voltage issues.
    - This solution is likely to provide limited benefits to long rural HV Feeders due to:

        - The level of voltage rise in SWER connected solar PV customers can be significantly higher than the corresponding voltage reduction of the tap step.
        - The tap capability of SWER transformers can be limited.
    - This solution will also, indirectly, help reduce the level of solar PV curtailment.
- Some additional – but minor – benefits (slightly less voltage issues) can also be achieved by adjusting the voltage target at the zone substation (followed by the adequate adjustment of off-load tap changers).
- Caution should be taken as the adjustment of the OLTC target and/or off-load tap positions may create issues during unexpected peak demand conditions (larger voltage drops) or due to the future adoption of technologies that increase demand (i.e., electric vehicles).
- Based on the above, it is recommended that for urban HV feeders as well as short rural HV feeders, the adjustment of off-load tap changers is exploited (when possible) to make it possible to host up to 40% of houses with solar PV.

Increasing HC with traditional solutions beyond 40% (as per Task 3)

- Beyond 40% penetration of solar PV, the HC is limited by both congestion issues (experienced by LV transformers and HV conductors) and voltage issues.
- Network augmentation is effective in mitigating congestion issues. However, while it indirectly helps reduce voltages (conductors have smaller impedances), the conductors considered in the analysis did not eliminate voltage issues. Consequently, at high penetrations, voltage issues will still remain (even with the adjustment of off-load tap changers).
- Based on the above, traditional solutions are unable to facilitate high solar PV penetrations. Thus, it is recommended that for such cases, non-traditional solutions are explored.

Increasing HC combining non-traditional and traditional solutions beyond 40% (Task 4)

- <u>LV OLTC-fitted Transformers and Traditional Solutions.</u>
    - The <u>HC of all urban and rural HV feeders can be shifted to 100%</u> (to be reached between 2040 and 2060 depending on the HV feeder) by installing OLTC-fitted LV transformers with an adaptive control logic (where the adjustment of off-load taps of LV transformers is not enough) and augmenting congested assets.
        - The adaptive operation of the OLTC can cater not only for voltage rise issues but for voltage drop issues as well. This highlights a more future proof solution able to cater also for voltage drop issues due to technologies that can increase demand such as electric vehicles.
        - The adoption of OLTC-fitted LV transformers in long rural feeders with long SWER connections might not be enough to solve voltage issues. At high penetration levels (>50%) voltages might still be close or above to the statutory limit. This effect can be explained because the magnitude of voltages in SWER-connected customers with solar PV can be significantly higher than the voltage reduction brought by the OLTC.
    - This solution leads to negligible curtailment. This is the effect of significantly reducing voltages, hence, the Volt-Watt function is not triggered.
    - This solution requires a significant percentage of LV transformers connected to an HV Feeder to be equipped with OLTC. At least 50% of LV transformers will need to be equipped with OLTC by 60% penetration (2030 and 2040 depending on the HV feeder).
        - For urban networks OLTCs installations correspond to relatively high rating transformers (>300kVA).
        - For rural networks OLTCs installations correspond to relatively low rating transformers (<100kVA).
        - Regardless the type of feeder, penetration and season, the average daily tap changes is not expected to exceed 10. This low number of tap changes can lead to a reduced wear and tear of the OLTC hence requiring less maintenance costs.

- These findings show that although OLTCs bring significant value to customers with solar PV (negligible curtailment), the overall value to customers needs to include the corresponding capital and operational expenditure associated with these new assets.

- Off-the-Shelf BES Systems and Traditional Solutions.
  - If the HC bottleneck for either urban or rural HV feeders are voltage issues, the adoption of OTS BES has little to no contribution in shifting the HC beyond what can be achieved with the traditional solutions alone. This is due to the following limitations:
    - OTS BES systems do not fully discharge overnight. This is due to insufficient energy consumption of most customers. As a consequence, their ability to store surplus PV generation the following day is significantly reduced.
    - OTS BES systems reach full SOC very early. With a partially charged BES system, surplus PV generation that occurs early in the morning can lead to a full SOC before or during high PV generation, resulting in PV exports
  - While compared to the BAU case the HC can be increased by at least 20%, this is only achieved due to the adjustment of off-load tap changers (i.e., voltage) and the corresponding augmentations (i.e., congestion).
  - These findings show that DNSPs, Government and other stakeholders should not expect significant network benefits from the widespread deployment of OTS BES systems.

- Network Smart BES Systems and Traditional Solutions.
  - The HC of all urban and rural HV feeders can be shifted to 100% (to be reached between 2040 and 2060 depending on the HV feeder) by adopting advanced battery controllers (such as the investigated Network Smart controller) in combination with the adjustment of off-load taps of LV transformers and augmenting congested assets.
  - BES systems with a network smart controller can significantly reduce voltages during the generation period while keeping the maximum voltages well below the statutory limit (<1.10p.u), regardless the penetration level and season. This performance is only achieved due to the Network Smart control logic that enables BES systems charge throughout the whole generation period, hence significantly reduce household exports.
    - The reduction of voltage during PV generation hours provides a significant voltage headroom that can help facilitate the provision of flexibility services from distribution networks.
  - BES systems with a Network Smart controller can significantly reduce the utilization level of all assets and more importantly alleviate congestion issues for the majority of otherwise congested assets.
    - The analyses highlight that the adoption of BES systems with a Network Smart controller can reduce augmentation requirements by at least 60%.
  - Curtailment of PV generation is almost negligible when adopting this non-traditional solution. Batteries are now able to indirectly keep all customer voltages always below 1.10p.u, hence the Volt-Watt function is not triggered.
    - However, compared to the OTS BES, the Network Smart controller increases customers' grid dependence by 2-4%.
  - These findings show that the adoption of advanced battery controllers has the potential to bring enormous benefits to both customers and the networks. At the expense of slightly higher grid imports for customers (compared to currently available battery controllers), advanced controllers can significantly reduce or even avoid the need for capital investments required to provide the same network benefits.
  - Based on the above, there is an opportunity for DNSPs and/or Governments to make the most of the potential benefits from advanced battery controllers. There are two potential pathways for this: 1) households can be incentivized to adopt advanced battery management strategies, or 2) such strategies become mandatory.

- The first pathway acknowledges the fact that households are helping electricity distribution companies deferring network investments. Hence, incentives such as direct payments or subsidized/discounted BES systems with those strategies can stimulate and accelerate the corresponding adoption.
- The second pathway, on the other hand, follows the philosophy of providing network support through regulation (e.g., standards, technical requirements). This is similar to what has already been seen with PV inverter functions such as Volt-Watt and Volt-Var which are required to be enabled (and with specific settings).

Increasing HC with a dynamic voltage target at zone substation OLTC

- A variable voltage target at the zone substation can be an effective option in creating additional headroom that targets peak generation hours. However, this solution is more applicable to zone substations where all the HV feeders connected to it have similar characteristics (demand/generation). Otherwise, the management of voltage rise issues on one HV feeder can result in voltage drop issues in another.
- Due to the limitation of existing OLTC designs, i.e., predominately targeted at boosting voltages, there are very few tap positions available to reduce voltages. Furthermore, the relatively large deadbands (typically between 2% and 3%) also poses issues to control voltages in a granular way, which can limit the overall flexibility of this solution
- Based on the above, it is recommended that future OLTC investments should consider additional taps to reduce voltages as well as more granular deadbands for more precise control of voltages.

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1 Introduction

According to the Australian PV Institute, the aggregated installed capacity of solar PV in Australia is currently exceeding 6.5 GW, with many these installations being residential. The percentage of dwellings with solar PV varies from 12% in the Northern Territory to 30% in Queensland. This, combined with a growing number of commercial customers adopting the technology, will soon pose 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 asset congestion or voltage rise issues (e.g., network augmentation, use of off-load tap changers).

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, this project is established to develop analytical techniques to rapidly assess residential solar PV hosting capacity of electricity distribution networks by leveraging existing network and customer data. Additionally, planning recommendations will be produced to increase the hosting capacity using non-traditional solutions that exploit the capabilities of PV inverters, voltage regulation devices, and battery energy storage systems.

The document at hand corresponds to the *"Deliverable 4: Non-Traditional Solutions"* part of the project Advanced Planning of PV-Rich Distribution Networks funded by the Australian Renewable Energy Agency (ARENA) and led by the University of Melbourne in collaboration with AusNet Services. It focuses on the investigation of "non-traditional solutions" aiming at increasing the solar PV hosting capacity (HC) of Distribution Networks considering the new Victorian Volt-Watt and Volt-var settings which mandates that both power quality response modes are enabled. Five non-traditional solutions, i.e., tailored Volt-Watt and Volt-var PV inverter settings, low voltage OLTC-fitted transformers, off-the-shelf residential battery energy storage, network smart residential battery energy storage, and dynamic voltage target at zone substation OLTC[1], are investigated on four (4) significantly different HV feeders considering progressive penetrations of solar PV. Two different types of analyses, single-day and seasonal, are performed for each feeder and solution considering time-series power flow simulations using the software OpenDSS.

In terms of structure, Chapter 2 presents the non-traditional solutions investigated in this Task and details the methodologies adopted for the corresponding solutions. Chapter 3 presents the data and considerations used for the analyses and case studies performed in this Task. Chapters 4-7 present and discuss the results obtained from each case study. Finally, conclusions and next steps are presented in Chapter 8 and 9, respectively.

[1] For completeness, the usage of a dynamic voltage target at zone substation OLTC is investigated for a selected HV feeder (CRE21). This analysis also complements the current trials of 'Solar Ready Settings' by AusNet Services for in-line voltage regulators in rural networks.

2 Non-Traditional Solutions

This chapter presents the solutions investigated in Task 4 "Non-Traditional Solutions" aiming at managing technical issues (i.e., voltage rise/drop, asset congestion) in distribution networks, hence increasing the corresponding hosting capacity. The term "Non-Traditional Solutions", in this document, refers to solutions not commonly adopted (today) by DNSPs in Australia (and internationally) in order to alleviate technical issues related to voltage and asset congestion. Such non-traditional solutions are based on the combined use of 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 that leverage existing controllable elements such as off-load or on-load tap changers as well as replacing or upgrading conductors and/or transformers.

Considering the above, the benefits of the following non-traditional solutions are explored in this report.

(1) Tailored Volt-Watt and Volt-Var PV Inverter Settings
(2) Low-voltage (LV) on-load tap changer (OLTC)-fitted distribution transformers;
(3) Off-the-shelf residential battery energy storage (BES) systems;
(4) Network smart residential battery energy storage (BES) systems; and,
(5) Dynamic voltage target at zone substation[2].

The following subsections detail the solutions and the corresponding adopted methodologies. It is important to note that the investigation of the aforementioned non-traditional solutions, with exception to the (1) Tailored Volt-Watt and Volt-var settings and (5) Dynamic Voltage Target at Zone Substation OLTC, will be considered on top of the traditional solutions investigated in Task 3 Traditional Solutions [1]. This is performed so that any investment of a non-traditional solution is adopted only after all traditional solutions (i.e., off-load tap changers) that leverage existing assets are adopted. As a last resort, if the adoption of the non-traditional solutions cannot alleviate all technical issues, network augmentation is considered.

2.1 Tailored Volt-Watt and Volt-Var PV Inverter Settings

While Task 3 Traditional Solutions [1], showed that the new PV inverter settings imposed by DNSPs in Victoria provide significant benefits to both customers (i.e., significantly less curtailment) and technical issues (i.e., significant reduction of voltage rise issues) voltage issues are not fully mitigated. As such while the hosting capacity due to voltage issues could be increased by at least 20% (with the Victorian settings), a considerable number of customers was still experiencing voltages issues with increasing solar PV penetrations.

Considering the above, this solution will consider the adoption of Tailored Volt-Watt and Volt-Var PV inverter settings compared to the ones imposed by the Victorian DNSPs and investigated in Task 3 Traditional Solutions [1]. This will help understand the extent to which Tailored settings aiming at fully mitigating voltage rise issues can help further increase the hosting capacity as well as understand the corresponding effects on customers (i.e., solar PV curtailment).

2.1.1 Settings

Table 2-1 and Table 2-2 provide the Volt-var and Volt-Watt numerical settings going to be investigated in this Task and their visual representation is shown in Figure 2-1. As it can be seen these settings aim at absorbing as much 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). An example of curtailment settings to 0% of rated power can be seen in Hawaii, USA, in Hawaiian Electric Rule 14H [4], and in Austria with the TOR D4 standard [5]. These settings are expected to limit the voltage of all customers with solar PV up

[2] For completeness, the benefits of adopting a dynamic voltage target at zone substation is explored in a selected case study (CRE21).

to 1.10 p.u. While these settings are likely to lead to higher volumes of PV curtailment, the seasonal and comprehensive analyses performed in this Task will allow understand the extent to which the corresponding curtailment level can be considered an acceptable trade-off between the mitigation of voltage issues and the effects on customers. Such information can help DNSPs to take more informed decisions when considering similar settings.

Table 2-1 Tailored Volt-var Settings – Numerical

Reference	Voltage (V)	Var % Rated VA
V1	208 (0.90 p.u)	44% leading (exporting Vars)
V2	220 (0.95 p.u)	0%
V3	241 (1.04 p.u)	0%
V4	251 (1.09 p.u)	44% lagging (sinking Vars)

Table 2-2 Tailored Volt-Watt Settings – Numerical

Reference	Voltage (V)	Power % Rated Power
V1	207 (0.90 p.u)	100%
V2	220 (0.95 p.u)	100%
V3	251 (1.09 p.u)	100%
V4	253 (1.10 p.u)	0%

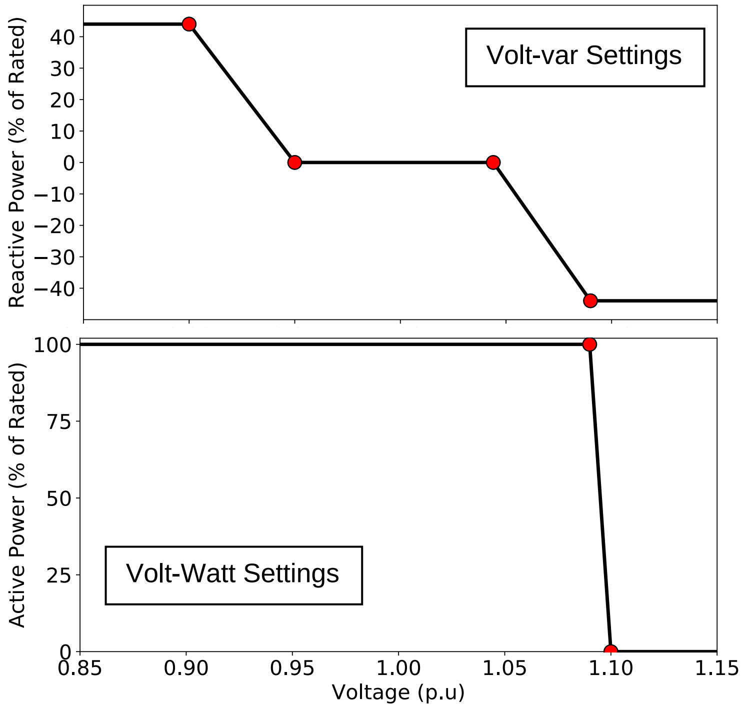


Figure 2-1 Tailored Volt-var and Volt-Watt Settings – Visual

2.1.2 Methodology

The methodology for this solution considers that every new solar PV follows the PV inverter settings specified above. As previously mentioned, this solution will not be considered on top of any traditional solution. This is performed so that the effects of the new PV inverter settings are clearly evident.

2.2 Low Voltage OLTC-fitted Transformers

Due to the passive nature of LV networks (i.e., unidirectional power flow, thus no controllable elements), transformers in distribution substations (e.g., 22kV/0.4kV) are designed with transformation ratios high enough to compensate voltage drops according to the worst case scenario (i.e., maximum load conditions without considering PV generation). More importantly these transformers are equipped with off-load tap changers which means that the ratio between the primary and the secondary voltage can only be changed after disconnecting the load. Consequently, once a given off-load tap position has been found to be adequate for the corresponding LV transformer loading conditions, it is very unlikely that this setting is changed in the lifetime of the transformer (unless the customer composition of the network itself changes significantly).

Considering the above, 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, as illustrated in Figure 2-2, is to maintain the voltage at the secondary side (point A) close to a predefined voltage target (commonly above the nominal) so that the voltage of all connected customers in the high (HV) and low voltage feeders (particularly those connected in the far end, point D) is within the statutory limits during maximum load (dark blue line). However, given the pre-defined settings (i.e., tap position) of off-load tap changers and the relatively high transformation ratio of transformers in LV networks, the connection of large numbers of residential-scale PV systems may result in voltages significantly higher than the upper statutory voltage limits (i.e., point D in Figure 2-2) during minimum load (red line).

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 therefore increase the corresponding solar PV hosting capacity.

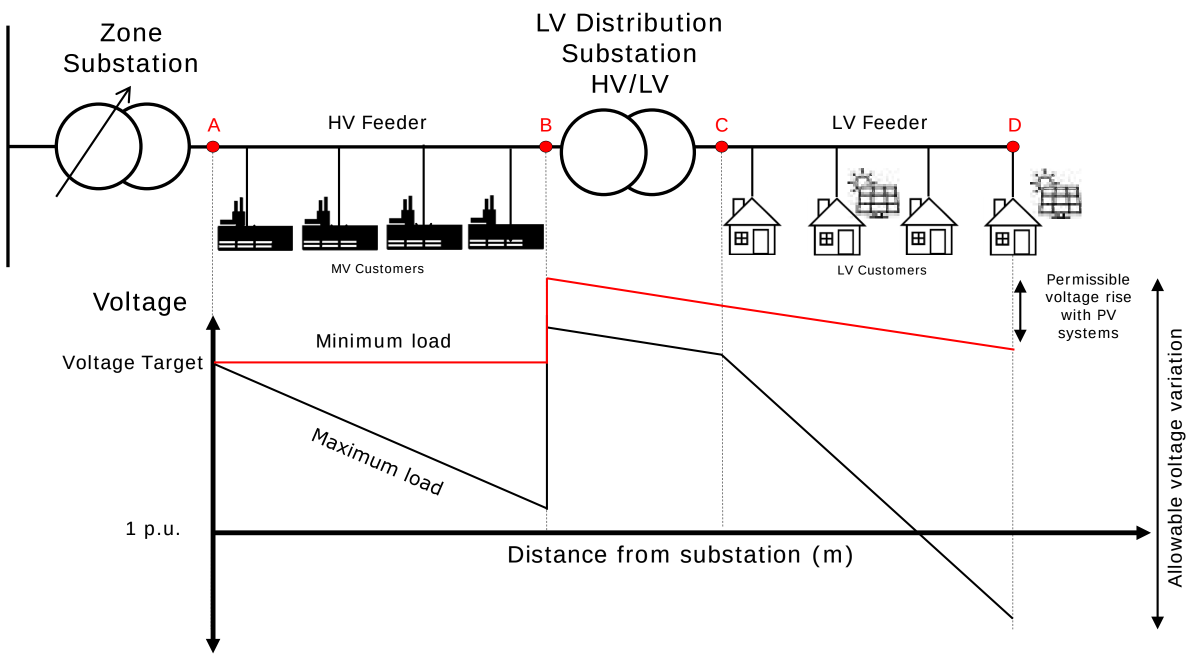


Figure 2-2 Voltage variation in radial distribution feeder

2.2.1 Transformer and OLTC Operating Principles

To understand how OLTC-fitted transformers can help in actively managing voltages closer to LV customers, the basic operation of transformers and OLTCs is discussed in the following sections.

2.2.1.1 Transformer Operating Principle

The operation of a transformer is based on the principles of electromagnetism to change an AC voltage level to another. Its basic operation principle, which is detailed in [6], is illustrated in Figure 2-3 which demonstrates a two winding ideal transformer. If voltage is applied (V_p) on a conductor (e.g. transformer primary winding), the resulted alternating current (I_p) flowing in the conductor will create a changing magnetic field, flux Φ, around the conductor which can induce a voltage (V_s) to another conductor ends (e.g. transformer secondary winding) connected also in the same magnetic field. The resulted voltage magnitude (V_s) on the secondary winding depends on the turns ratio (N_p/N_s) of the transformer. For example, if the secondary winding has half the number of turns of the primary winding, then the voltage on the secondary winding will be half the voltage across the primary winding. Therefore, the secondary winding voltage, step up or down, can be approximated using (2.1)
.

$$V_s = \frac{V_p}{N_p} \times N_s \tag{2.1}$$

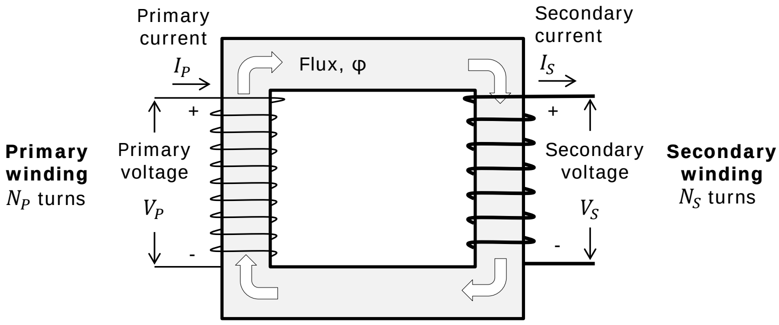


Figure 2-3 Basic transformer operation (ideal transformer)

OLTC-fitted transformers, using a mechanical device, are able to change the number of turns to be used, in discrete steps. Hence, this ability can offer the advantage to change the transformation ratio according to the available tap positions. This allows voltage adjustments at the substation, under loading conditions, to increase or reduce the voltage level.

2.2.1.2 OLTC Typical Operating Principle

OLTCs are typically installed on the primary side of transformers and they are controlled by the Automatic Voltage Control (AVC) relay which uses voltage measurements from the secondary side of the transformer to define the corresponding control actions (i.e., tap change). This operation is illustrated in Figure 2-4 where a voltage transformer (VT) measures the voltage on the secondary side of the transformer (i.e., V_s) [7]. This measured voltage is always compared with a pre-defined and fixed voltage target and no regulation is performed if it is within the defined bandwidth settings (defined based on acceptable voltage variations). Once the measured voltage deviates from the bandwidth, the AVC sends a signal to the OLTC in order to change the tap position (i.e., up or down). To avoid excessive tap changes due to short period voltage deviations (e.g., a few seconds) the tap change signal is delayed.

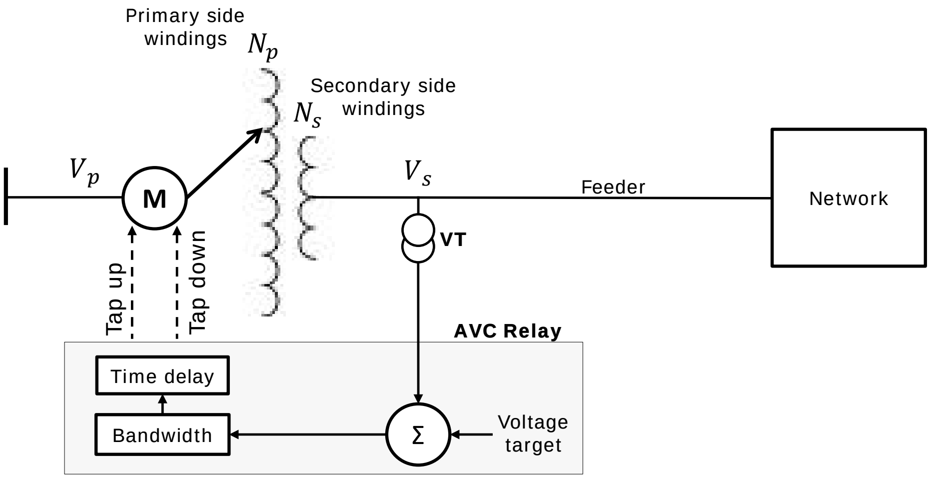


Figure 2-4 Voltage control using OLTC

While the typical operating principle allows to regulate the voltage source to a fixed voltage target, it does not guarantee that the voltage at the far end of the LV feeders will be within the statutory limits. Moreover, such operation becomes even more critical in situations where contrasting voltage issues exist (rise and drop) given the fact that the typical operating principle considers a fixed voltage target and measurements only at the substation. As such, any OLTC actions might lead to a poor voltage management performance in the presence of uneven penetration of solar PV (or new loads such as electric vehicles) within the LV feeders (some feeders with voltage rise issues and others with voltage drop issues). Therefore, effective OLTC-based solutions are required to manage voltage issues brought by the simultaneous adoption of these low carbon technologies (e.g., solar PV, electric vehicles) whilst minimising the number of tap changes, as this is a significant factor to the wear and tear of the OLTC.

2.2.2 Adaptive OLTC Control

In contrast to the traditional operation of OLTC this section provides the details of an adaptive OLTC control logic proposed, and adopted in this study, aiming at managing contrasting voltages issues (rise and drop). leverage smart meter data to actively calculate a voltage target (at the busbar) that brings contrasting voltages issues (rise and drop) closer to a middle point, thus satisfying voltage limits. Crucially, this provides the significant benefit of easily adapting to network changes (i.e., additional PV system installations or loads) without the need of reconfiguring OLTC settings.

2.2.3 Architecture

Figure 2-5 shows a simplified schematic, demonstrating the control architecture of the proposed control scheme which considers smart meter data to collect voltage measurements to a programmable logic unit (PLC) located at the HV/LV distribution substation. The PLC is, in this case, the physical device in which any control logic is coded. Based on this logic, the PLC can then send to the OLTC controller a command to produce a busbar voltage (VT) that ultimately alleviates any voltage issues.

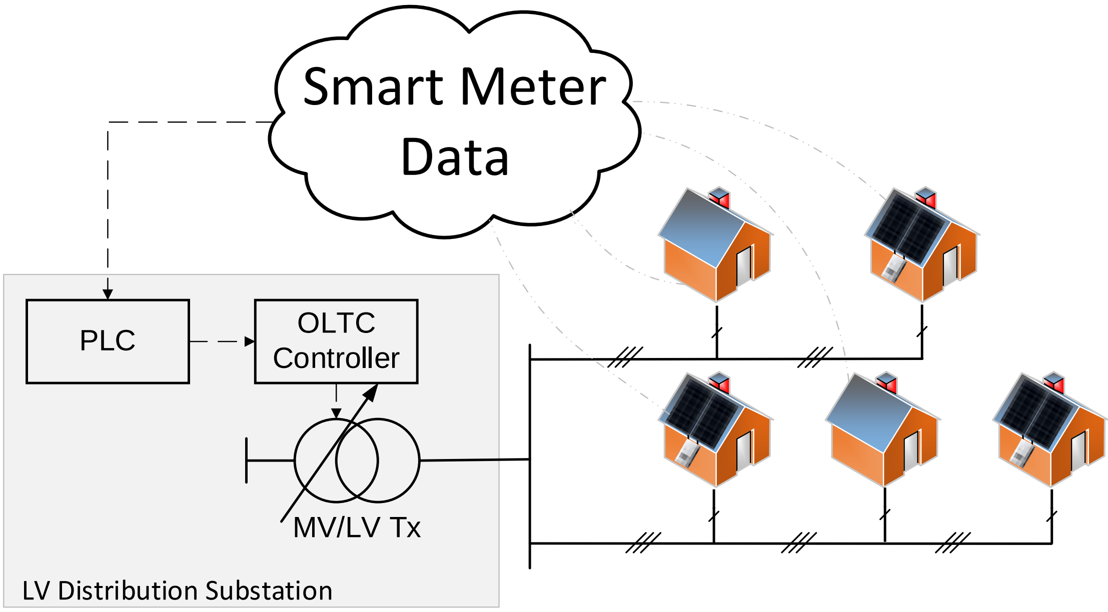


Figure 2-5 OLTC proposed control architecture

2.2.4 Control Logic

The control logic considers voltages from the smart meter data to calculate the voltage at the busbar (VT, to be sent to the OLTC controller). The OLTC voltage target (VT_t) is calculated in a way that the maximum and minimum customer voltages (V_t^{MAX}, V_t^{MIN}) across the area of interest are always within the statutory limits ($\overline{V}$ and $\underline{V}$) but, crucially, also centered with respect to those limits. The centering of customer voltages is a key feature as it creates adequate headroom and footroom to prevent issues due to sudden changes in PV generation or demand.

At every control cycle (t), the minimum and maximum values (V_t^{MAX}, V_t^{MIN}) among all monitored voltages from all smart meter data are found. Then, it is checked whether these two values are within the controller's safe zone ($V_{SAFE}^{MAX}, V_{SAFE}^{MIN}$) as shown in Figure 2-6. The latter (i.e., the safe zone), considers a bandwidth (green area in Figure 2-6) which is defined as a percentage value, Δ, above and below a reference voltage (V^{REF}); where V^{REF} is the center of the statutory limits. The reference voltage and safe zone are parameters that can be adjusted according to the DNSP requirements. Thereafter, and as illustrated in Figure 2-6 (a), if both values V_t^{MAX} and V_t^{MIN} are within the safe zone, then no action is taken and the controller proceeds to the next control cycle. On the other hand, and as shown in Figure 2-6 (b), if any of the two values lies outside the safe zone, then their differences from the V^{REF} are calculated (ΔV_t^{MIN}, ΔV_t^{MAX}). The average of these voltage differences (ΔV_t^{MEAN}) is then used to calculate the new voltage target (VT_t) as in (2.2).

$$VT_t = VT_{t-\Delta t} + \Delta V_t^{MEAN} \tag{2.2}$$

If the new voltage target is outside the statutory limits ($\overline{V}$, $\underline{V}$), then the corresponding value is set to its nearest limit. The flowchart for the proposed control logic is given in Figure 2-7. It is important to highlight that due to the nature of the control logic (i.e., considering both highest and lowest voltages), the voltage target calculated will be influenced by the higher difference (ΔV_t^{MIN}, ΔV_t^{MAX}) and, therefore, the new voltage target is expected to maintain the monitored voltages within the statutory voltage limits. It is important to highlight that in case of simultaneous voltage rise and drop of same magnitude, the average voltage difference will be equal to zero and, therefore, the voltage target will not change.

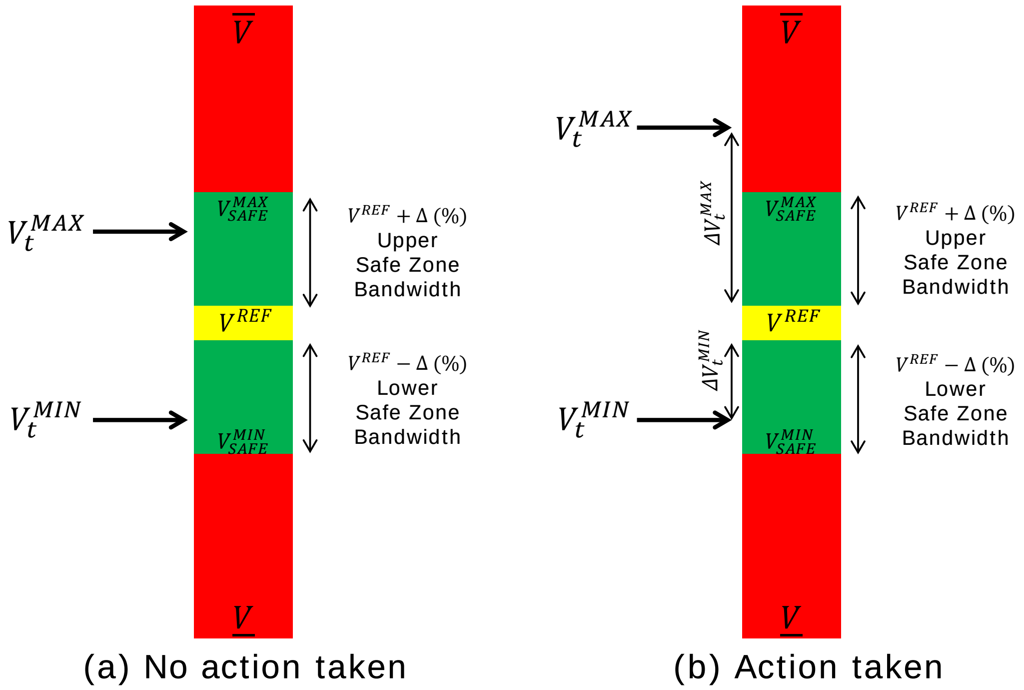


Figure 2-6 OLTC control logic example

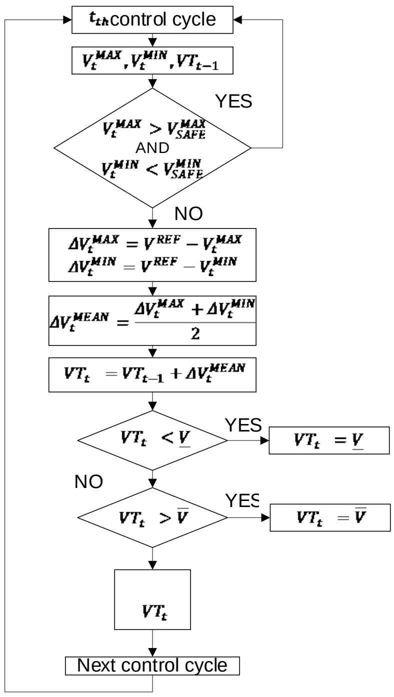


Figure 2-7 OLTC control logic flowchart

2.2.5 Methodology

Given that the adoption of this solution requires a new asset investment (i.e., OLTC-fitted transformer), the analysis considers first the adjustment of off-load tap changers and if a voltage management is still required the off-load tap changer is replaced to an OLTC. The methodology of investigating the adoption of LV OLTC-fitted transformers with the adaptive control logic in this Task is provided below:

For a given HV feeder and for each day and solar PV penetration the following process is performed:

1. The off-load taps of all transformers are adjusted considering the methodology adopted in Task 3.
2. Daily time-series power flow analyses are performed where at each time-step:
    a. **OLTC installation requirement check.**
        i. For the given time-step and for each LV network the maximum and minimum voltage (Vmax, Vmin) among all customers connected to the network are identified.
        ii. If the Vmax >= 1.09 p.u. or Vmin =< 0.95 p.u., then the off-load tap changer is replaced with an OLTC adopting the proposed control logic.
        iii. Store the capacity of the transformer that the OLTC is installed. This information will be used to calculate the level of investment required.
    b. **Asset augmentation requirement check**
        i. Transformers.
            1. The loading of each transformer in the corresponding feeder is checked.
            2. If a transformer is overloaded, the asset is replaced by the next suitable one (in terms of capacity).
            3. Store the capacity of the transformer replaced. This information will be used to calculate the level of investment required.
        ii. Conductors.
            1. The loading of each conductor section (LV and HV) is checked.
            2. If a section is overloaded, this is replaced with the next available conductor size (in terms of capacity).
            3. Store the length of the conductor replaced. This information will be used to calculate the level of investment required.
3. Run the same daily time-series power flow analysis considering all changes performed in step 2.

2.3 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) BES systems and their corresponding effects on the solar PV hosting capacity.

2.3.1 Operating Principle

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 [8].

To demonstrate the operation of an OTS BES system, Figure 2-8 is provided which illustrates an example of a household with solar PV and OTS BES. First, to better understand the effects of the and operation of an OTS BES systems, the household behaviour with just the solar PV is presented. Figure 2-8 (a) shows the household load and PV generation profiles and Figure 2-8 (b) presents the resulting household net profile in the presence of solar PV only (without OTS BES). As observed during high PV generation hours, the household net profile results in large exports, P_{PV}^{exp}, due to the large PV generation and small load demand. As previously discussed, large exports from multiple households are leading to significant technical challenges (e.g., voltage rise, asset congestion) in the distribution network.

When an OTS BES is adopted and as shown in Figure 2-8 (c), all the excess of PV generation is being stored in the BES system until it becomes full (i.e., full SOC). After that point, any excess of PV generation is exported back to the grid (here, the maximum exported power is denoted as P_{OTS}^{exp}) until local demand exceeds generation, to which point the BES system discharges to meet the local demand. Since the BES systems can reach full SOC quite early, the peak exported power can be virtually the same as with the case of PV Only ($P_{OTS}^{exp} \approx P_{PV}^{exp}$). In practice, this can mean large exports at times of high PV generation, resulting in similar challenges as the case shown in Figure 2-8 (b) which does not consider a BES system (i.e., PV Only).

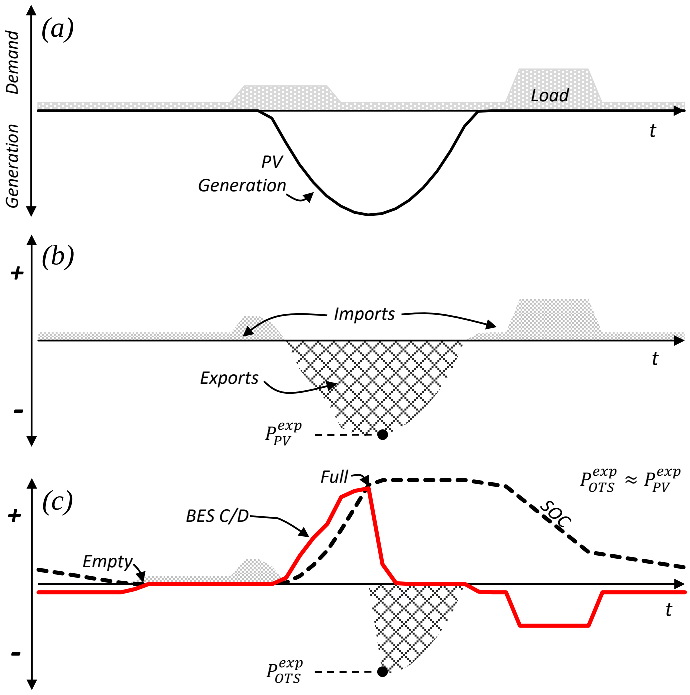


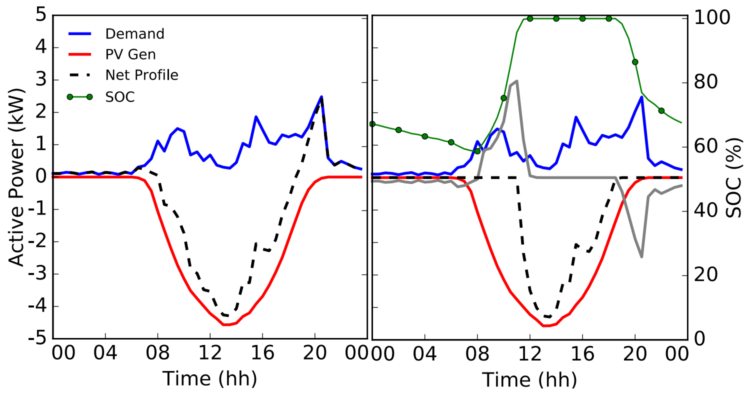
Figure 2-8 OTS BES Operation example

2.3.2 Household Operation Example

To demonstrate the operation of the OTS BES controller, a household with a 5kWp PV system and a 5kW/13.5kWh BES system (100% depth of discharge and 88% round-trip efficiency) is considered as an example using a summer clear-sky and a cloudy-sky day. To adopt a realistic SOC at the beginning of the day of interest, the prior day is also considered in which the BES system starts from empty.

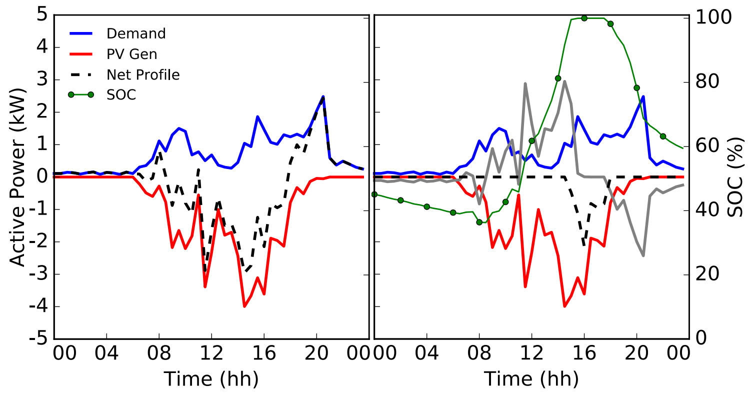
Figure 2-9 (a) and Figure 2-10 (a) present the behaviour of the household's net demand (dashed black line) when only the PV system is installed for the cases of clear-sky and cloudy-sky days, respectively. Regardless the type of day, a large amount of the household's demand (blue line) is supplied by the PV generation (red line). More specifically, for the clear-sky day, 69% of the daily household demand is supplied by the PV system whereas for the cloudy-sky day the same number reduces to 62%. It is important, however, to highlight that in both cases, due to the high PV generation and low demand around midday, the household's net profile results in significant exports. If multiple neighbouring customers have the same behaviour, then, the resulting reverse power flows can lead to voltage rise and congestion issues in the network.

From the perspective of the customer, the installation of a BES system with an OTS control brings major benefits, as shown in Figure 2-9 (b) and Figure 2-10 (b). In these cases, the net demand is never positive; all the demand is supplied by the PV and BES systems, i.e., the customers have become self-sufficient. However, from the perspective of the network, the OTS controller is unable to reduce the PV exports during midday (>4kW in the case of clear-sky and >2kW in the case of cloudy-sky). This is due to the fact that the BES system does not fully discharge overnight and, hence, starts charging (grey line) all the excess of PV generation with a relatively high SOC. More specific, considering the two cases (sunny and cloudy day) the BES system starts charging around 8:30am with already 58% and 36% SOC (green line), respectively. Therefore, the full SOC is reached either before or just after midday. PV exports are not reduced after that point.



(a) PV Only (b) OTS

Figure 2-9 Household-level operation considering an OTS BES system on a sunny day



(a) PV Only (b) OTS

Figure 2-10 Household-level operation considering an OTS BES system on a cloudy day

2.3.2.1 Limitations

The adoption of residential-scale BES systems using the OTS BES Systems as described above suffers of the following two important limitations:

- **BES systems might not adequately discharge.** Due to the uncertainty of household demand each day, the normal operation modes might not be able to fully discharge the battery overnight. This in turn limits the ability of the battery to fully utilise its storage capacity the following day. This issue becomes even more critical in cases where the household demand is significantly low.
- **BES systems reach full SOC very early.** Due to the fact that the normal operation modes cannot guarantee full discharge of the battery during the night, the battery might become full earlier the next day. From a DNSP perspective, this operation might not provide significant benefits in terms of voltage and thermal issues since batteries might not be able to absorb excess PV generation (exports) during critical periods (around midday).

2.3.3 Methodology

This solution does not require the investment of any new DNSP owned controllable assets but instead tries to understand the extent to which the adoption of OTS BES systems in households with solar PV can help reduce the corresponding reverse power flows due to excess solar PV generation. As such, this solution could potentially help mitigate technical problems across the distribution network, hence increase the corresponding solar PV hosting capacity. The methodology of investigating the adoption of OTS BES systems in households with solar PV is provided below:

For a given HV feeder and for each day and solar PV penetration to be investigated the following process is performed:

1. The off-load taps of all transformers are adjusted considering the methodology adopted in Task 3.
2. An OTS BES system is allocated to each household with solar PV.
3. Daily time-series power flow analyses are performed where at each time-step:
    a. **Asset augmentation requirement check**
        i. Transformers.
            1. The loading of each transformer in the corresponding feeder is checked.
            2. If a transformer is overloaded, the asset is replaced by the next suitable one (in terms of capacity).
            3. Store the capacity of the transformer replaced. This information will be used to calculate the level of investment required.
        ii. Conductors.
            1. The loading of each conductor section (LV and HV) is checked.
            2. If a section is overloaded, this is replaced with the next available conductor size (in terms of capacity).
            3. Store the length of the conductor replaced. This information will be used to calculate the level of investment required.
4. Run the same daily time-series power flow analysis considering all changes performed in step 2.

2.4 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. These new BES management strategies could become an alternative to otherwise required costly network reinforcements, saving billions of dollars in investments.

Considering the aforementioned and to overcome the limitations of the OTS BES Systems, a network smart controller aiming at reducing high PV exports by adapting the BES charging power proportionally to the PV generation, and ensuring available capacity by discharging overnight is proposed and presented in this section.

2.4.1 Operating Principle

This solution considers the case where BES systems adopt a “network smart” (NS) controller, designed to overcome the limitations of the OTS control (BES systems reaching full SOC very early; hence inadequate to reduce reverse power flow). The NS control reduces high PV exports by adapting the BES charging power proportionally to the PV generation, and ensuring available capacity by discharging overnight. The design allows it to adapt in real time changes such as cloud transients and household demand. Considering the same example as shown in Figure 2-8 (a)-(b), Figure 2-11 (c) illustrates the household behaviour when adopting a NS BES systems where PV exports (here, the exported power is denoted as P_{NS}^{exp}) can be significantly reduced while meeting the local needs of the household. This, in turn, means that the integrity of the distribution network might not be compromised as the magnitude of the reverse power is significantly reduced ($P_{NS}^{exp} \ll P_{OTS}^{exp}$).

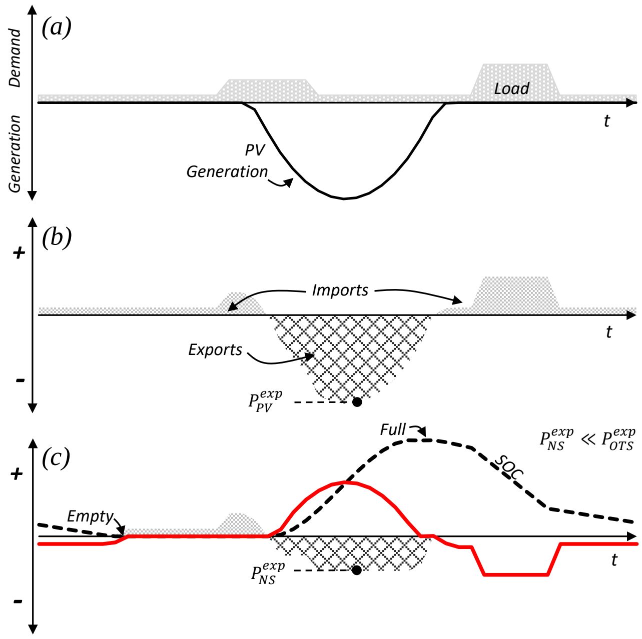


Figure 2-11 Network Smart BES Example

2.4.2 Network Smart Control Logic

To achieve this operation, first, the daily maximum PV generation is estimated by using well-established methods to compute ideal clear-sky generation profiles. This is used to produce an ideal charging profile that follows the bell-shape of the maximum PV generation with an area that matches the BES capacity; directly tackling reverse power flows as the BES will charge with higher power rates during critical times (Figure 2-12a). The resulting ideal charging profile, as shown in Figure 2-12, allows automatically defining the start (α) of the BES system charging period. The end (β) of the charging period, on the other hand, is derived from the clear-sky profile and corresponds to the moment where the PV generation stops. Since, in practice, at any given time, surplus PV generation can be below that expected by the ideal charging profile (e.g., 'gap' shown in Figure 2-12b), the corresponding power charging rate is re-calculated using actual measurements (PV generation and demand). To cater for the energy mismatch created, the ideal charging profile is updated accordingly (dark grey area after the generation gap, Figure 2-12b).

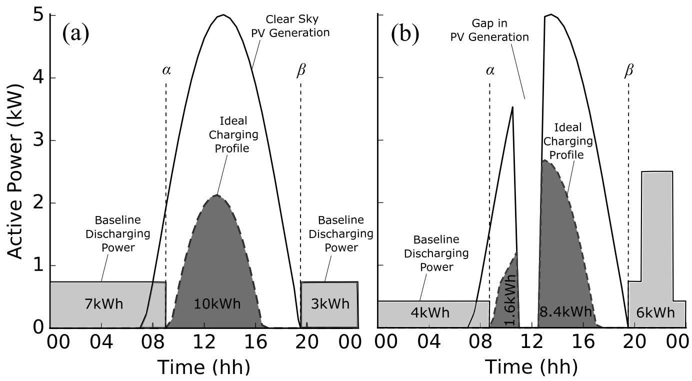


Figure 2-12 BES charging profile example: (a) without and (b) with generation gap

The above charging strategy can only be successful if the BES has an adequate available capacity at the beginning of the charging period. To achieve this, a baseline discharging power rate is calculated considering the time at the end of the maximum PV generation profile, the corresponding SOC, and the time at the beginning of the charging period next day by which a pre-defined SOC should be achieved. To ensure that the customer makes the most of the BES system, the discharging power rate is updated to match the demand whenever it exceeds the baseline value. To still achieve the pre-defined SOC at the beginning of the charging period, the baseline discharging power is updated accordingly.

2.4.2.1 Ideal Charging Power Profile

The ideal charging power profile is calculated at each sampling interval, Δt (minutes). From the current instant i to the time at which PV generation ends, β, this profile is defined by a set of charging power values, C_t (kW), where $t \in [i, \beta]$ in steps of Δt. This is calculated by iteratively reducing the corresponding clear-sky generation profile (a set of maximum PV power generation values, CS_t, where $t \in [i, \beta]$ in steps of Δt), so that the resulting area (i.e., energy to be stored) is less or equal to the energy required to achieve full SOC, as in (2.3).

$$\sum_{t=i}^{\beta} C_t \frac{\Delta t}{60} \leq \frac{\overline{E^s} - E_i^s}{\eta^+} \tag{2.3}$$

where $\overline{E^s}$, E_i^s and η^+ are the rated capacity (kWh), stored energy (kWh), and the charging efficiency, respectively.

The clear-sky power generation profile can be directly calculated beforehand considering the position of the Earth with respect to the Sun (changing every day, every hour) as well as the characteristics of the PV installation (i.e., geographical location, panel tilt, azimuth). Models found in [9] or readily available tools such as the one in [10] can be utilized to produce these daily clear-sky profiles.

Based on the above, the ideal charging power profile for a particular day and PV installation can be produced using Algorithm 1, where n is an arbitrarily small number (a fraction of the peak clear-sky PV power generation). The adequate definition of this number is a trade-off between computational efficiency (larger n) and accuracy (smaller n).

Algorithm 1: Ideal Charging Power Profile
A1-1: Let $C_t[i, \beta] \leftarrow CS_t[i, \beta]$
A1-2: **while** (2.3) = *False* **do**
A1-3: **for** $t = i$ **to** β **do**
A1-4: $C_t \leftarrow C_t - n$
A1-5: **end for**
A1-6: $C_t[C_t < 0] \leftarrow 0$
A1-7: **end while**
A1-8: **return** C_t

2.4.2.2 Baseline Discharging Power Value

The baseline discharging power value, D (kW), is defined, at the current instant i, to ensure that the BES system will adequately discharge at the start of the next charging period, α (time at which BES system can start charging). This is given by (2.4).

$$D_i = \eta^- \frac{E_i^s - E^{min}}{(\alpha - i)/60} \tag{2.4}$$

where $(\alpha - i)$ is the remaining period (minutes) until the start of the next charging period, η^- is the discharging efficiency and E^{min} (kWh) is the pre-defined minimum energy that should always be stored (manufacturer or user preference).

2.4.2.3 Start (α) and End (β) of the Charging Period

As previously stated, the parameters α and β, denote the time where the charging period starts and ends, respectively. These, and as shown in in Fig.1, are automatically defined at the beginning of each day (i.e., i=1 as shown in A3-3) based on A2-2 and A2-3, where the reduced ideal charging profile, (i.e., calculated in Algorithm 1) is passed to Algorithm 2 (A2-2). The value α is defined as the first period where the C_t is larger than zero (i.e., BES starts to charge, shown in A2-3). On the other hand, the end of the charging period, β, is defined as the last period where CS_t is larger than zero (i.e., PV generation stops, shown in A2-1).

Algorithm 2: Defining α and β

A2-1: $\beta \leftarrow CS_t[CS_t > 0]_{-1}$
A2-2: $C_{t\in[1,T]} \leftarrow$ **Algorithm 1**
A2-3: $\alpha \leftarrow C_t[C_t > 0]_1$
A2-4: **return** α, β

2.4.2.4 Daily Operation BES System

Based on the defined ideal charging profile and baseline discharging value at instant i, the daily operation of the BES system (split into a number of discrete Π periods), is thereby described in Algorithm 3, where P_i^d and P_i^g are the demand and PV generation (kW), respectively. The BES system power output, P_i^s, and energy stored in the BES system are constrained as shown in (2.5) and (2.6), respectively.

$$P_i^s \in [\, \underline{P^s}\, , \overline{P^s}\,] \tag{2.5}$$

$$E_i^s \in [\overline{E^s} \times (\,100 - DoD)/100\, , \overline{E^s}\,] \tag{2.6}$$

where $\underline{P^s}$ and $\overline{P^s}$ are the minimum (discharging) and maximum (charging) power ratings (kW), respectively, and DoD is the maximum permitted depth of discharge (%).

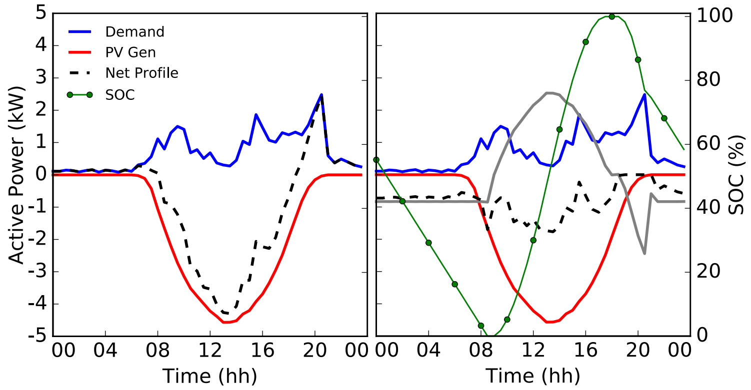
It is worth mentioning that Algorithm 3 is designed to maximize benefits to customers. As such, during the charging period $[\alpha,\ \beta]$, any time there is a positive net demand, $P_i^d - P_i^g > 0$, the available energy stored will be used (lines A3-12, A3-13). This means that in periods in which the PV generation is smaller than demand (positive net demand), the BES system will use the stored energy to supply the required demand (that would otherwise be imported from the grid). This feature is aligned with the operation of commercially available BES systems as it helps reducing electricity bills. Similarly, outside the charging period, the BES system will help meeting the demand if larger than the baseline discharging power rate (lines A3-8, A3-9).

Algorithm 3 Daily operation of the BES system
A3-1: **for** $i = 1$ **to** Π **do**
A3-2:   **if** $i = 1$ **do**
A3-3: $\alpha, \beta \leftarrow$ **Algorithm 2**
A3-4:   **end if**
A3-5:   Measure E_i^s, P_i^d, P_i^g
A3-6:   **if** ($i < \alpha$ or $i > \beta$) **do**
A3-7:   **if** $E_i^s \geq E^{min}$ **do**
A3-8: $D_i \leftarrow$ **(2)**
A3-9: $P_i^s \leftarrow -\max(D_i, P_i^d - P_i^g)$
A3-10:   **end if**
A3-11:   **else**
A3-12: $C_{t\in[i,\beta]} \leftarrow$ **Algorithm 1**
A3-13: $P_i^s \leftarrow \min\,(C_i, P_i^g - P_i^d)$
A3-14:   **end if**
A3-15: **end for**

2.4.3 Household Operation Example

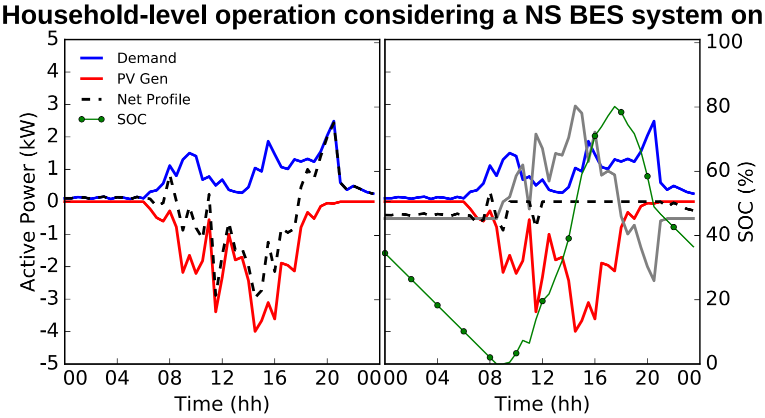
To demonstrate the operation of the NS BES controller, the same example as presented in section 2.3.2 is used here where a household with a 5kWp PV system and a 5kW/13.5kWh BES system (100% depth of discharge and 88% round-trip efficiency) is considered for a summer clear-sky and a cloudy-sky day.

To adopt a realistic SOC at the beginning of the day of interest, the prior day is also considered in which the BES system starts from empty.



(c) PV Only (d) NS

Figure 2-13 Household-level operation considering a NS BES system on a sunny day



(c) PV Only (d) NS

Figure 2-14 Household-level operation considering a NS BES system on a cloudy day

As also presented in the previous section, Figure 2-13 (a) and Figure 2-14 (a) present the behaviour of the household's net demand (dashed black line) when only the PV system is installed for the cases of clear-sky and cloudy-sky days, respectively. Regardless the type of day, a large amount of the household's demand (blue line) is supplied by the PV generation (red line). More specifically, for the clear-sky day, 69% of the daily household demand is supplied by the PV system whereas for the cloudy-sky day the same number reduces to 62%. It is important, however, to highlight that in both cases, due to the high PV generation and low demand around midday, the household's net profile results in significant exports. If multiple neighbouring customers have the same behaviour, then, the resulting reverse power flows can lead to voltage rise and congestion issues in the network.

The adoption of the proposed NS controller overcomes all the limitations of the OTS controller while still making the householder energy self-sufficient, except some moments during the cloudy day case where a tiny fraction (0.9%) of demand had to be supplied from the grid during 8-8:30am. As shown in Figure 2-13 (b) and Figure 2-14 (b) the NS controller follows the early morning demand, achieving full discharge by 8:30am in both cases (i.e., clear and cloudy-sky). This means that the full storage capacity is available throughout daylight. Considering both cases, from time α=8:30am (defined using Algorithm 2), the BES system starts to adaptively charge with the power rate specified by the NS controller. The charging profile (grey line) resembles the shape of clear-sky PV generation, allowing a progressive increase in the SOC. This, in turn, significantly reduces exports (<2kW) for both days. In the case of clear-sky conditions, a full (100%) SOC is reached around 5pm, whereas for the case of cloudy-sky, a lower SOC (80%) is reached for the same time. This highlights that despite the lower and fluctuating PV generation throughout the day, the NS controller still manages to achieve a high enough SOC to support the demand-only period (9pm-6am). This can be explained as the NS controller continuously recalculates the 'ideal charging profile' and effectively charging the battery with a higher power rate to capture more excess PV generation (as explained in section 2.4.2.1 and shown in Figure 2-12). This can be observed by comparing the charging power at 2.30pm during the sunny (2.3kW) and cloudy day (2.95kW).

Between this 5pm and time β=8pm, in both cases, PV generation is smaller than demand, therefore the BES systems discharges enough to avoid grid imports. After 8pm, when the PV system stops generating, the household demand is higher than the baseline discharging power value (0.85kW for the sunny day and 0.5kW for the cloudy day), hence the BES system is discharging with a power rate equal to the demand. Thereafter, once the demand becomes lower than the baseline, the BES system continues discharging with the baseline discharging power (i.e., the SOC progressively reduces). While this feature results in power exports, the values are significantly smaller than those found by the OTS and, therefore, unlikely to lead to network issues. More importantly, this ensures that the specified storage capacity (in this case, full capacity, i.e., $E^{min} = 0$), will be available for the next charging period.

This example demonstrates that the performance of the proposed NS controller can significantly enhance the BES system operation in a way that is beneficial to the network with limited (or no) impact on the customers.

2.4.4 Methodology

This solution does not require the investment of any new DNSP owned controllable assets but instead tries to understand the extent to which the adoption of network smart BES systems in households with solar PV can help reduce the corresponding reverse power flows due to excess solar PV generation. As such, this solution could potentially help mitigate technical problems across the distribution network, hence increase the corresponding solar PV hosting capacity. The methodology of investigating the adoption of network smart BES systems in households with solar PV is provided below:

For a given HV feeder and for each day and solar PV penetration to be investigated the following process is performed:

1. The off-load taps of all transformers are adjusted considering the methodology adopted in Task 3.
2. A network smart BES system is allocated to each household with solar PV.
3. Daily time-series power flow analyses are performed where at each time-step:
    a. **Asset augmentation requirement check**
        i. Transformers.
            1. The loading of each transformer in the corresponding feeder is checked.
            2. If a transformer is overloaded, the asset is replaced by the next suitable one (in terms of capacity).
            3. Store the capacity of the transformer replaced. This information will be used to calculate the level of investment required.
        ii. Conductors.
            1. The loading of each conductor section (LV and HV) is checked.
            2. If a section is overloaded, this is replaced with the next available conductor size (in terms of capacity).
            3. Store the length of the conductor replaced. This information will be used to calculate the level of investment required.
4. Run the same daily time-series power flow analysis considering all changes performed in step 2.

2.5 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.

Based on the above, a generic response curve, i.e., the voltage target of the OLTC as a function of the active power import through the zone substation, is shown in Figure 2-15. The response curve is defined by the two critical points (P1, V1) and (P2, V2). The methodology to define these critical points for each network is outlined below.

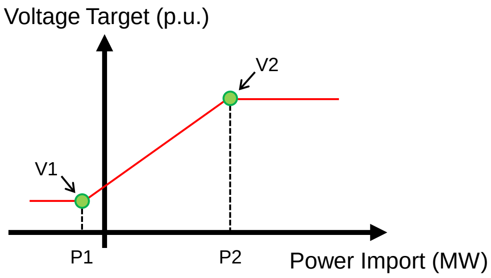


Figure 2-15 OLTC Response Curve

2.5.1 Defining the OLTC response curve

In Figure 2-15, the point (P2, V2) defines the boundary condition when a reduction in voltage target at the zone substation OLTC is required. Therefore, its value can be calculated based on the existing settings of an OLTC and the prior knowledge of the power flow characteristics of downstream networks. Particularly, the existing voltage target (e.g., typically around 1.0 pu) can be used as V2 and the minimum expected power import from the upstream network can be used for P2. As a result of this selection criteria, the behaviour of the zone substation OLTC remains unchanged until the power imported falls below the critical point P2, a sign that indicates substantial reverse power flow in downstream networks. The selection of (P1, V1) determines the ‘aggressiveness’ of the OLTC’s response to the estimated volume of reverse power flows. This can be tailored to the specific characteristic of each network.

3 Data and Analysis Considerations

This chapter presents the data and considerations used for the analyses performed in this Task. First, the residential and non-residential demand used for the analyses are described. Then, the modelling of solar PV such as irradiance profiles, penetrations, panel sizes and inverter settings are detailed, followed by the list of transformers and conductors used for the augmentation analyses. Lastly, the case studies considered in this report are presented.

3.1 Residential and Non-Residential Demand

For the modelling and analyses a pool of 30-min resolution, year-long (i.e., 17,520 points), anonymized smart meter demand data (i.e., P and Q), collected from 342 individual residential customers in the year of 2014 is used. These data where facilitated to the University of Melbourne for the purposes of a previous project "*AusNet Mini Grid Clusters*" [11] and "Solar PV Penetration and HV-LV Network Impacts" [12-14]. Using this pool, the yearly demand profiles were broken down in daily profiles, resulting in a pool of ~30,000 daily demand profiles. For demonstration purposes sample residential demand profiles are presented in Figure 3-1.

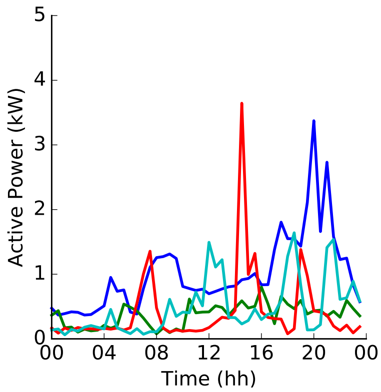


Figure 3-1 Sample Residential Demand Profiles

Given the fact that no information is provided in terms of the type of customers (i.e., residential or non-residential) supplied by the secondary distribution substations, the type is assumed based on the substation name (as provided in the feeder's database), size and number of customers connected to it. Considering this information, a secondary distribution substation in the analyses is considered to supply a non-residential customer if:

a) The substation name is clearly stating a non-residential customer and its corresponding customer type (e.g., hospital, prison, sewerage etc.); or
b) The substation rating is ≥100kVA and the number of customers supplied is ≤10. This is assumed to be an Office/Shop load.

In an effort to provide a more realistic modelling of non-residential customers', real-world commercial and industrial load profiles, provided by CSIRO[3] 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). The procedure followed to create these load profiles is described below.

1. Based on the load profiles provided by CSIRO 30-min resolution load 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). For demonstration purposes Figure 3-2, shows the yearly daily load profiles for a hospital.
2. Using all daily profiles, the average profile for the year is created. This is shown with a black thick line in Figure 3-2.

[3] Representative Australian Electricity Feeders with load and solar generation profiles, Australia: CSIRO. [Online]. Available: https://doi.org/10.4225/08/5631B1DF6F1A0. Accessed on April 2018.

3. The average profile for each of the 5 common non-residential customers found in the feeders (i.e., Hospital, Prison, Sewerage, Water Treatment, Office/Shop) is then normalised. Figure 3-3 shows the normalised average daily load profiles for all 5 non-residential customers considered in this study.

All non-residential customers are then modelled using the corresponding normalised load profiles shown in Figure 3-3 multiplied with 70% of the transformer's capacity, except the case where load is assumed to be an office/shop and is multiplied with the 50% of the transformer's capacity.

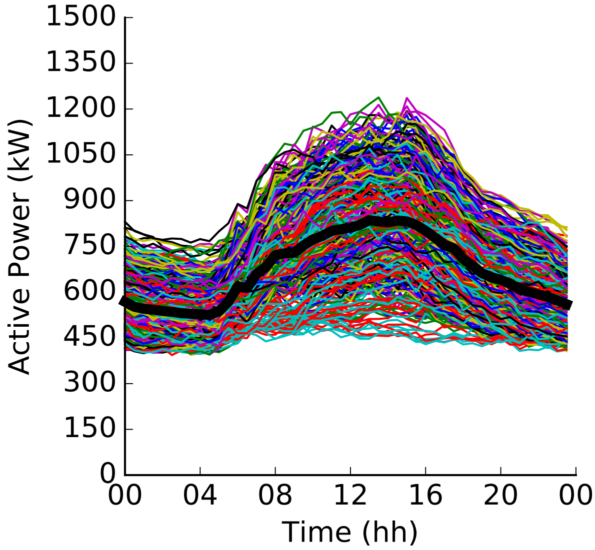


Figure 3-2 Daily load profiles for a hospital during 2014-2015

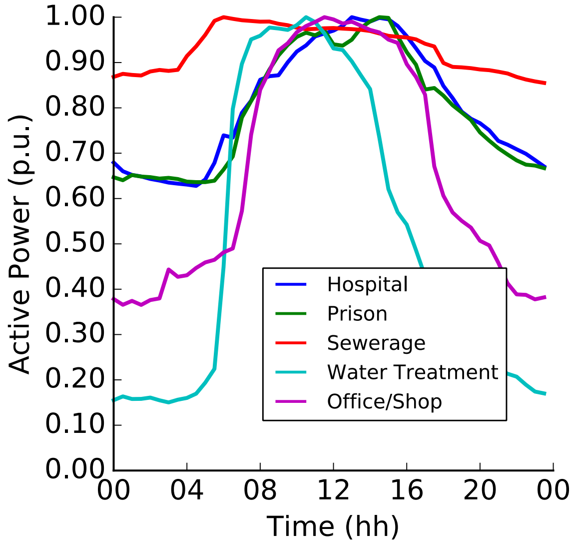


Figure 3-3 Normalised load profiles for non-residential customers

3.2 Solar PV

This section details the modelling aspects of the solar PV such as irradiance profiles, penetrations levels and definitions, panel sizes and inverter settings.

3.2.1 Irradiance

Two datasets of PV irradiance (a) clear sky and (b) actual (measured) are used in this task to model the solar PV generation. The clear sky irradiance is used to understand the worst-case scenario of PV generation whereas the actual (measured) allows for a more realistic representation of the solar PV impacts to the distribution network.

3.2.1.1 Clear-sky

The first dataset consists of pool of 30-min resolution, year-long (i.e., 17,520 points) clear-sky irradiance profiles considering Melbourne. These profiles are modelled using an available tool developed by the University of Loughborough, Centre for Renewable Energy Systems Technology (CREST) [10, 15]. In this tool, once the day and the configuration information of the installed PV panel (e.g., location, efficiency, area, etc.) are determined, 1-min resolution generation and net radiation profiles can be produced. Both profiles correspond to the outdoor irradiance on the chosen day of the year.

Using the aforementioned tool [10, 15], considering PV panels with tilt angle of 35°, azimuth of 0° (north facing), and Melbourne as the geographical location, it was possible to extract the daily clear-sky irradiation profile of each day of the year. The normalised (in p.u.) daily clear-sky irradiance profiles for each day of the year are presented in Figure 3-4. The clear-sky irradiance profiles are used in the single day analysis (details in the following section) to investigate the worst-case scenario (i.e., peak generation) for each season, hence capture the effect of seasonality in the corresponding analyses.

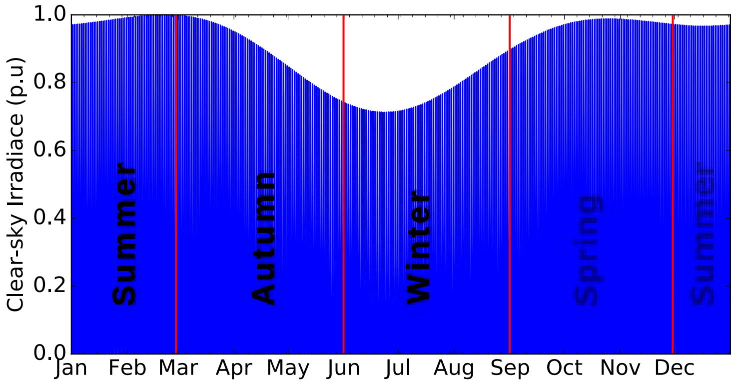


Figure 3-4 Normalised Daily Clear-sky Irradiance

3.2.1.2 Real PV Irradiance Profiles

The second dataset consists of pool of 30-min resolution, year-long (i.e., 17,520 points) real irradiance measurements facilitated to the University of Melbourne 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. For demonstration purposes the normalised (in p.u.) daily actual (measured) irradiance profiles for each day of the year are presented in Figure 3-5.

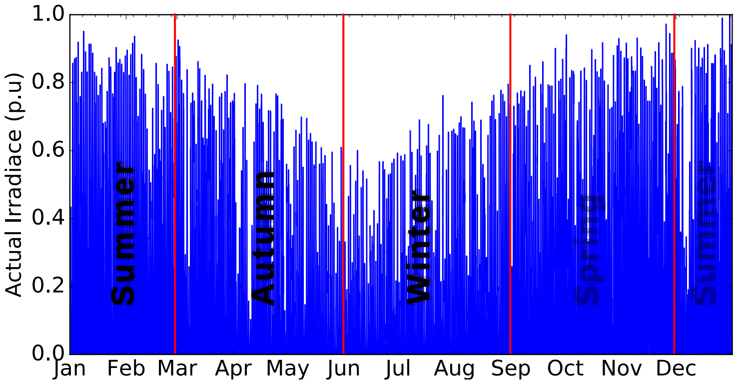


Figure 3-5 Normalised Daily Actual (Measured) sky Irradiance

3.2.2 Penetration and Forecasts

The PV penetration approach adopted in this project is agreed after discussions with AusNet Services and is defined as the percentage of residential customers (i.e., houses) that have a PV system. A realistic PV allocation is adopted by allowing uneven penetrations per feeder and multiple PV installed capacities based on Australian PV installation statistics [16].

Six PV penetration levels, 0, 20, 40, 60 80 and 100% are considered in this Task where the year where each of the penetrations is expected to occur depends on forecasted data specific to each HV feeder considered in this Task and shown in Figure 3-6. Solar PV forecasts until the year 2030 were provided by AusNet Services and these were extended using linear regression up to the year were 100% of penetration is achieved.

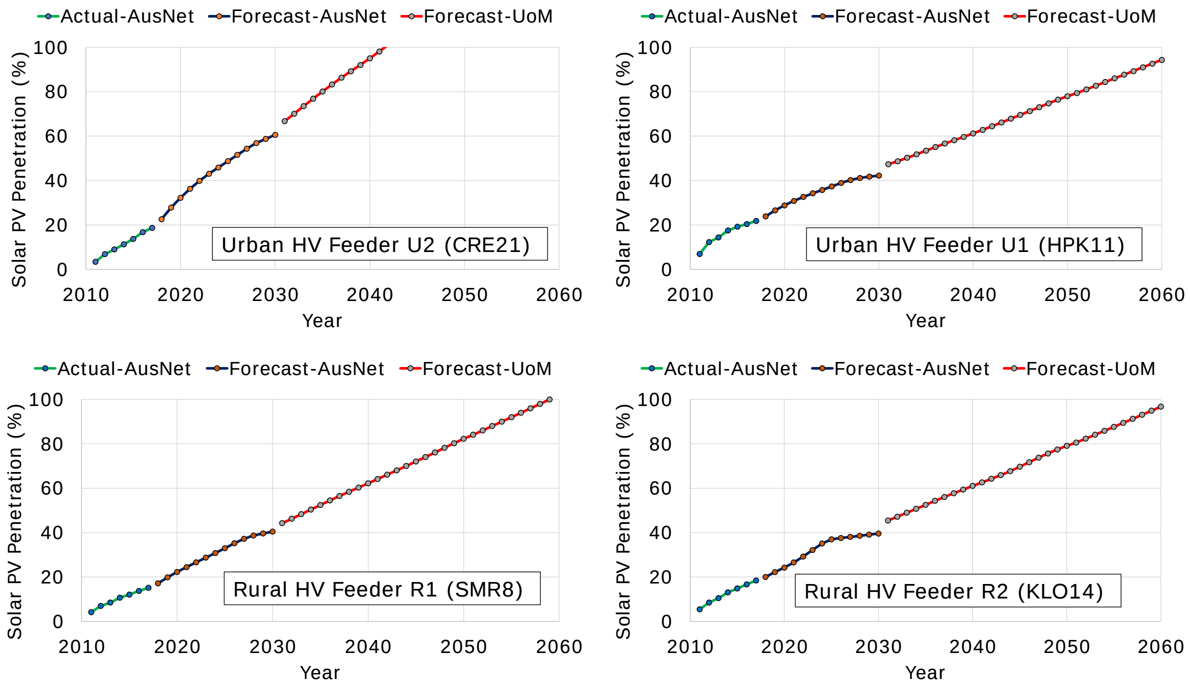


Figure 3-6 Solar PV Penetration Forecasts

3.2.3 Panel and Inverter Sizes

The size of the PV panels considered in this Task is based on Australian installation statistics where the proportion of single-phase PV installations with 2.5, 3.5, 5.5, and 8kWp is 8, 24, 52 and 16%, respectively. A realistic PV uptake is adopted by allowing uneven penetrations per LV networks and feeders as well as multiple PV installed capacities based on Australian PV installation statistics.

For simplicity, all single-phase solar PV installations less or equal than 5kWp are assumed to have inverters with a rated capacity matching the corresponding kW (e.g., 3.5kVA for a 3.5kWp installation). For installations larger than 5kWp, inverters are assumed to have a rated capacity of 5kVA. This assumption is adopted to model the 5kVA export limit (per phase) requirement imposed by AusNet Services; as most customer are likely to use a 5kVA inverter than advanced functionalities.

3.2.4 Victorian PV Inverter Settings

As agreed with AusNet Services, all PV inverters in the studies of this Task consider, as a default, the new Victorian Volt-Watt and Volt-var settings which are defined by the new standard mandating both power quality response modes being enabled [2]. All settings are based on the Australian standard AS/NZS 4777 (Grid connection of energy systems via inverters).

3.2.4.1 Volt-Watt

Characteristics. Volt-Watt manages the active power output of the PV systems trying to maintain the voltage at the terminal of the PV system within predefined voltage limits (e.g., statutory voltage limits). It essentially limits the maximum generation capability of each individual PV system according to:

1) the voltage at the point of connection (at the terminals of the PV system); and,
2) the predefined Volt-Watt set-points (set either by the DNSP or the owner itself).

This is illustrated in Figure 3-7.

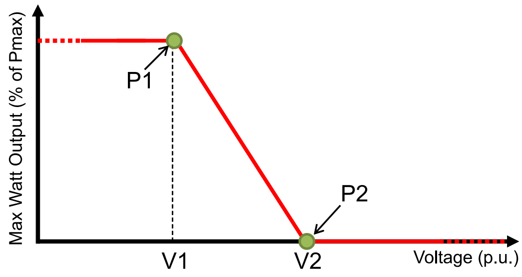


Figure 3-7 Generic Volt-Watt curve

Considering situations where high PV output and low demand might result in high feeder voltages, the Volt-Watt control function can be used to limit the maximum active power output of the PV systems and, therefore, bring voltages within the statutory limits. This control can also be beneficial in situations where existing controls (e.g., voltage control through OLTC-fitted transformer) are not able to prevent the occurrence of these high voltages. Moreover, this control function can be used to also manage thermal issues (provided that the overvoltages and the thermal overloads occur at the same time) by adopting conservative Volt-Watt settings while managing voltages.

Settings. Table 3-1 provides the Volt-Watt numerical settings specified by the new Victorian standard [2] and their visual representation is shown in Figure 3-8. As it can be seen a curtailment of the generated power is triggered once 1.1 p.u. of voltage is reached. Then the generation is linearly dropping down for higher voltages until 1.12 p.u. where the PV system generates only 20% of its rated power.

Table 3-1 Volt-Watt Settings – Numerical

Reference	Voltage (V)	Power % Rated Power
V1	207 (0.90 p.u)	100%
V2	220 (0.95 p.u)	100%
V3	253 (1.10 p.u)	100%
V4	259 (1.12 p.u)	20%

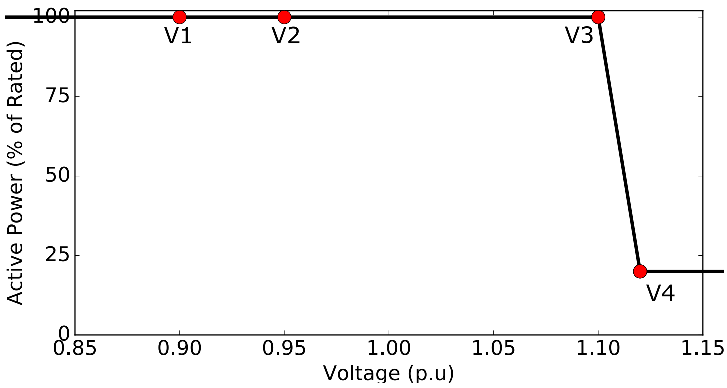


Figure 3-8 Volt-Watt Settings – Visual

3.2.4.2 Volt-var

Characteristics. The Volt-var control function, like the Volt-Watt, tries to maintain the voltage at the terminal of a PV system within predefined voltage limits (e.g., statutory voltage limits). It essentially allows each individual PV system to provide a unique var response according to:

3) the voltage at the point of connection (the terminals of the PV system);
4) the available reactive power capacity of the inverter at that point in time; and,
5) the predefined Volt-var set-points as illustrated in Figure 3-9.

Such control function can be applied in a control approach where reactive power is absorbed if the local voltage begins to exceed the pre-determined upper level (as defined by the Volt-var set-points). On the contrary, if the voltage begins to fall below the pre-determined lower level (e.g., due to the reduction in active power output) reactive power can be injected in the network to help boost the voltage back to normal levels.

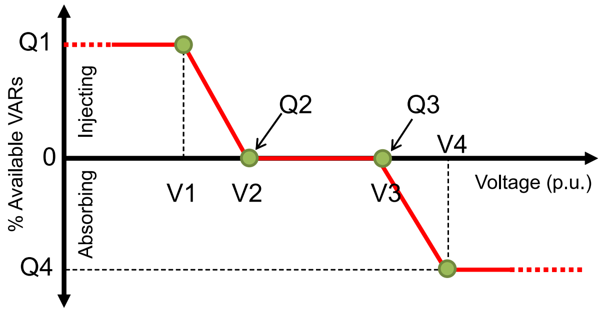


Figure 3-9 Generic Volt-var Curve

Settings. Table 3-2 provides the Volt-Watt numerical settings specified by the new Victorian standard [2] and their visual representation is shown in Figure 3-10.

Table 3-2 Volt-var Settings – Numerical

Reference	Voltage (V)	Var % Rated VA
V1	208 (0.90 p.u)	44% leading (exporting Vars)
V2	220 (0.95 p.u)	0%
V3	241 (1.04 p.u)	0%
V4	253 (1.10 p.u)	44% lagging (sinking Vars)

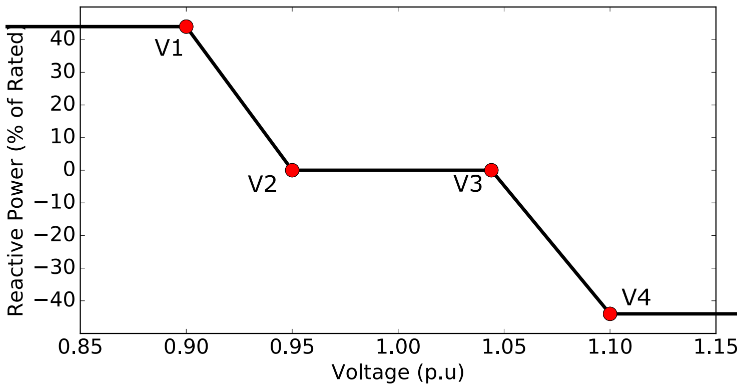


Figure 3-10 Volt-var Settings – Visual

3.2.5 Power Priority of PV Inverters

Commercially available PV inverters are commonly operating with an active power priority (i.e., Watt-priority), unless otherwise specified. Given that the primary goal of a customer, when buy and install a PV system, is to harvest the maximum possible energy (kWh) from their systems, commercially available PV inverters come with a Watt-priority as a default power priority mode. Considering the aforementioned and given the fact that the current Australian and Victorian standards do not explicitly specify the power priority mode of the PV system installations, all PV inverters modelled in the analyses operate in an active power priority (i.e., Watt-priority) mode which is detailed below. For completeness, the reactive power priority and the case with oversized inverters are also described.

Active Power Priority. When a PV inverter operates in an active power priority mode, this means that the reactive capability of the corresponding PV inverter might be limited at peak generation periods. To provide additional understanding, equation (3.1) can be considered to calculate the maximum available reactive power capability, Q_t^{max}, at each instant *t.*

$$Q_t^{max} = \sqrt{(S^{max})^2 - (P_t)^2} \tag{3.1}$$

Q_t^{max} is calculated with respect to the real power generation, P_t, and the apparent power rating of the inverter S^{max}. This is also illustrated in Figure 3-11 (a) considering a normally sized PV inverter (i.e., illustrated considering $S^{max} = 1\ p.u.$) with a power factor capability of 0.9 (leading or lagging) during a sunny day. As the figure shows, the reactive power capability of the inverter is directly influenced by the generation of the PV system (P_t). More specifically, it is observed that during periods of high generation (full irradiance, $P_t = 1\ p.u.$), the inverter is not able to absorb or inject any reactive power posing an important limitation during the periods where reactive absorption is most needed (to reduce voltages).

Reactive Power Priority. PV inverters, however, have also the capability to operate with reactive power priority. This means that the inverter will always prioritize the absorption or injection of reactive power by reducing the generation (i.e., active power). This operation can also be demonstrated in Figure 3-11 (b) which shows that during peak generation periods (i.e., midday) the active power production is reduced to increase the absorption of reactive power.

Oversized Inverter. Another option to allow PV inverters absorb or inject reactive power during peak generation periods, while not sacrificing active power (i.e., active power priority), is the adoption of oversized inverters. Considering the same example (i.e., 0.9 p.f. capability), adopting a 10% oversized inverter (e.g., $S^{max} = 1.1\ p.u.$) allows absorbing up to 0.46 p.u of reactive power (var) at peak generation (e.g., $P_t = 1\ p.u.$). The reactive capability of a 10% oversized PV inverter is demonstrated in Figure 3-11 (c). As the figure shows and compared to the case of Watt-priority inverter, during periods of high generation (full irradiance/clear sky) the inverter is still able to absorb or inject reactive power.

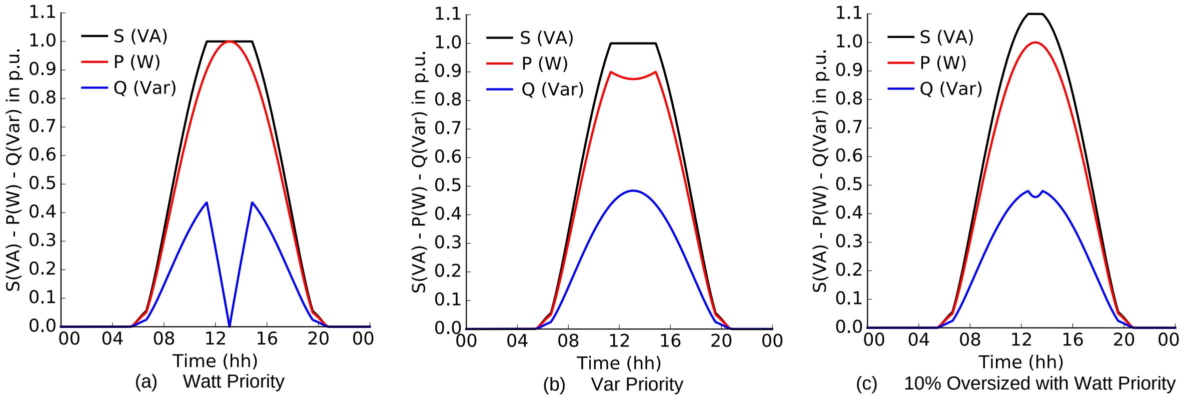


Figure 3-11 PV Inverter Power Capabilities

3.3 LV OLTC-Fitted Transformers

The modelling of the LV OLTCs in this Task considers +/- 8% with 2% per tap, i.e., 9 tap positions in total. Assuming a voltage at the primary of the HV/LV transformer is the nominal line-to-line voltage (i.e., 22,000V), the voltages at the busbar corresponding to different tap positions are shown in Table 3-3.

Table 3-3 Voltage Regulation of HV/LV OLTC-fitted transformer

Transformer Tap position	HV	LV	
	L-L (V)	L-L (V)	L-N (V)
1 (+8%)	22000	400.9	231
2 (+6%)	22000	408.5	236
3 (+4%)	22000	416.3	240
4 (+2%)	22000	424.5	245
5 (0%)	22000	433.0	250
6 (-2%)	22000	441.8	255
7 (-4%)	22000	451.0	260
8 (-6%)	22000	460.6	265
9 (-8%)	22000	470.7	271

3.4 Battery Energy Storage Systems

The solutions presented in sections 2.3 and 2.4 consider the installation of a widely popular residential-scale BES system, currently available in the market. In particular, the technical specifications of the modelled battery correspond to a single-phase 5kW/13.5kWh system with 100% depth of discharge and 88% round-trip efficiency.

3.5 Augmentation

This section provides information of the conductors and transformers used for the augmentation studies. The following data correspond to assets typically used by many DNSPs in Australia.

3.5.1 HV (22kV) Conductors

Table 3-4 Augmentation Data - HV (22kV) Conductors

Stranding/Area (mm/mm^2)	Type	Temperature (C)	Ampacity (A)
19/3.25	All Aluminium Conductor (AAC)	65	375
6/.186 7/.062	Aluminium conductor steel reinforced (ASCR)	65	285
6/1/3.0	Aluminium conductor steel reinforced (ACSR)	65	165
7/3.0	All Aluminium Conductor (AAC)	65	185

3.5.2 LV (0.4kV) Conductors

Table 3-5 Augmentation Data - LV (0.400kV) Conductors

Stranding/Area (mm/mm^2)	Type	Temperature (C)	Ampacity (A)
19/3.25	All Aluminium Conductor (AAC)	65	375
7/3.0	All Aluminium Conductor (AAC)	65	185
6/4.75 7/1.60	Aluminium conductor steel reinforced (ACSR)	65	285
185	Underground Cable (in conduit)	65	315
240	Underground Cable (in conduit)	65	360

As specified in Deliverable 1 “Modelling of selected HV feeders”, the pseudo LV networks have been modelled using a 240mm^2 underground cable for all feeders, regardless of the number of customers they supply. Therefore, given that it corresponds to the largest conductor option commonly used by DNSPs, augmentation does not bring benefits to the LV feeders.

3.5.3 LV Transformers

Table 3-6 Augmentation Data – LV Transformers

Capacity (kVA)	Voltage (kV)	Phases (#)	Taps Positions (#)
16	22/0.230	1	5
25	22/0.230	1	5
50	22/0.230	1	5
25	22/0.400	3	5
63	22/0.400	3	5
100	22/0.400	3	5
200	22/0.400	3	5
315	22/0.400	3	5
500	22/0.400	3	5

3.6 Case Studies

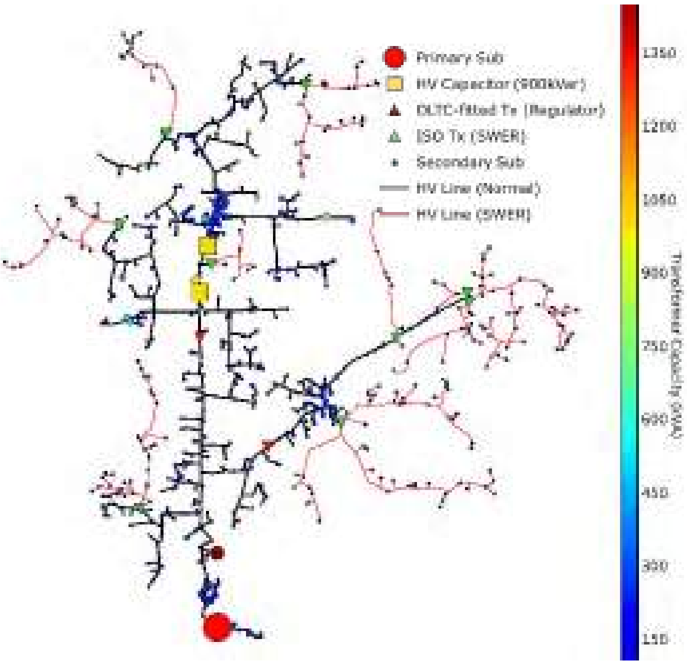
This section provides information of the case studies performed in Task 4 and presented in this report.

3.6.1 HV Feeders

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” [17]. These correspond to:

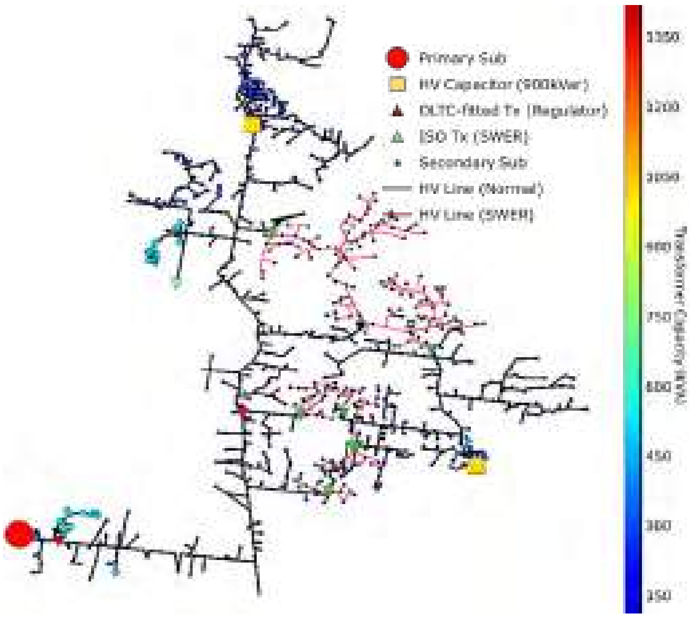
- HV Feeder R1 (long rural, SMR8), Figure 3-12
- HV Feeder R2 (short rural, KLO14), Figure 3-13
- HV Feeder U1 (urban, HPK11), Figure 3-14
- HV Feeder U2 (urban, CRE21), Figure 3-15

The topology and general characteristics of each feeder are provided in the following pages.



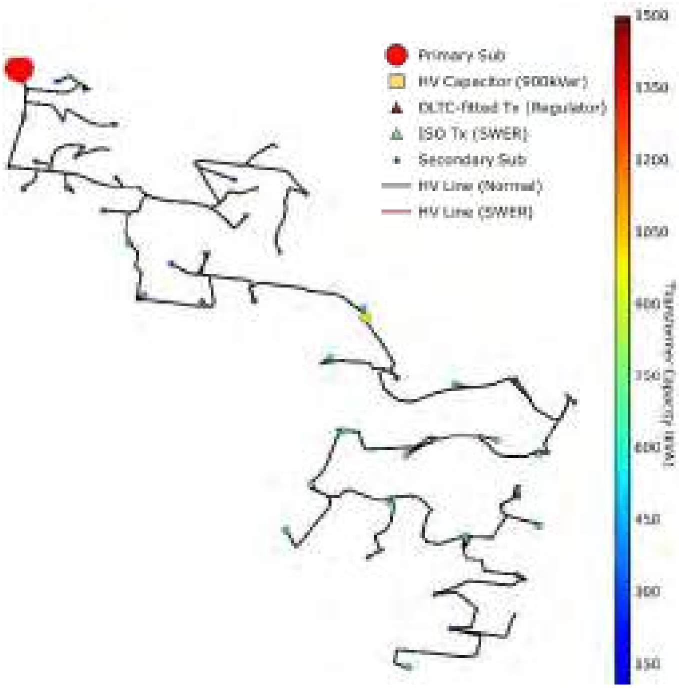
# of LV Residential Substations:	704
# of LV Residential Customers:	3608
# of LV Non-Residential Substations:	61
# of LV Non-Residential Customers:	61
Distance of Farthest Transformer (km):	52
# of HV Capacitors (900kVar each):	2
# of SWER Transformers:	10
# of REGULATOR Transformers:	2
Total HV Conductors (km):	486
Total HV SWER Conductors (km)	194

Figure 3-12 Feeder R1 (SMR8, Long Rural) – Topology and General Characteristics



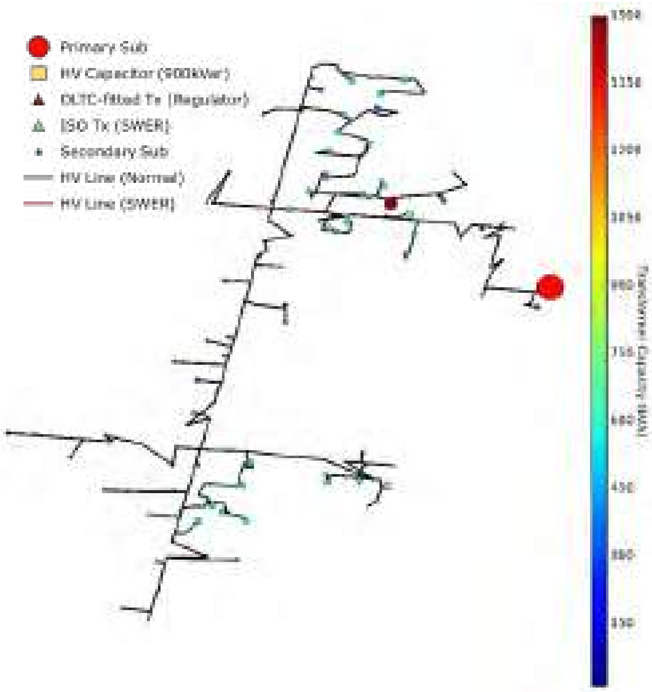
# of LV Residential Substations:	700
# of LV Residential Customers:	4691
# of LV Non-Residential Substations:	24
# of LV Non-Residential Customers:	24
Distance of Farthest Transformer (km):	36
# of HV Capacitors (900kVar each):	2
# of SWER Transformers:	7
# of REGULATOR Transformers:	2
Total HV Conductors (km):	275
Total HV SWER Conductors (km)	54

Figure 3-13 Feeder R2 (KLO14, Short Rural) – Topology and General Characteristics



# of LV Residential Substations:	44
# of LV Residential Customers:	5274
# 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 3-14 Feeder U1 (HPK11, Urban) – Topology and General Characteristics



# 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 3-15 Feeder U2 (CRE21, Urban) – Topology and General Characteristics

3.6.2 Single-Day Analysis

This analysis is performed to provide a time-series demonstration of the network performance, when adopting the non-traditional network solution described in Chapter 2, aimed at increasing the hosting capacity of PV-rich distribution networks. The analyses represent the “worst-case” scenario of peak generation combined with low demand, hence, PV generation is modelled considering clear-sky irradiance profiles (see section 3.2.1.1) and residential demand is modelled considering low demand days.

In more details, the lowest demand day (from the poll of profiles presented in section 3.1) for each season (i.e., Spring, Summer, Autumn, Winter) is selected. Then for each selected day (per season), six (6) different, progressively increasing solar PV penetration levels (i.e., 0, 20, 40, 60, 80 and 100%) are investigated. The PV irradiance profiles used for each day of the season investigated correspond to the peak clear-sky irradiance within the season examined. For each day a 24hr time-series, three-phase, power flow is performed, and results are collected and presented for each HV Feeder.

Table 3-7 provides an overview of the volume of simulations performed for this type of Analysis and for each HV Feeder in Task 4. The approximate total simulation time for the 4 HV feeders being considered for this type of analysis is 48 hours (18,432 power flow simulations).

Table 3-7 Single-Day Analysis – Volume of Simulations per HV Feeder

	Solutions (#)	Penetrations (#)	Seasons (#)	Days per Season (#)	Power Flow Simulations Per Day	Power Flow Simulations (#)
	4	6	4	1	48	4,608
Comments/ Details	(1) BAU (2) LV OLTC (3) OTS BES (4) NS BES	0% 20% 40% 60% 80% 100%	Spring Summer Autumn Winter	Load Demand Peak Irradiance	30-min resolution	Approximate total time 12 hours

In terms of results for this type of analysis, six (6) figures are presented in this report, for each HV Feeder and solution. Table 3-8 provides an overview of the information provided in each figure.

Table 3-8 Single-Day Analysis – Overview of Results

Daily Customer Voltage Profiles	Contains 24 plots for each day simulated per season (4) and penetration (6). Each plot presents the daily time-series voltage profiles of each customer in the corresponding feeder. This allows to visualize the effects of PV generation and adopted solution in terms of voltage rise/drop.
Daily HV Line Utilization Profiles	Contains 24 plots for each day simulated per season (4) and penetration (6). Each plot presents the daily time-series utilization level of all HV conductors in the corresponding feeder. This allows to visualize the effects of PV generation and adopted solution in terms of asset congestion.
Daily LV Line Utilization Profiles	Contains 24 plots for each day simulated per season (4) and penetration (6). Each plot presents the daily time-series utilization level of all LV conductors in the corresponding feeder. This allows to visualize the effects of PV generation and adopted solution in terms of asset congestion.
Daily LV Transformer Utilization Profiles	Contains 24 plots for each day simulated per season (4) and penetration (6). Each plot presents the daily time-series utilization level of all LV Transformers in the corresponding feeder. This allows to visualize the effects of PV generation and adopted solution in terms of asset congestion.
Daily PV Systems Active Power Output Profiles	Contains 24 plots for each day simulated per season (4) and penetration (6). Each plot presents the daily time-series active power output all PV Systems the corresponding feeder. This allows to visualize the effects the adopted solution in terms of customer impact (i.e., curtailment).
Daily PV Systems Reactive Power Output Profiles	Contains 24 plots for each day simulated per season (4) and penetration (6). Each plot presents the daily time-series reactive power output all PV Systems the corresponding feeder. This allows to visualize the effects the adopted solution in terms of reactive power absorption/injection.
LV OLTC Installations	Presents the total number of OLTC installed in the investigated networks for each penetration (6).
LV OLTC Transformer Capacities	Presents the capacities of the LV transformer on which the OLTCs are installed for each penetration (6).
LV OLTC Daily Tap Changes	Statistical representation (boxplot) of the daily number of tap changes of each LV OLTC-fitted transformer.
Grid Dependence Index	Statistical representation (violin plot) of the grid dependence index of each household with BES system. The violin plot allows visualising the distribution of the GDI indexes while presenting also the mean (red dot) and median (black cross) values.
Conductor and Transformer Replacement Information	Presents information of the meters of conductors and number of transformers being replaced due to augmentation, for each penetration level (6).
Transformer Replacement Capacities	Presents the capacities of the LV transformer which have been replaced due to augmentation for each penetration level.

3.6.3 Seasonal Analysis

This analysis is performed to provide a more realistic seasonal representation of the network performance when adopting the traditional network solution described in Chapter 2 (aimed at increasing the hosting capacity of PV-rich distribution networks). PV generation is modelled considering real PV irradiance profiles (see section 3.2.1.2) and residential demand is modelled considering real smart meter data (see section 3.1).

More specifically, fourteen (14) consecutive days (from the pool of profiles presented in section 3.1) for each season (i.e., Spring, Summer, Autumn, Winter) are selected. Then, considering the selected days (per season), six (6) different, progressively increasing solar PV penetration levels (i.e., 0, 20, 40, 60, 80 and 100%) are investigated. The PV irradiance profiles used for each selected day correspond to the real PV irradiance of the corresponding day. For each day a 24hr time-series, three-phase, power flow is performed, and results are collected and presented for each HV Feeder. Given that the analysis considers only fourteen (14) days per season[4], results related to the curtailment of energy are scaled

[4] The two weeks-worth (i.e., 14 days) of simulation per season was found to be the most adequate trade-off between the computational performance and realistic representation of the seasonal energy curtailment. 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.

up to represent the seasonal and yearly curtailment. To provide additional information, Table 3-9 presents the days considered for the corresponding analyses.

Table 3-9 Seasonal Analysis - Days Considered

Spring	5th October – 18th October
Summer	20th January – 2nd February
Autumn	6th April – 19th April
Winter	6 July – 19th July

Table 3-10 provides an overview of the volume of simulations performed for this type of Analysis and for each HV Feeder in Task 4. The total number of power flow simulations for the 4 HV feeders being considered for this type of analysis is 258,048 or approximately 720 hours of simulations.

Table 3-10 Seasonal Analysis – Volume of Simulations per HV Feeder

	Solutions (#)	Penetrations (#)	Seasons (#)	Days per Season (#)	Power Flow Simulations Per Day	Power Flow Simulations (#)
	4	6	4	14	48	64,512
Comments/ Details	(1) BAU (2) LV OLTC (3) OTS BES (4) NS BES	0% 20% 40% 60% 80% 100%	Spring Summer Autumn Winter	14 consecutive days in the middle of each season	30-min resolution	Approximate total time 180 hours

In terms of results for this type of analysis, eight (8) figures are presented in this report, for each HV Feeder and solution. Table 3-11 provides an overview of the information provided in each figure.

Table 3-11 Seasonal Analysis – Overview of Results

Voltage Non-Compliant Customers (%)	Statistical representation (boxplot) of the percentage of voltage non-compliant customers per season (4) and penetration (6). This allows to visualize the seasonal effects of PV generation and adopted solution in terms of voltage compliance.
Maximum LV Transformer Utlisation (%)	Statistical representation (boxplot) of the maximum utilization level of among all LV transformers per season (4) and penetration (6). This allows to visualize the seasonal effects of PV generation and adopted solution in terms of asset congestion.
Maximum HV Line Utilization (%)	Statistical representation (boxplot) of the maximum utilization level of among all HV conductors per season (4) and penetration (6). This allows to visualize the seasonal effects of PV generation and adopted solution in terms of asset congestion.
Maximum LV Line Utilization (%)	Statistical representation (boxplot) of the maximum utilization level of among all LV conductors per season (4) and penetration (6). This allows to visualize the seasonal effects of PV generation and adopted solution in terms of asset congestion.
Seasonal Curtailment of Individual Customers (kWh)	Statistical representation (boxplot) of the amount to energy curtailed per individual customer with solar PV per season (4) and penetration (6). This allows to visualize the seasonal effects of PV generation and adopted solution in terms of customer impact (i.e., curtailment).
Seasonal Curtailment of Individual Customers (%)	Statistical representation (boxplot) of the percentage of energy curtailed (relative to the total solar PV energy that could ideally harvested) per individual customer with solar PV per season (4) and penetration (6). This allows to visualize the seasonal effects of PV generation and adopted solution in terms of customer impact (i.e., curtailment).
Total Seasonal Curtailment Customers (MWh)	Bar plot representing the amount to energy curtailed considering the whole network per season (4) and penetration (6). This allows to visualize the seasonal effects of PV generation and adopted solution in terms of customer impact (i.e., curtailment).
Total Seasonal Curtailment Customers (%)	Bar plot representing the percentage to total energy curtailed (relative to the total solar PV energy that could ideally harvested) considering the whole network per season (4) and penetration (6). This allows to visualize the seasonal effects of PV generation and adopted solution in terms of customer impact (i.e., curtailment).
LV OLTC Installations	Presents the total number of OLTC installed in the investigated networks for each penetration (6).
LV OLTC Transformer Capacities	Presents the capacities of the LV transformer on which the OLTCs are installed for each penetration (6).

LV OLTC Daily Tap Changes	Statistical representation (boxplot) of the daily number of tap changes of each LV OLTC-fitted transformer.
Grid Dependence Index	Statistical representation (violin plot) of the grid dependence index of each household with BES system. The violin plot allows visualising the distribution of the GDI indexes while presenting also the mean (red dot) and median (black cross) values.
Conductor and Transformer Replacement Information	Presents information of the meters of conductors and number of transformers being replaced due to augmentation, for each penetration level (6).
Transformer Replacement Capacities	Presents the capacities of the LV transformer which have been replaced due to augmentation for each penetration level.

3.6.4 Performance metrics

To quantify the technical impacts caused by different penetrations of residential-scale PV systems, the performance metrics presented in this section are adopted for the simulation impact analyses.

3.6.4.1 Voltage Compliance

To understand the impacts of the residential-scale solar PV in terms of the voltage performance, the number of customers with voltage issues will be calculated for each a single daily simulation.

Number of non-compliant customers: This metric takes the voltage profile calculated for each customer connection point from the power flow simulation to then check if the Australian standard AS 61000.3.100 is satisfied. If the customer's voltage does not comply with the standard, then this costumer is considered to have a voltage issue. Thus, the total number of AS 61000.3.100 non-compliant customers in the network is calculated.

The AS 61000.3.100 indicates that the nominal voltage of customers in LV networks is 230 V (between phases and neutral) and under normal operating conditions, excluding situations arising from faults or voltage interruptions, should be ranging between +10%/- 6% of the nominal.

It is important to clarify that the compliance of customer connection points with the AS 61000.3.100 standard is used here for quantification purposes. Consequently, the quantification of non-compliant customers as adopted in this work is a good metric but does not necessarily mean that the corresponding customers will actually experience voltage issues.

Note: While the aforementioned national standard (AS 61000.3.100) is considered throughout this project, it should be noted that a new revised Electricity Distribution Code [18] was issued in April 2020 in Victoria, stating that the nominal voltage of customers in LV networks is 230 V (between phases and neutral) and under normal operating conditions, excluding situations arising from faults or voltage interruptions, should be ranging between +13%/- 10% of the nominal. Considering that voltage limits in Victoria are now bounded by a larger bandwidth (compared to the national standard), voltage compliance presented in this project might be overestimated.

3.6.4.2 Asset Congestion

To understand the impacts of the residential-scale solar PV in the adequacy (capacity to supply demand) of distribution networks, the utilization level of all HV conductors, LV conductors and LV transformers is calculated in each daily simulation.

Maximum utilisation level of conductors: This metric assesses the utilisation level of all conductors. This index is calculated as the maximum daily current divided by the ampacity (cable rating) of the corresponding segment of the feeder.

Maximum utilisation level of transformers: This metric assesses the utilisation level of the distribution transformer. This index is calculated as the maximum daily power divided by the transformer capacity.

The idea of these metrics is to show how the utilisation of the most important and expensive assets (i.e., feeder cables, transformers) of the network behaves with different PV penetration levels. These metrics allow visualising the assets' maximum utilisation levels and therefore identifying if they increase above their maximum specified limits (i.e., thermal limits). It is important to highlight that increasing the utilisation level of the assets above their limits might lead to the increment of their insulation temperature above their operational limit which may result in damaging or accelerating the ageing of the corresponding assets. Crucially, these metrics help understanding how the increasing penetrations of PV systems impact the utilisation level of the assets.

3.6.4.3 Solar PV Curtailment

To understand the effects and impacts of the investigated solutions on customers, the amount of solar PV curtailment, per season, is calculated for each customer. The level of curtailment is presented considering the actual energy curtailed in kWh as well as a percentage relative to the total solar PV energy that could ideally be harvested. This metric allows highlighting any customer value proposition (if applicable) when adopting solutions that might affect customers.

3.6.4.4 Number of daily OLTC tap changes

This metric is used in the case of the OLTC-fitted LV transformer solution. The total number of daily tap changes required is used as a metric to assess the performance of the proposed OLTC control logic, or any other logic, might have on the new asset. This metric is important as it allows understanding the extent to which the corresponding proposed solution is considered to be practical.

3.6.4.5 Grid Dependency Index (GDI)

This metric is used in the cases where a BES system solution is investigated and is helps quantifying the effects of any BES controller, other than the off-the-shelf controller, might have on the owner. The GDI quantifies how much of the total customer's energy consumption is provided by the grid. As shown in (3.2), the GDI is defined as the ratio of daily energy imported (E_{import}^{house}) from the grid to the house over the daily household energy consumption ($E_{consumption}^{house}$). A value of 100% indicates that all the energy consumed by the house is provided by the grid, while a value of 0% indicates that all the energy consumed is self-supplied (excess PV generation stored by the BES system). This index helps understanding the impact on the electricity bill of a household. The lower the GDI, the less dependent is the household from the grid, thus resulting in lower bills.

$$GDI = \frac{E_{import}^{house}}{E_{consumption}^{house}} \tag{3.2}$$

4 Case Study 1: HV Feeder U2 (Urban, CRE21)

4.1 Tailored Volt-Watt and Volt-Var Settings

This section presents the results obtained from the operation of the CRE21 HV feeder with Tailored Volt-Watt and Volt-Var PV inverter settings (T-VW-VV) across different penetration levels (0 to 100% in 20% steps) and for different seasons (i.e., Spring, Summer, Autumn, Winter).

4.1.1 Key Findings

A summary of the key findings is listed below.

- When Tailored PV inverter settings are adopted (compared to those imposed by the DNSPs in Victoria) and without any other solution put in place (e.g., adjustment of off-load taps) the feeder is now able to host up to 40% PV penetration (2022). At this point, the bottleneck becomes the distribution transformers which become overloaded.
- It has been observed that voltage issues are fully mitigated when compared with the BAU case. This highlights that more tailored Volt-Watt and Volt-Var settings can be an effective solution to voltage issues.
- A slight reduction of the HV lines utilisation is observed when compared to the BAU case. This is due to the higher active power curtailment from solar PV due to the more tailored and tailored Volt-Watt settings. Consequently, the HV lines operate within their thermal limits for all penetration levels.
- A slight reduction of utilisation of LV lines is noticed when compared to the BAU case. This is due to the higher active power curtailment from solar PV due to the more tailored and Tailored Volt-Watt settings.
- A reduced utilisation and number of congested LV transformers is observed when compared to the BAU case. Congestion occurs from 40% PV penetration onwards for a small number of transformers.
- The curtailment of PV generation was found to be an additional 1% for each penetration when compared to the BAU case. While the amount of curtailment is doubling, this can still be considered negligible given the significant benefits provided (i.e., full mitigation of voltage issues). For example, considering the most critical penetration (i.e., 100%) the total curtailment accounts to just 1.2% of the total solar PV generation.

Furthermore, a summary of the analysis (technical issues highlighted in red and curtailment highlighted in green) for the different penetration levels is presented in Table 4-1.

Table 4-1 HV Feeder U2 (CRE21) – T-VW-VV Key Findings

	0% (2011)	20% (2017)	40% (2022)	60% (2030)	80% (2035)	100% (2042)
Non-Compliant Customers [%]	0	0	0	0	0	0
Max Voltage [p.u]	1.082	1.095	1.098	1.099	1.099	1.099
Max HV Conductor Utilization [%]	71	64	61	60	76	100
Congested HV Conductors [km]	0	0	0	0	0	0
Max LV Conductor Utilization [%]	53	51	73	77	78	82
Congested LV Conductors [km]	0	0	0	0	0	0
Max LV TX Utilization [%]	89	98	149	149	149	212
Congested LV TXs [#,%]	[0, 0]	[0, 0]	[3, 3]	[4, 5]	[5, 6]	[14, 17]
Annual Curtailment [MWh,%]	[0, 0]	[7, 0.17]	[46, 0.52]	[98, 0.72]	[185, 1.01]	[279, 1.2]

4.1.2 Single-Day Analysis

This section presents a single-day analysis for each of the penetration levels and season for the case where more tailored Tailored Volt-Watt and Volt-Var PV inverter settings (T-VW-VV), compared to those imposed by DNSPs in Victoria (detailed in section 3.2.4), are adopted. As mentioned in Section 3.6.2, these assessments use a clear-sky day (for their corresponding season) as this is expected to result in higher technical problems for the network.

The daily assessments demonstrate the operation of the network through:

1. Customer voltages (Figure 4-1, Page 56);
2. HV line utilisation (Figure 4-2, Page 57);
3. LV line utilisation (Figure 4-3, Page 58); and,
4. LV transformer utilisation (Figure 4-4, Page 59).

Furthermore, to understand the effects of seasonality and PV penetration on the operation of PV inverters, the analysis also demonstrates:

5. the daily active power output of PV systems (Figure 4-5,Page 60); and,
6. the reactive power of PV systems (Figure 4-6, Page 61).

Starting first with the customer voltages (Figure 4-1, Page 56), it is demonstrated that regardless the penetration and season, the upper voltage limit (1.10pu) is never violated. Compared to the BAU case presented in Task 3 [1], where voltage issues occur as early as 20%, the adoption of more tailored PV inverter settings can efficiently help eliminate all voltage issues while keeping the maximum voltage in the network always below 1.10pu.

Looking at the utilisation of the HV lines (Figure 4-2, Page 57), all HV lines operate within their rated capacity for all PV penetrations and seasons. Compared to the BAU case (Task 3 [1]), a slight reduction of the utilization is observed as the adopted Tailored inverter settings result to slightly higher curtailment. At 100% PV penetration, a very small portion of lines are operating slightly 100% of their rated capacity during midday for all seasons. The HV operating within or very close to their limit for all assessed penetration levels and seasons is an effect which is primarily attributed to:

a) the 5kW export limit;
b) the existence of commercial customers in the network; and,
c) the natural voltage boost that distribution transformers offer when operated at their nominal tap position (1pu:1.085pu).

As far as b) is concerned, commercial customer profiles tent to have large consumption during working hours (9am to 5pm) which reduces reverse power flows at the head of the HV feeder as PV generation is used locally within the HV feeder. As for c) this results in higher active power curtailment from the Volt-Watt function at the PV inverters, which effectively mitigates all issues at the HV feeder level. A similar effect is also seen with the utilisation of the LV feeders (Figure 4-3, Page 58), where all LV lines operate within their rated capacity for all assessed cases.

When assessing the utilisation of LV transformers (Figure 4-4, Page 59), overloading starts appearing from penetration levels as low as 20%. Unlike the HV lines which supply both residential and commercial customers, a large number of LV networks is purely residential. Therefore, these transformers do not have adequate load to absorb the generated PV power during midday, which is mostly exported into the HV network. Furthermore, the existence of very small transformers in the network (e.g., 10kVA) exacerbates the issues shown in this analysis. Due to the random assignment of PV systems to customers, such transformers can be overloaded at very small penetration levels if the households they supply are assigned large PV systems. Finally, the absorption of reactive power from the PV inverters due to the Volt-var function increases currents which consequently increases the utilisation of the transformers. Similar to the HV utilization levels, a slightly lower utilization level is also observed to the LV Transformers when compared to the BAU case (Task 3 [1]) given the higher curtailment levels due to the Tailored PV inverter settings.

To understand how the residential PV inverters operate for the assessed PV generations and seasons, the active and reactive power of PV inverters is shown in Figure 4-5, Page 60 and Figure 4-6, Page 61, respectively. Starting with the active power, and compared to the BAU case, customers experience higher levels of curtailment at all penetrations and seasons. This is, as aforementioned, strongly correlated with the Tailored Volt-Watt settings that force PV systems curtail generation from as early as 1.09p.u (instead of 1.1p.u as defined in the Victorian DNSP settings) and limit generation to 0% at 1.10p.u (instead to 20% at 1.12p.u. as defined in the Victorian DNSP settings). While an obvious higher level of curtailment is noticed when Tailored settings are adopted, it should be noted that the single day analysis presented here considers the worst-case scenario (i.e., peak generation) which might be overestimating the curtailment level. To realistically understand the level of curtailment a seasonal analysis present in the following section needs to be considered.

Reactive power, as also observed in the BAU case (Task 3) is absorbed quite prominently for all penetration levels and seasons. Since the voltages in the LV network are “boosted” by the distribution transformer, and the Volt-var function starts absorbing reactive power from 1.04pu, all inverters in the network absorb reactive power regardless of PV penetration. The main difference between the adoption of Tailored inverter settings and the BAU is that a higher absorption is noticed at the shoulders of the peak PV generation hours (midday) due to the fact that the adopted Tailored Volt-Var settings lead to the peak absorption levels at a lower voltage level (i.e., 1.09p.u instead of 1.10p.u in BAU). Another interesting difference between lower penetrations and higher penetrations is the “dip” in reactive power being absorbed during midday at lower penetrations. This, and as explained in 3.2.5, is due to the inverter not having adequate capacity (in kVA) to fully export active power and absorb reactive power. Due to the assumed *active power priority* used in the Volt-var in this analysis, this results in PV inverters not being able to absorb reactive power. At higher penetration levels this becomes a lot less prominent. Since the Volt-Watt function curtails active power when the voltage exceeds 1.09pu (more common in higher penetrations), there is enough inverter capacity to also absorb reactive power.

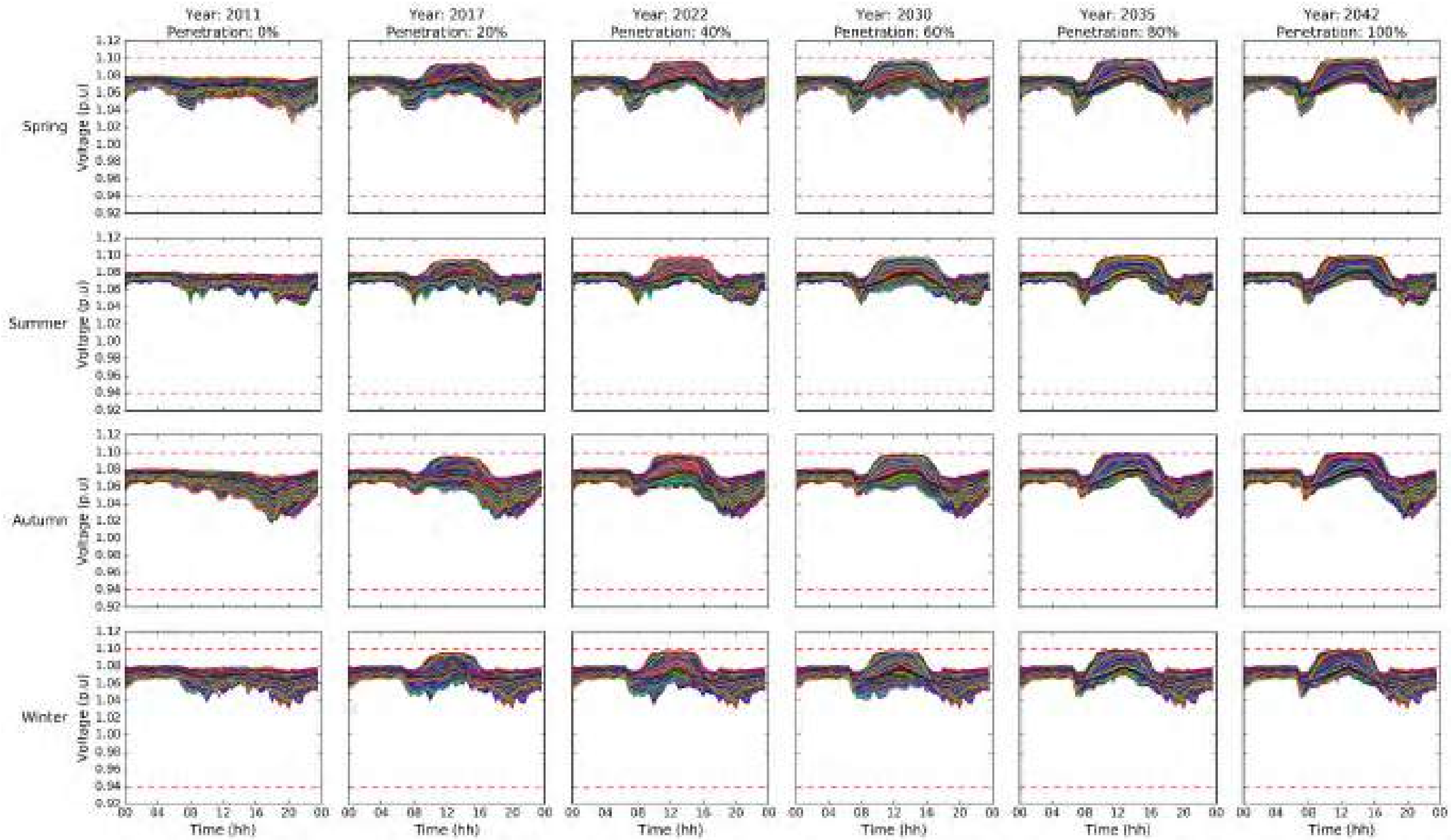


Figure 4-1 CRE21 T-VW-VV Daily Customer Voltages

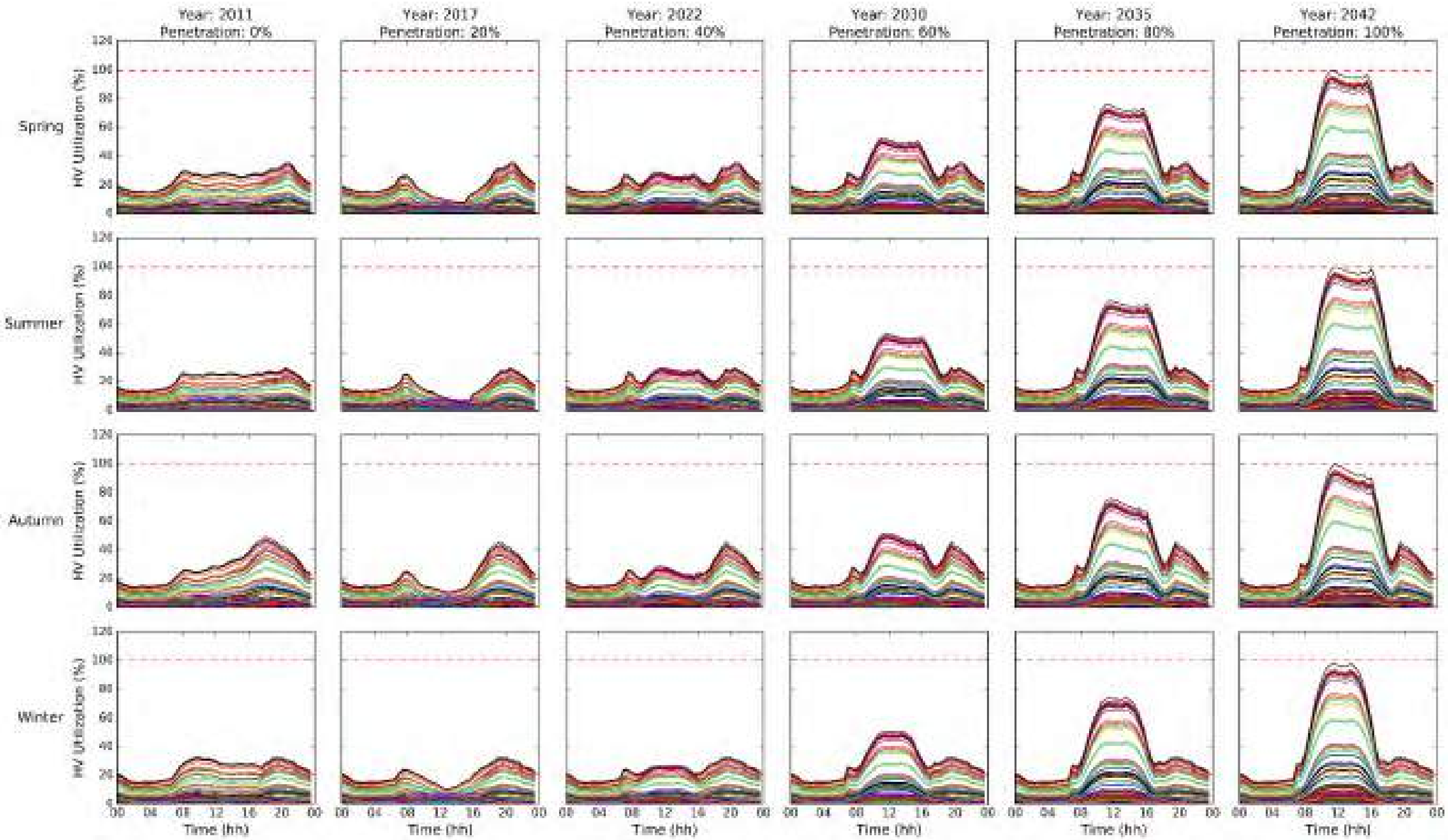


Figure 4-2 CRE21 T-VW-VV Daily HV Line Utilisation

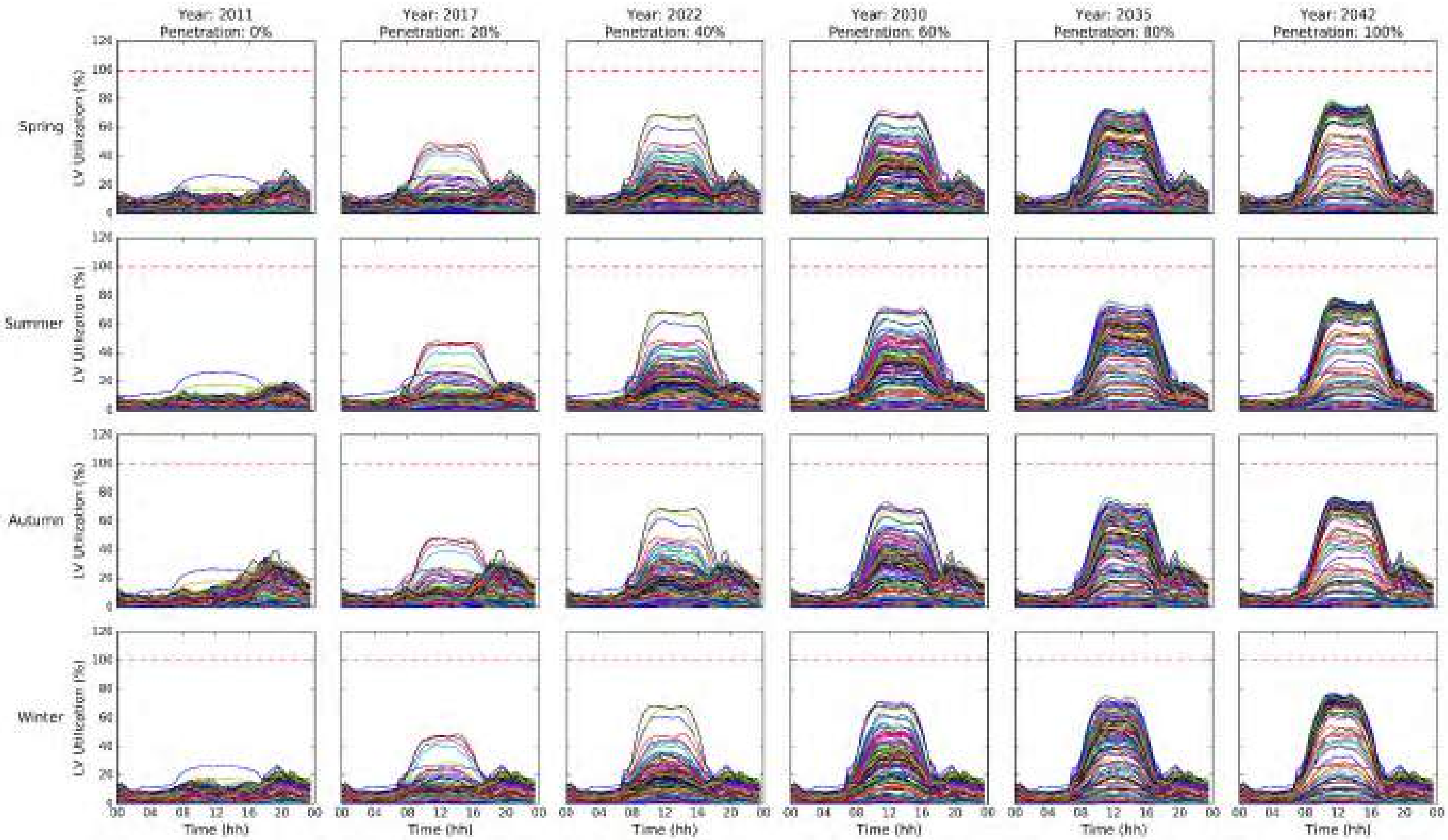


Figure 4-3 CRE21 T-VW-VV Daily LV Line Utilisation

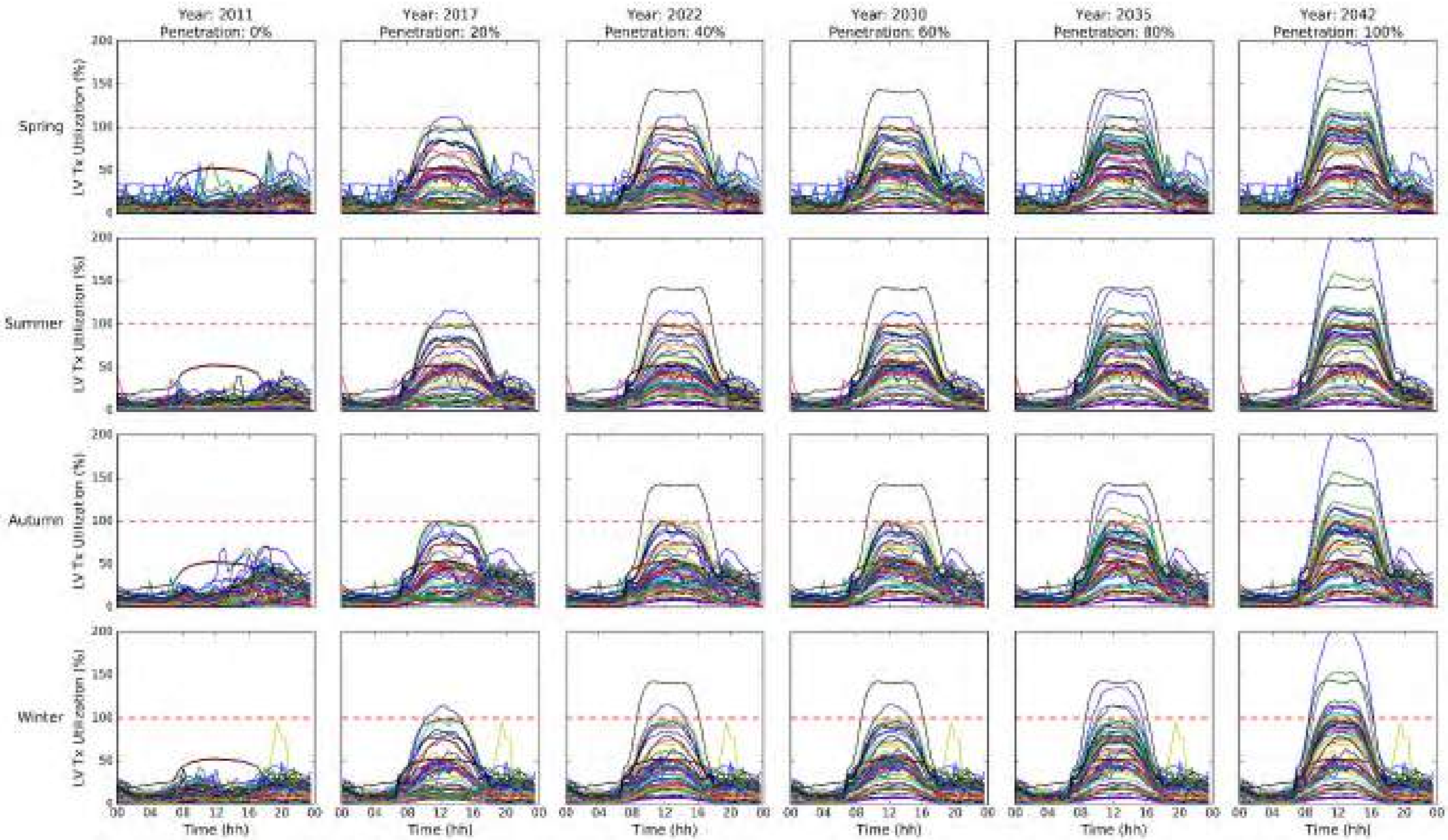


Figure 4-4 CRE21 T-VW-VV Daily LV Transformer Utilisation

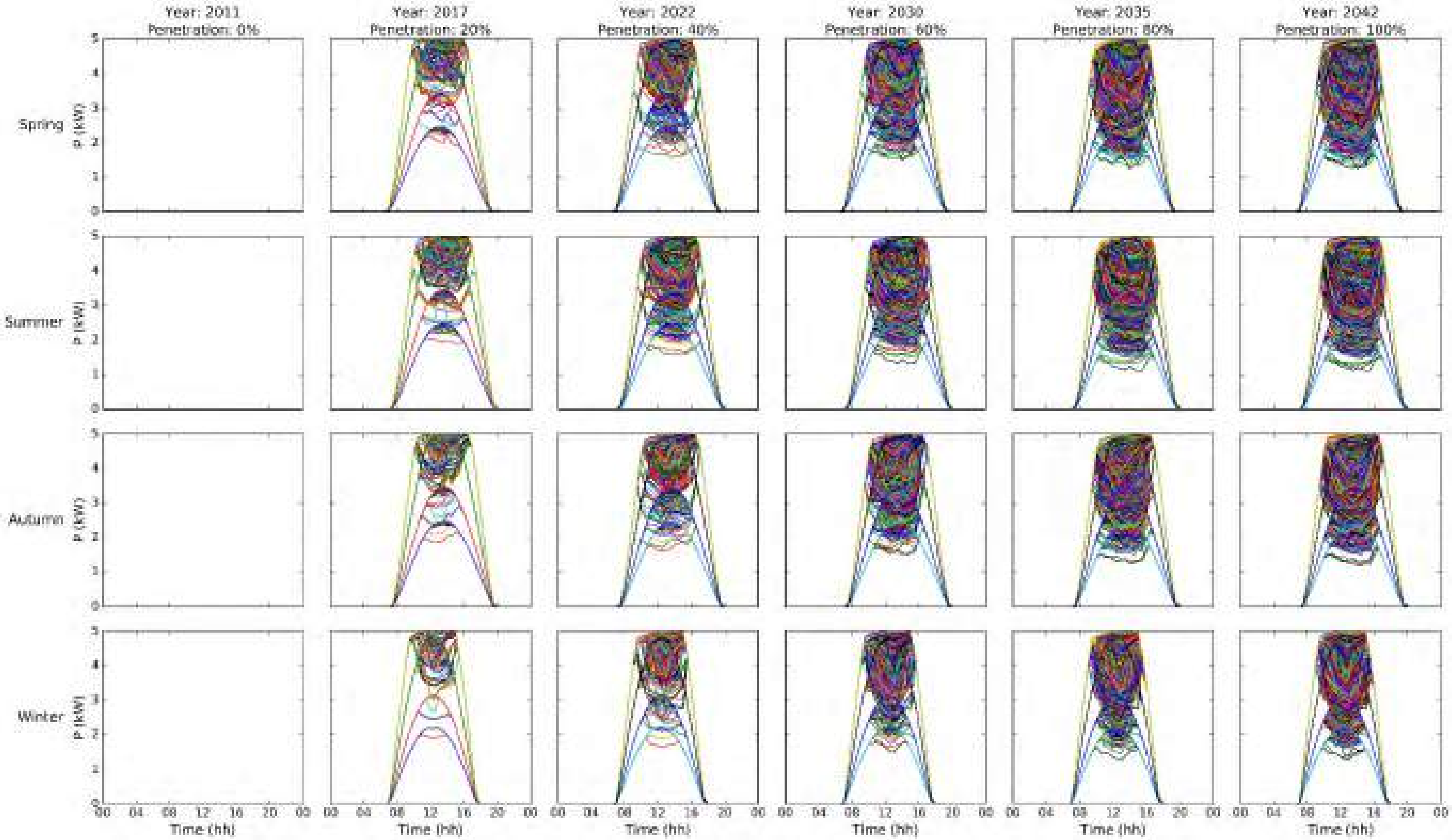


Figure 4-5 CRE21 T-VW-VV Daily PV System Active Power Output

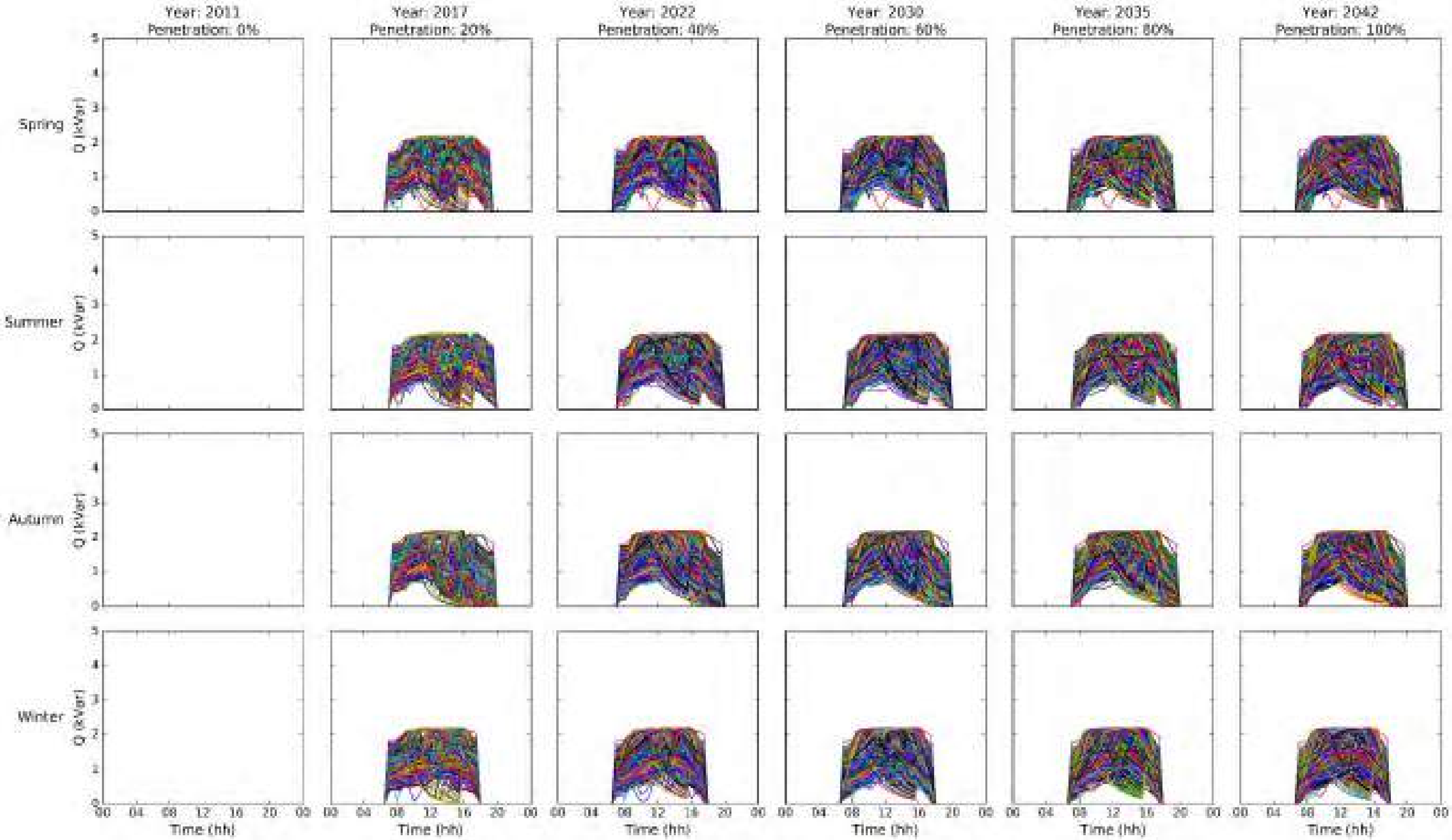


Figure 4-6 CRE21 T-VW-VV Daily PV System Reactive Power Absorption

4.1.3 Seasonal Analysis

The results for the seasonal analysis for the T-VW-VV case are demonstrated in this section. Starting with Figure 4-7, the two most constraining factors in this network (as defined by the BAU case), customer voltages and transformer utilisation, are shown. Aligned with the results demonstrated in the single-day analysis, it can be seen that the voltage problems are fully mitigated for all penetration levels, showing a significant benefit offered when adopting more tailored PV inverter settings as opposed to the BAU case, where the percentage of non-compliant customers in the worst case scenario (i.e., 100% penetration during Summer) was found to go up to 37%.

The utilization of LV transformers, on the other hand, was found to have almost the same performance with the BAU case where congestions occur at a much lower penetration level. At 40% PV penetration, 3 out of 79 LV transformers (i.e., ~3%) become congested due to PV generation. This number increases further as PV penetration increases, with 14 transformers (i.e., ~17%) become overloaded at 100% PV penetration.

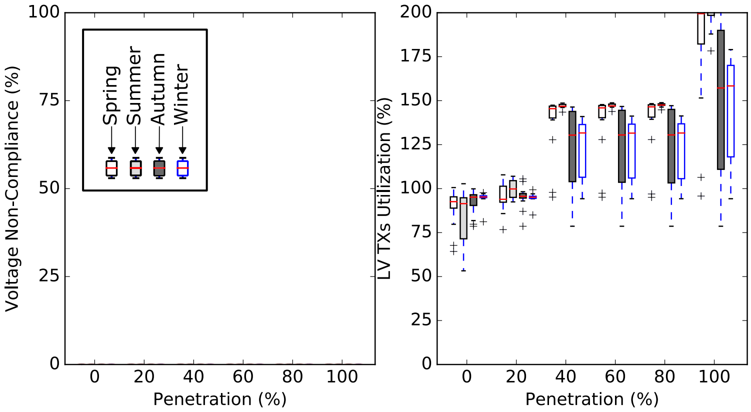


Figure 4-7 CRE21 T-VW-VV Percentage of Voltage Non-Compliant Customers (left) and Maximum LV Transformer Utlisation (right)

Figure 4-8 is used to demonstrate and reinforce the findings that all HV and LV lines operate within their limits across all penetration levels and seasons. More specifically, LV lines appear to have significant headroom to operate within, as the most congested line across all simulations operates at a maximum of 85% of its rated capacity. A small portion of HV lines, on the other hand, operate very close to their thermal limit; 98% utilisation at 100% PV penetration. While a slight reduction is observed when compared to the BAU case, the reduction level can be negligible, hence, almost the same performance is observed.

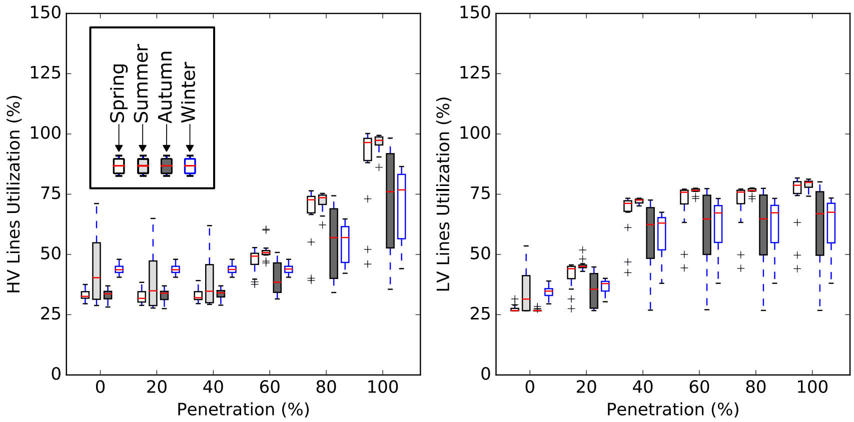


Figure 4-8 CRE21 T-VW-VV HV and LV Lines Utilisation

To understand how the penetration level and seasonality affects the curtailment of PV generation, Figure 4-9 presents the PV curtailment information obtained from the corresponding analyses. Starting with the seasonal curtailment for individual customers, as PV penetration increases, the majority of customers experience no curtailment (median = 0) at all penetration levels. A small number of customers (assumed to be located in weak parts of the network), experience up to 12% energy curtailment across the different seasons at 20% penetration. This value increases up to 40% when 100% penetration is explored (summer only). When the total curtailment is explored (in MWh), as PV penetration increases there is an upwards trend in curtailment. When the total curtailment is explored as a percentage of the total energy generation, however, the total curtailment, in fact, does not increase significantly. When compared to the BAU case, the curtailment of PV generation was found to be an additional 1% for each penetration when compared to the BAU case. However, while the amount of curtailment is doubling, this can still be considered negligible given the significant benefits provided (i.e., full mitigation of voltage issues). For example, considering the most critical penetration (i.e., 100%) the total curtailment accounts to just 1.2% of the total solar PV generation.

The reasoning behind these interesting trends is also associated with the adoption of Tailored Volt-var PV inverter settings that require absorbing reactive power at even lower voltage levels. As such, as the penetration increases, the voltages are managed better due to the increased number of PV inverters absorbing reactive power, and thus, less curtailment is needed per customer on average (customers in weak areas are penalised more).

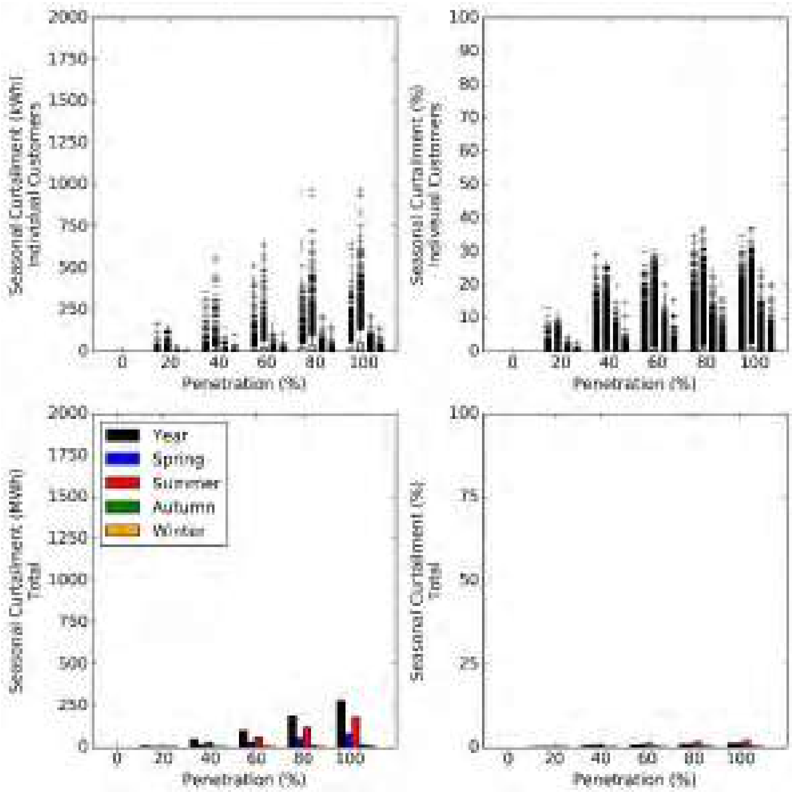


Figure 4-9 CRE21 T-VW-VV PV Generation Curtailment Information

4.2 LV OLTC-fitted Transformers

This section presents the results obtained from the operation of the CRE21 HV feeder considering the solution of replacing off-load tap changer-fitted LV transformers with OLTC-fitted LV transformers according to the methodology specified in section 2.2.5. In the case of an OLTC-fitted LV transformer being installed the corresponding control logic detailed in section 2.2.4 is adopted and the analysis results are collected across different penetration levels for different seasons. The presentation of results follows a similar format as presented in the previous section.

It should be noted, and as stated in section 2.2.5, that this solution (installation of LV OLTC -fitted transformers) is only considered once the off-load capability of a LV transformers is fully utilised and available taps to reduce/increase are exhausted. This allows to utilise – to the extend is possible – any flexibility provided by existing assets (i.e., off-load tap changers), hence reduce the overall investment in new assets (i.e., OLTC). Considering the congestion issues, given that the investigated solution does not manage any power flows, augmentation is considered for congested assets (i.e., conductors, transformers).

4.2.1 Key Findings

A summary of the key findings is listed below.

- The adoption of this solution (i.e., off-load taps, OLTC, augmentation) can effectively manage all technical issues and shift the Hosting capacity to 100% (compared to 40% when off-load taps are considered alone, see Task 3 section 5.2 [1]).
- For those LV transformers where their off-load tap capability was not able to mitigate the voltage rise/drop issues, their replacement with an OLTC-fitted LV transformer and adopting the proposed OLTC control logic proves to be highly effective in keeping all customer voltages within the statutory voltage limits, regardless the penetration and season.
    - The total number of OLTC-fitted transformers installed for this Feeder accounts to 35% of the total LV transformers (25 out of 71). While the 35% of total LV transformers were installed an OLTC, most installations (>26%) happened after 60% of penetration.
    - The capacities of the OLTCs correspond to relatively high rating transformers (>400kVA).
    - The average daily number of tap changes was found to around 3 while the maximum number of taps never exceeded 19. These low number of tap changes can lead to a reduced wear and tear of the OLTC hence requiring less maintenance costs.
- No augmentations on the LV and HV conductors were needed regardless the penetration levels. This was aligned with the findings in Task 3.
- Augmentation of transformers was required, and it was found to be very effective for the congested LV networks as it allows host more solar PV penetration. Small number of LV transformers (up to 2) is required to be augmented at penetration levels of up to 80%. Significant increase in transformers that need to be replaced (10) was found at 100% PV penetration.
- Augmentation results, and as expected, were found to be almost the same as those presented in Task 3.
- The curtailment of PV generation was found to be almost negligible when compared to the BAU case shown in Task 3. In particular, the level of curtailment was almost the same as when the adjustment of off-load taps alone is considered (see Task 3 section 5.2 [1]). Considering the most critical penetration (i.e., 100%) the total curtailment accounts to just 0.02% of the total solar PV generation. In other words, the adoption of this solution provides significant benefits to both customers (i.e., minimal curtailment) and network (i.e., voltage and congestion issues).

A summary of the technical issues (highlighted red), curtailment (highlighted green), and augmentation (highlighted blue) for the different penetration levels is presented in Table 4-2.

Table 4-2 HV Feeder U2 (CRE21) – LV OLTC Key Findings

	0% (2011)	20% (2017)	40% (2022)	60% (2030)	80% (2035)	100% (2042)
Non-Compliant Customers [%]	0	0	0	0	0	0
Max Voltage [p.u]	1.052	1.068	1.078	1.082	1.086	1.096
Max HV Conductor Utilization [%]	71	64	61	59	72	95
Congested HV Conductors [km]	0	0	0	0	0	0
Max LV Conductor Utilization [%]	57	54	80	83	83	90
Congested LV Conductors [km]	0	0	0	0	0	0
Max LV TX Utilization [%]	89	98	100	98	99	100
Congested LV TXs [#,%]	[0, 0]	[0, 0]	[0, 0]	[0, 0]	[0, 0]	[0, 0]
Annual Curtailment [MWh,%]	[0, 0]	[0, 0.02]	[1, 0.01]	[1, 0.01]	[3, 0.02]	[4, 0.02]
HV Conductors Replaced [km]	0	0	0	0	0	0
LV Conductors Replaced [km]	0	0	0	0	0	0
LV TXs Replaced [#,%]	[0, 0]	[0, 0]	[2, 2]	[0, 0]	[2, 2]	[10, 12]
LV TXs Replaced per Capacity**	[0, 0, 0, 0, 0, 0, 0, 0]	[0, 0, 0, 0, 0, 0, 0, 0]	[0, 0, 1, 1, 0, 0, 0, 0]	[0, 0, 0, 0, 0, 0, 0, 0]	[0, 0, 0, 0, 0, 0, 2, 0]	[0, 0, 0, 0, 0, 0, 0, 10]
LV OLTC Installed [#,%]	[0, 0]	[7, 9]	[0, 0]	[3, 4]	[5, 6]	[10, 13]
LV OLTC Installed per Capacity**	[0, 0, 0, 0, 0, 0, 0, 0]	[1, 0, 0, 0, 0, 0, 5, 1]	[0, 0, 0, 0, 0, 0, 0, 0]	[0, 0, 0, 0, 1, 0, 2, 0]	[0, 0, 0, 0, 0, 0, 5, 0]	[0, 0, 0, 1, 2, 0, 5, 2]
LV OLTC Mean/Max Daily Taps [#,#]	[0, 0]	[1, 19]	[2, 19]	[2, 19]	[3, 19]	[2, 19]

***The transformer kVA capacities correspond to: [>=10, 10-50, 50-100,100-200, 200-300, 300-400, 400-500, 500-700]*

4.2.2 Single Day Analysis

This section presents a single-day analysis for each of the penetration levels and season for the LV OLTC case. As defined previously, these assessments use a clear-sky day (for their corresponding season) as this is expected to result in higher technical problems for the network. It should be noted that all simulation parameters (customer P, Q, phase connections, PV system sizes, etc.) remain the same as the BAU case (Task 3).

Starting first with the customer voltages, shown in Figure 4-10 Page 67, it is demonstrated that adjusting the off-load tap changers as well as considering OLTC LV transformers can effectively keep customer voltages within the statutory limits regardless the penetration and season. Compared to the to the BAU case, the “flattening” of voltages does not appear anymore as this solution keeps voltage below 1.10 p.u., hence generation is not curtailed (Volt-Watt is not triggered). It is also important to note that the adoption of LV OLTC-fitted transformers, is not only helping to manage voltage rise issues but also voltage drop. This is an effect of the proposed OLTC control logic that tries to bring both maximum and minimum voltages close to the middle of the voltage limits. In more details, considering the 60% penetration onwards, it is observed that during the period where voltages rise (around 8am), the tap position of the OLTC reduces bring the monitored (max and min across customers) voltages closer to the middle of the statutory limits (i.e., 1.02 p.u). Similarly, when the PV generation starts to reduce, and hence the voltages (around 5pm), the OLTC control logic is increasing the voltage target so that the remote end voltage will be will not violate the lower limits. Indeed as observed in Figure 4-10 Page 67 (60% penetration onwards), the tap position starts to reduce from around 5pm in order to increase the voltages.

Figure 4-16, Page 73, Figure 4-17, Page 73 provide a detailed information of the number of OLTC installations required and the corresponding OLTC transformer capacities, respectively. Considering this analysis (single-day),7 OLTC installations were required at 60% penetration and additional 14 and

9 OLTCs were installed at 80 and 100% penetrations. As shown in Figure 4-17, Page 73, the majority of transformers which required an OLTC installation had a rated capacity larger than 300kVA. These figures provide an important information that will allow accurately calculate the amount of investment required when adopting such solution.

In terms of the OLTC control actions, Figure 4-18, Page 73, presents a statistical representation of the daily number of tap changes triggered from each LV OLTC-fitted transformer. As it can be seen the median of daily tap changes was found to always be below 5, highlighting the effectiveness of the proposed OLTC control logic to keep a low number of tap changes; an important factor to the wear and tear of the OLTC.

As seen in Figure 4-11, Page 68, similar with the BAU case, the HV lines utilisation remains within limits at any penetration level. In fact, the utilisation of the HV lines is slightly reduced in the LV OLTC case. Since most customers in the network have lower voltages at the connection point (due to the adjusted off-load tap positions and OLTC actions), the PV inverters absorb less reactive power which results in a slightly smaller utilisation of the HV lines. A similar behaviour is also demonstrated with the LV line utilisation, shown in Figure 4-12, Page 69.

In terms of the LV transformers utilization levels, shown in Figure 4-13, Page 70 all of them operate within their rated capacities without facing congestion issues. These results, as opposed to the BAU case where LV transformers start facing congestion issues from as early as 20% of penetration are due augmentation performed. With augmentation, the LV transformers are upgraded to increase their capacity and therefore increase the hosting capacity of the network. As it can be seen in Figure 4-13, Page 70, all LV transformers are now operating within their rated capacity for all penetration levels. The number of LV transformers replaced and corresponding capacities for each PV penetration can be seen in Figure 4-16, Page 73 and Figure 4-17, Page 73, respectively. It should be noted that once a transformer has been upgraded, the new capacity is used in the next penetration level assessment.

Another interesting change in the behaviour of PV inverters in the LV OLTC case is in the behaviour of reactive power. As it can be seen in Figure 4-15, Page 72, there are a few key differences when compared with the BAU case, with all of them related to lower penetration levels (up to 60%):

a) There is significantly less reactive power being absorbed by PV inverters; and,
b) Reactive power absorption is reduced dramatically during midday.

Regarding a), this is attributed to the significantly reduced voltages in the network due to the change in the tap position of the off-load tap changers and OLTCs which require PV inverters to absorb less reactive power. Regarding b), this is attributed to the inadequate capacity (in kVA) of PV inverters to both export maximum active power (since it is midday) and also absorb reactive power. As the PV penetration further increases, and PV generation is curtailed (due to the Volt-Watt function) there is adequate capacity in the PV inverters to both inject active power and absorb reactive power.

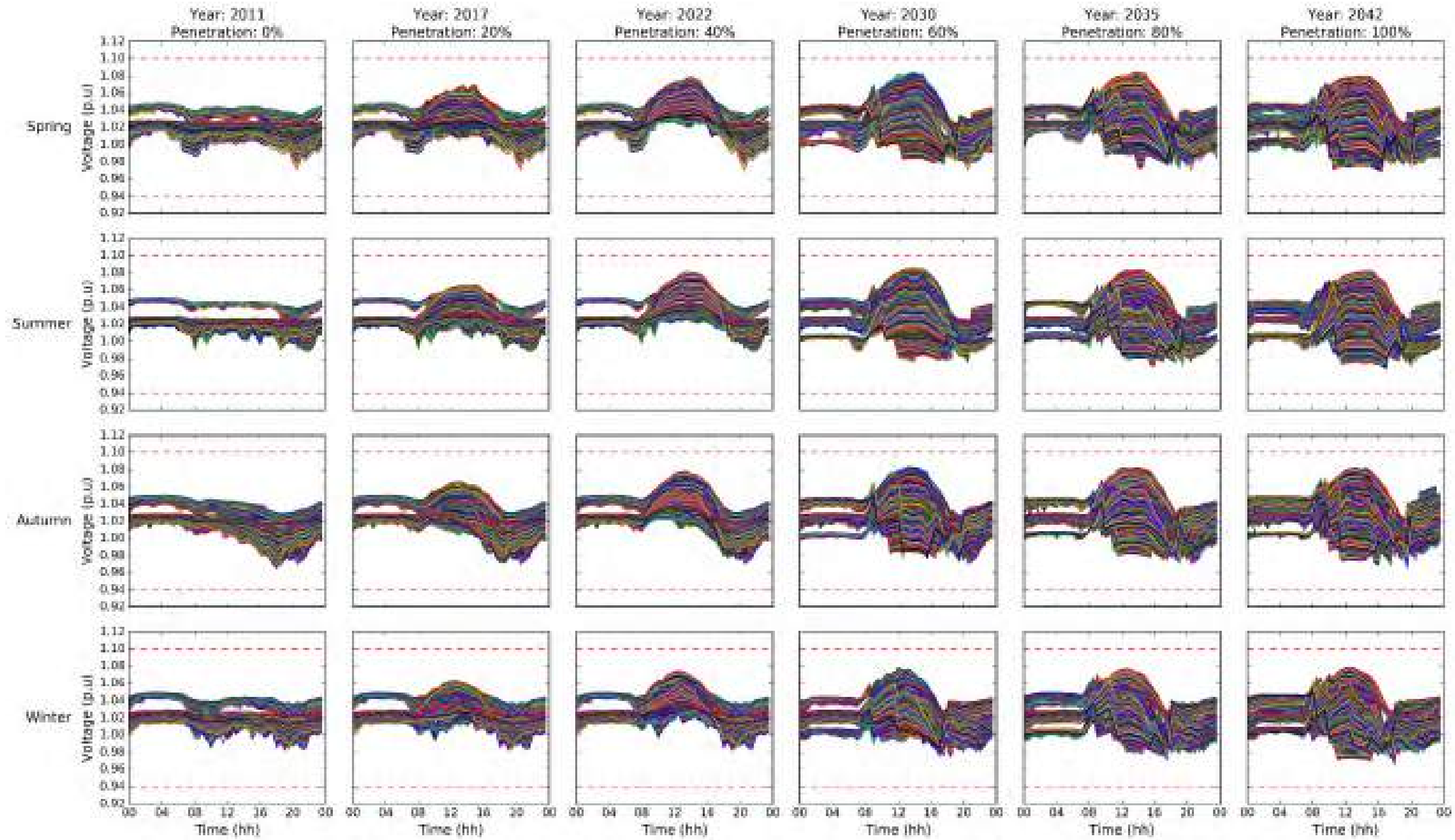


Figure 4-10 CRE21-LV-OLTC Daily Customer Voltages

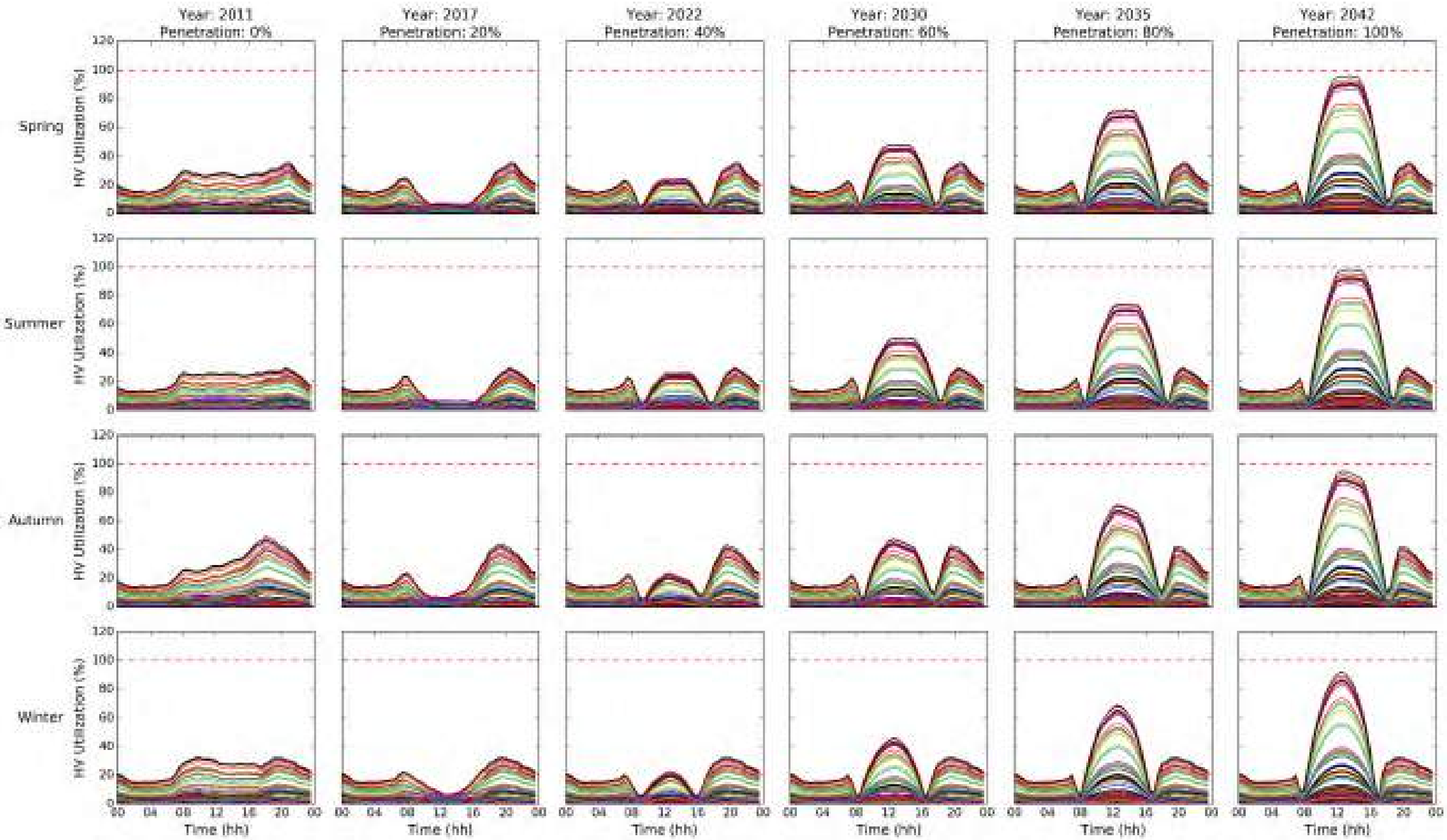


Figure 4-11 CRE21 LV-OLTC Daily HV Line Utilisation

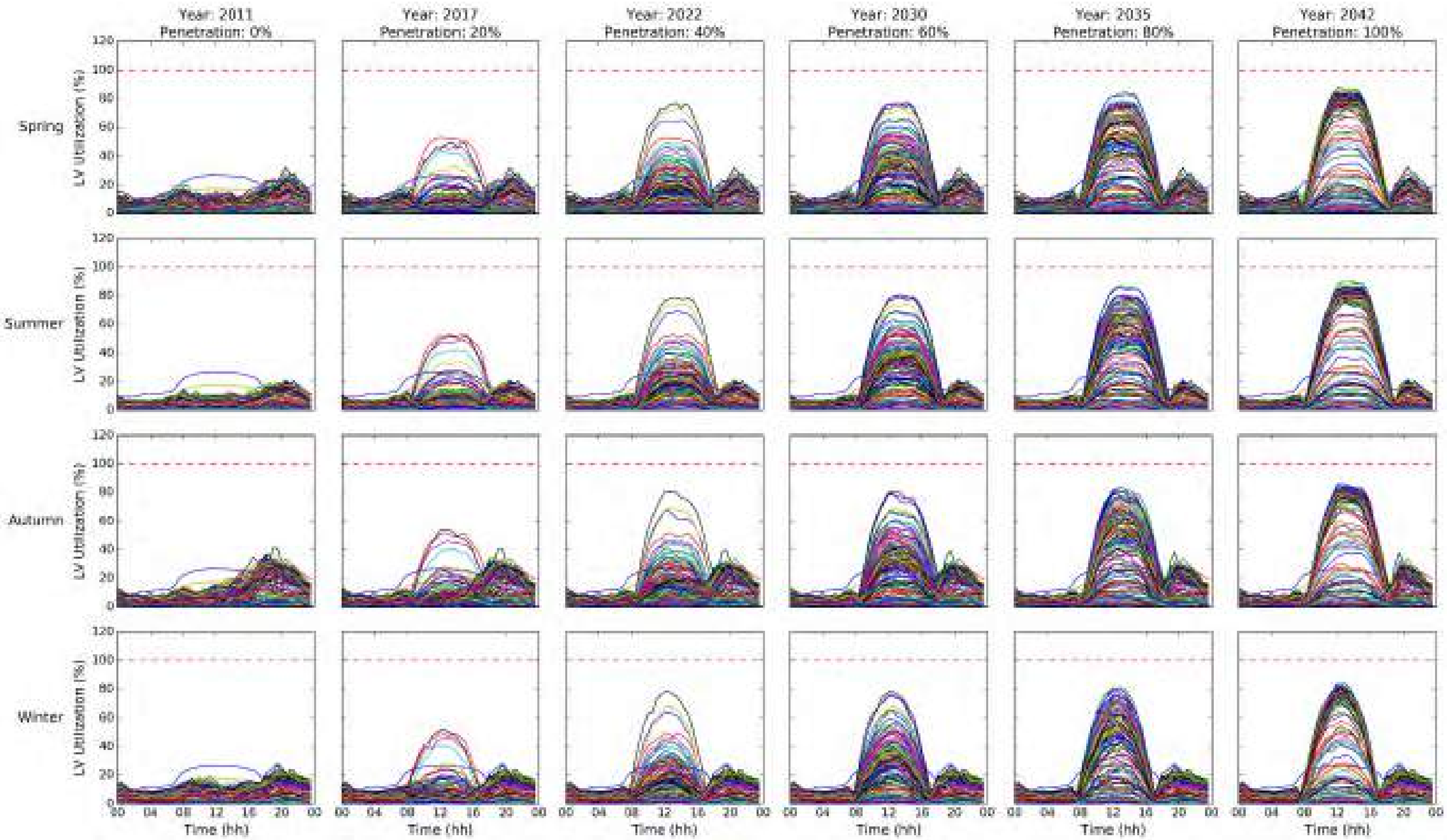


Figure 4-12 CRE21 LV-OLTC Daily LV Line Utilisation

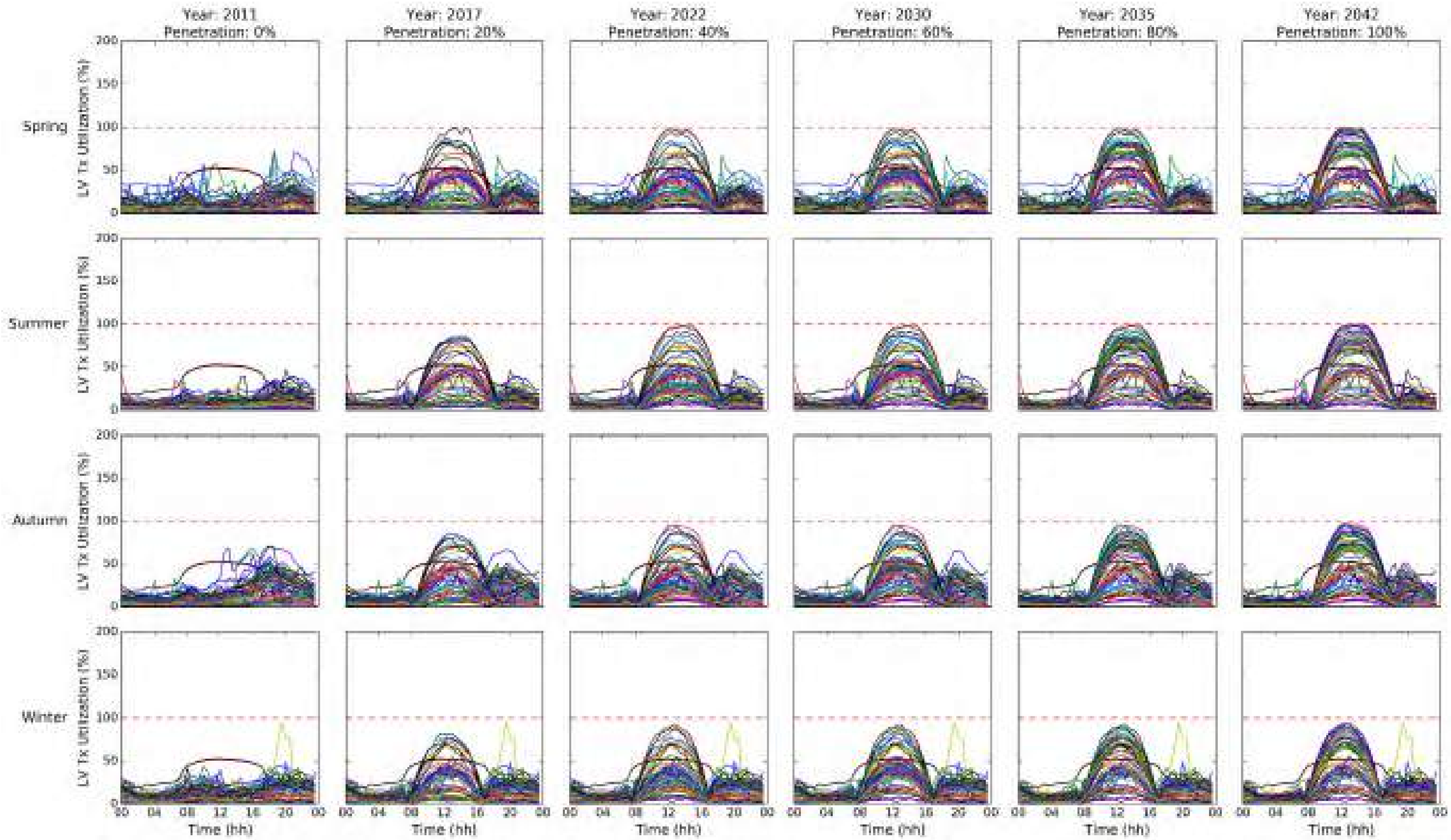


Figure 4-13 CRE21 LV-OLTC Daily LV Transformer Utilisation

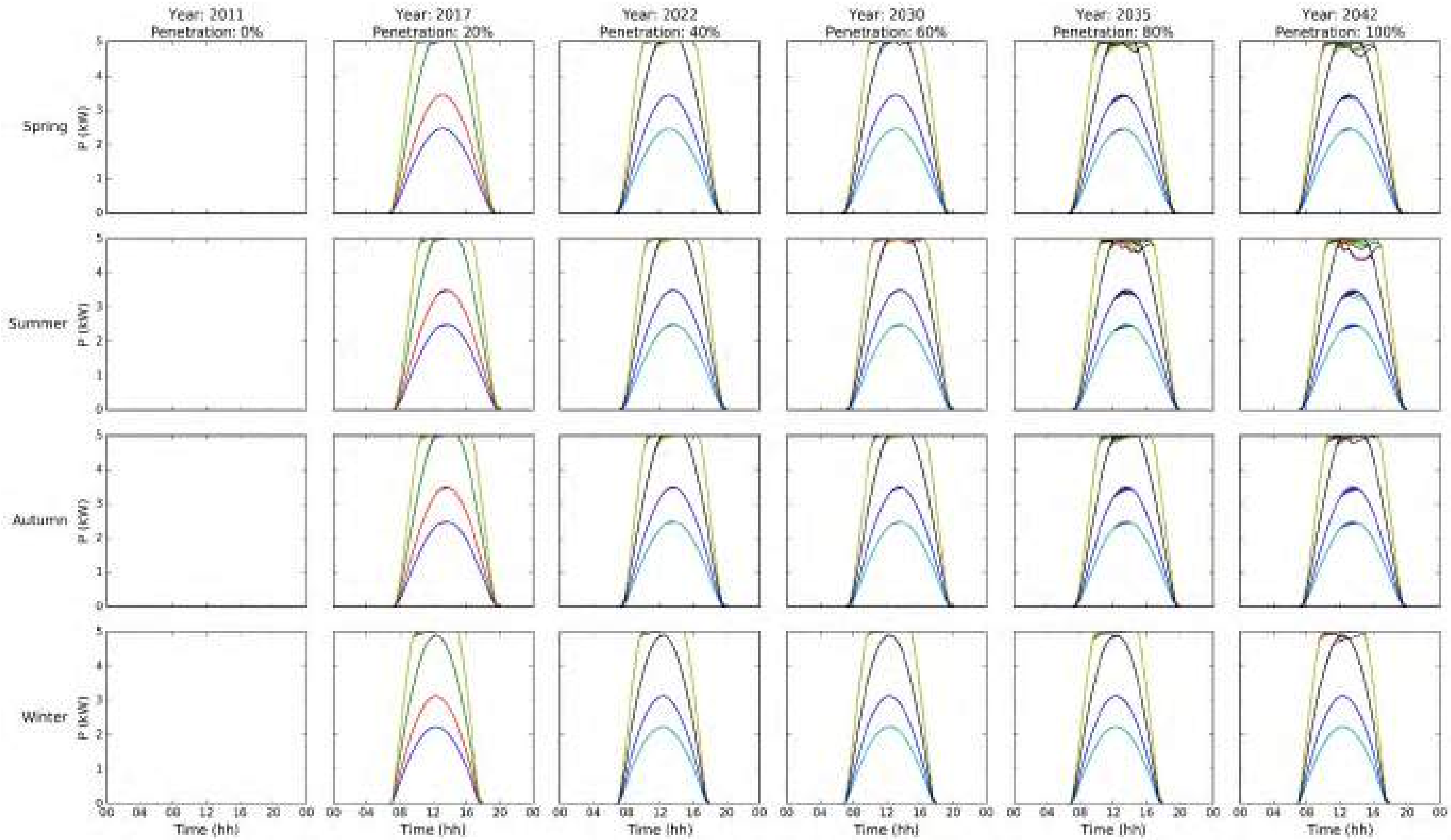


Figure 4-14 CRE21 LV-OLTC Daily PV System Active Power Output

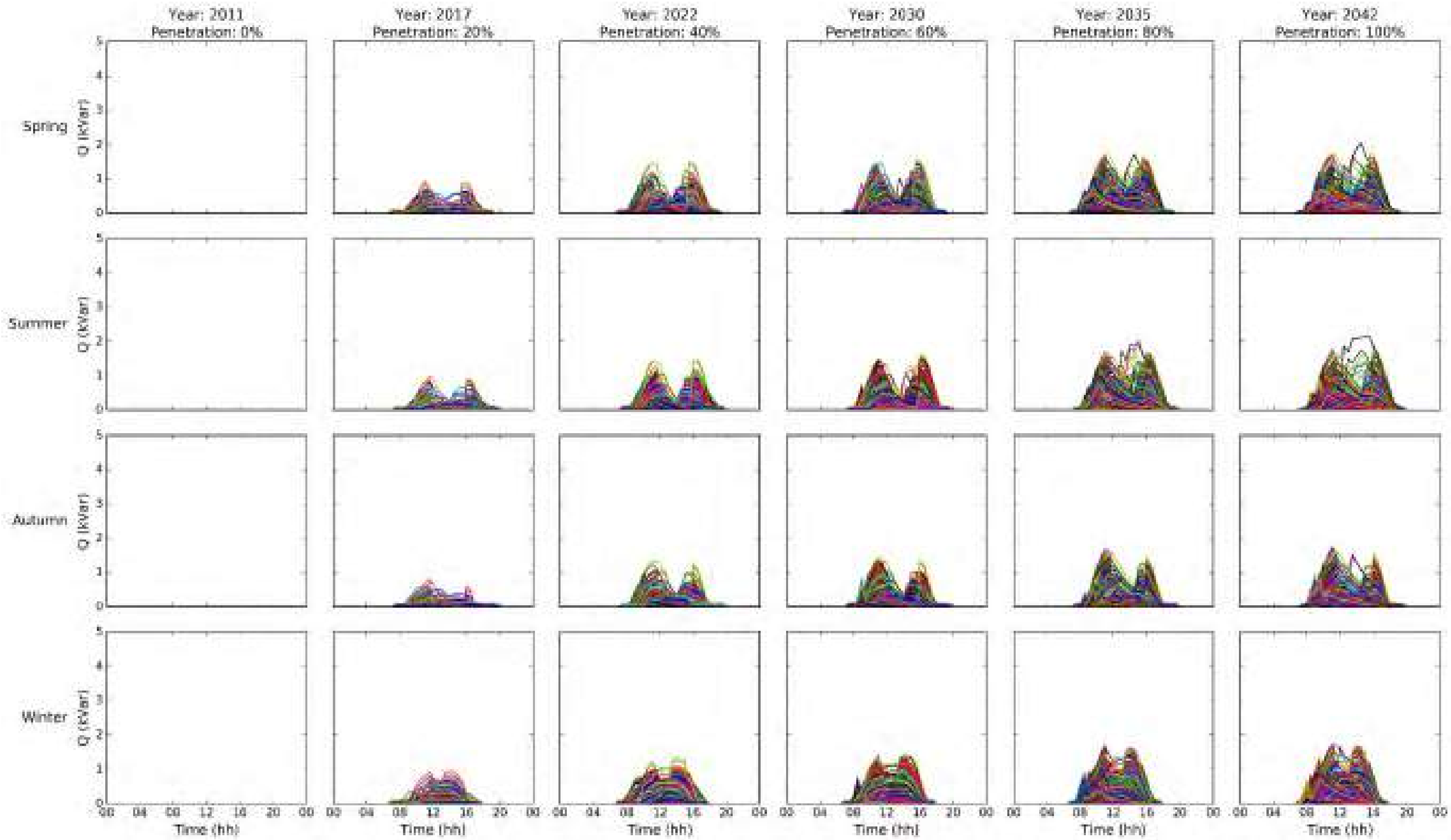


Figure 4-15 CRE21 LV-OLTC Daily PV System Reactive Power Absorption

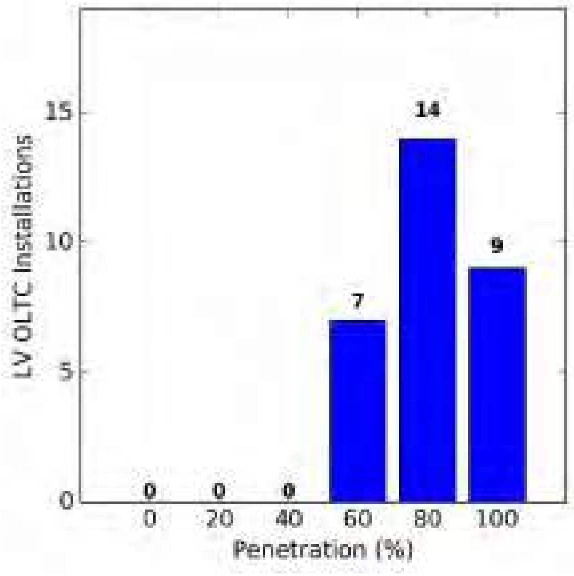


Figure 4-16 CRE21 LV-OLTC Installations

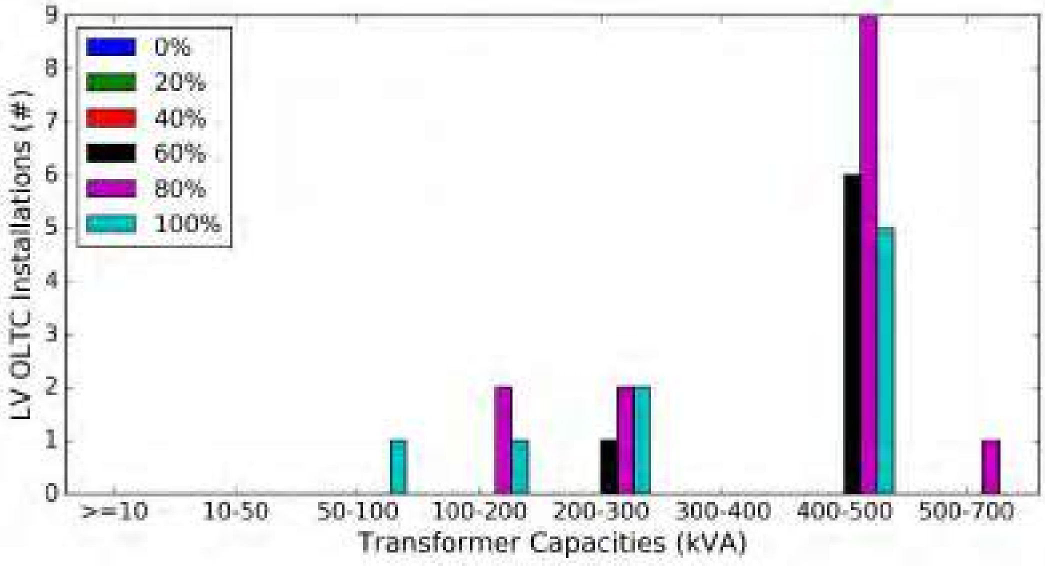


Figure 4-17 CRE21 LV-OLTC TX Capacities

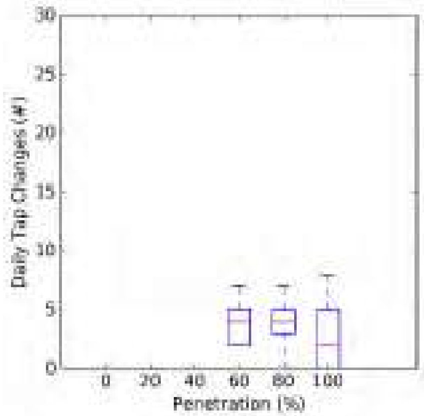


Figure 4-18 CRE21 LV-OLTC Daily Tap Changes

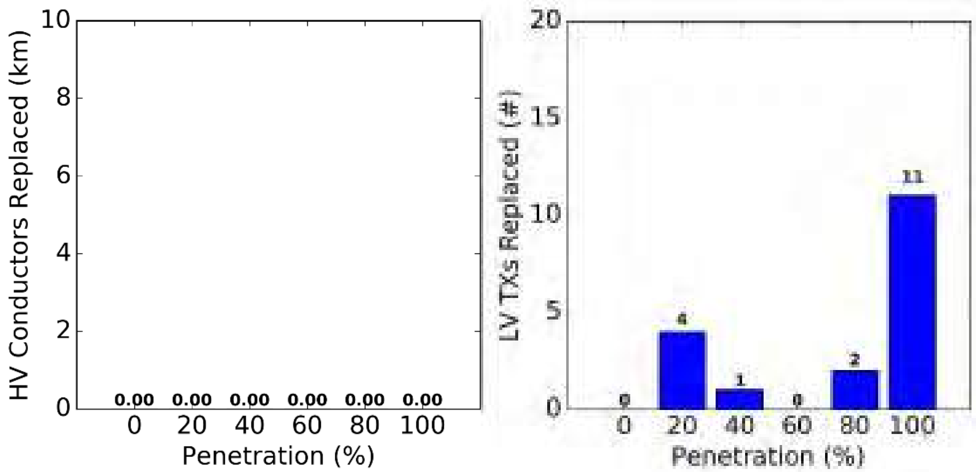


Figure 4-19 CRE21 LV-OLTC LV-OLTC Conductor and Transformer Replacement Information

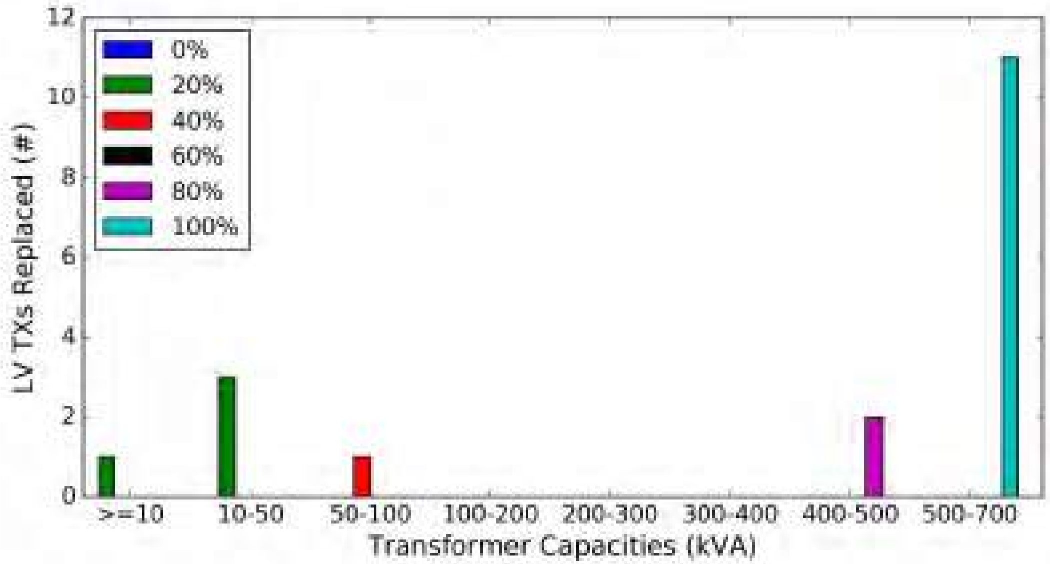


Figure 4-20 CRE21 LV-OLTC LV-OLTC Transformer Replacement Capacities

4.2.3 Seasonal Analysis

The results for the seasonal analysis for the LV OLTC case are demonstrated in this section. Starting with Figure 4-21, the two most constraining factors in this network (as defined by the BAU case), customer voltages and transformer utilisation, are shown. Aligned with the results demonstrated in the single-day analysis, it can be seen that the voltage problems are fully mitigated for all penetration levels, showing a significant benefit offered when combining the adjustment of off-load-tap changers along with the installation (where required) of OLTC-fitted transformers as opposed to the BAU case, where the percentage of non-compliant customers in the worst case scenario (i.e., 100% penetration during Summer) was found to go up to 37%. Considering the results when the adjustment of off-load taps is adopted as a solution alone (Task 3, section 5.2 [1]), the performance in terms of the number of non-compliant customers, it should be noted that the adoption of OLTC-fitted transformers with the proposed control logic not only helps lower voltages during peak generation (midday) but also helps increase the voltage during peak loading conditions (evening/night). As such the adoption of OLTC-fitted LV transformers with the proposed logic, which can manage voltages according on the network state (without reconfiguring any control settings), can be considered a future proof solution as the increase of load such as electric vehicles will lead also to voltage drop issues in the years to come.

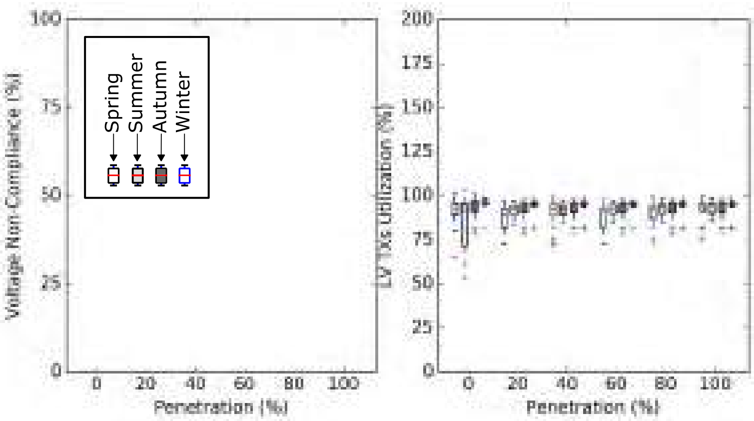


Figure 4-21 CRE21 LV-OLTC Percentage of Voltage Non-Compliant Customers (left) and Maximum LV Transformer Utlisation (right)

Given that the adjustment of off-load tap changers as well as adoption of OLTC-fitted transformers is not managing the power flows, augmentation was required to alleviate all congestion issues. Indeed, as observed in Figure 4-21 (right) and Figure 4-22 augmentation is very effective in keeping the utilization of all assets within their limits across all penetration levels. To understand the level of augmentations necessary to keep the HV lines and LV transformers within their limits, Figure 4-23 shows the length of HV conductors replaced (left) and number of LV transformers replaced (right). As it can be seen, no reinforcements required on the HV network, however, transformers require replacement as the PV penetration increases. In the case of LV transformers, 2 transformers need to be replaced for the 40 and 80% penetration levels. At 100%, on the other hand, 10 transformers need to be replaced. In total, this results in 14 out of 79 LV transformers in the network required to be replaced for the network to allow 100% PV penetration. For more clarity, the capacities of the transformers replaced are provided in Figure 4-24. Augmentation results were found to be aligned and almost the same as those presented in Task 3.

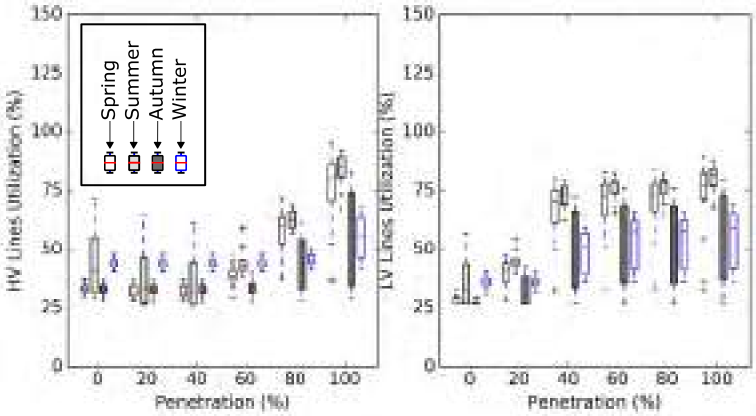


Figure 4-22 CRE21 LV-OLTC HV and LV Lines Utilisation (Seasonal)

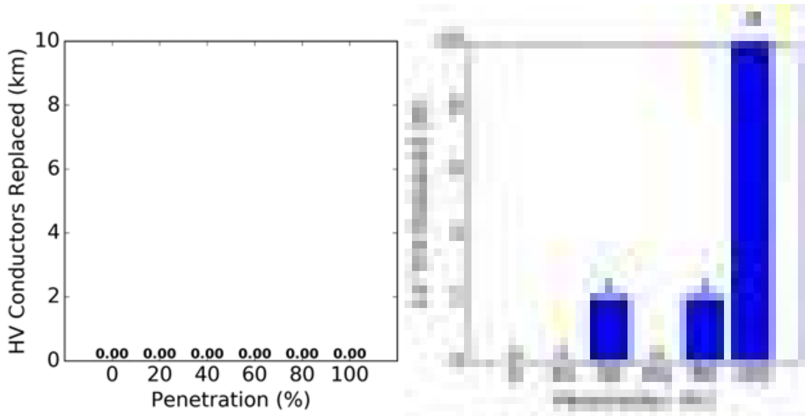


Figure 4-23 CRE21 LV-OLTC Conductor and Transformer Replacement Information (Seasonal)

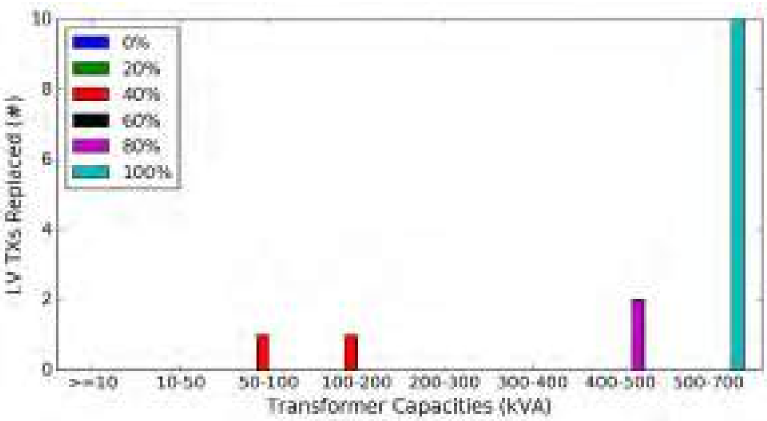


Figure 4-24 CRE21 LV-OLTC Transformer Replacement Capacities (Seasonal)

In terms of the effects the investigated solution has on the customers, Figure 4-25 shows the curtailment recorded across all penetration levels and seasons, both for individual customers and in the aggregate. As it can be seen, there is no curtailment for customers below the 80% PV penetration level. At 100% PV penetration a very small number of customers experiences curtailment, with the most penalised customer having 5% annual curtailment (extreme case). Considering the entire HV feeder, only 0.02% of the total PV generated energy is curtailed.

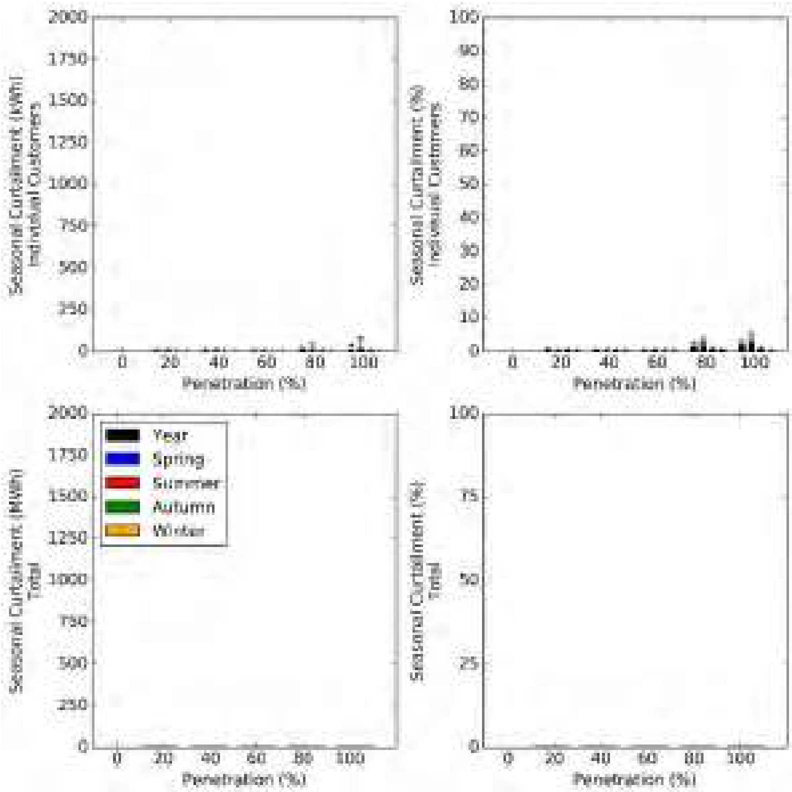


Figure 4-25 CRE21 LV-OLTC PV Generation Curtailment Information (Seasonal)

Finally, Figure 4-26 provides a detailed information of the number of OLTC installations required and the corresponding OLTC transformer capacities, respectively. Considering this analysis, 7 OLTC installations were required at 20% penetration and additional 3, 5 and 10 OLTCs were installed at 60%, 80 and 100% penetrations. As also shown, most transformers which required an OLTC installation had a rated capacity larger than 300kVA. These figures provide an important information that will allow accurately calculate the amount of investment required when adopting such solution.

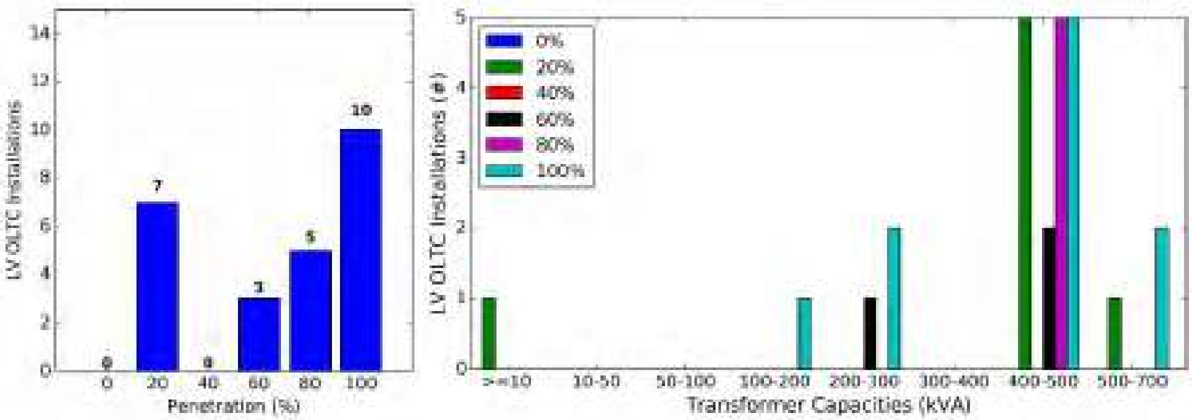


Figure 4-26 CRE21 LV-OLTC Installations and TX Capacities (Seasonal)

In terms of the OLTC control actions, Figure 4-27, presents a statistical representation of the daily number of tap changes triggered from each LV OLTC-fitted transformer. As it can be seen the median of daily tap changes was found to always be below 5, highlighting the effectiveness of the proposed OLTC control logic to keep a low number of tap changes; an important factor to the wear and tear of the OLTC.

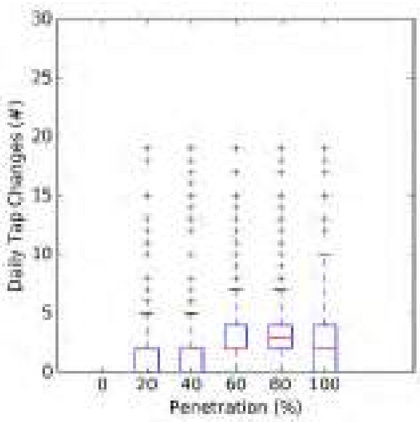


Figure 4-27 CRE21 LV-OLTC Daily Tap Changes (Seasonal)

4.3 Off-the-Shelf BES Systems

This section presents the results obtained from the operation of the CRE21 HV feeder considering the adoption of OTS BES systems by solar PV owners. Such analysis will allow understand the extent to which the widespread adoption of this emerging commercially available residential-scale technology (i.e., OTS BES system) can help reduce the household exports from excess solar PV generation, hence reduce or alleviate the corresponding technical issues. The analysis follows the methodology specified in section 2.3.3 and results are collected across different penetration levels for different seasons. The presentation of results follows a similar format as presented in the previous sections. It is important to highlight that this solution considers the adjustment of off-load tap changers and augmentation where assets (i.e., conductors, transformers) are congested.

4.3.1 Key Findings

A summary of the key findings is listed below.

- The adoption of this solution (i.e., off-load taps, OTS BES, augmentation) can effectively manage all technical issues and shift the Hosting capacity to 80% (compared to 40% when off-load taps are considered alone, see Task 3 section 5.2 [1]). At this point, the bottleneck becomes the voltage issues.
- Despite the ability to increase hosting capacity, this performance is only achieved due to the adjustment of off-load tap changer (i.e., voltage) and the corresponding augmentation (i.e., congestion). The adoption of OTS offers limited to almost no benefits for either technical issue. This is due to the following limitations:
    - <u>OTS BES systems do not fully discharge overnight</u>. This is due to insufficient energy consumption of most customers. As a consequence, their ability to store surplus PV generation the following day can be significantly reduced.
    - <u>OTS BES systems reach full SOC very early</u>. With a partially charged BES system, surplus PV generation that occurs early in the morning can lead to a full SOC before or during high PV generation, resulting in PV exports.
- No augmentations on the LV and HV conductors were needed regardless the penetration levels. This was aligned with the findings in Task 3.
- Augmentation of transformers was required, and it was found to be very effective for the congested LV networks as it allows host more solar PV penetration. Small number of LV transformers (up to 2) is required to be augmented at penetration levels of up to 80%. Significant increase in transformers that need to be replaced (7) was found at 100% PV penetration.
    - Augmentation results, and as expected, were found to be almost the same as those presented in Task 3.
- The curtailment of PV generation was found to be almost negligible when compared to the BAU case shown in Task 3. In particular, the level of curtailment was almost the same as when the adjustment of off-load taps alone is considered (see Task 3 section 5.2 [1]). This effect is primarily due to the adjustment of the off-load tap changers which reduce voltages hence the Volt-Watt function is not triggered. Considering the most critical penetration (i.e., 100%) the total curtailment accounts to just 0.02% of the total solar PV generation. It should be noted that the adoption of OTS BES has limited to no contribution to this effect (i.e., reduction of voltage, hence reduced curtailment).
- From the households' perspective, the adoption of the OTS BES systems shows to be an excellent investment as it allows them to significantly reduce their grid dependence, hence electricity bills. For example, the average and median yearly GDI of customers was found to be 11% and 0%. It is important to note that these numbers are influenced by the seasonality, with Spring and Summer having a much lower GDI (i.e., average of 2%) than Autumn and Winter (i.e., 18 and 22%, respectively).

A summary of the technical issues (highlighted red), curtailment (highlighted green), and augmentation (highlighted blue) for the different penetration levels is presented in Table 4-3.

Table 4-3 HV Feeder U2 (CRE21) – OTS BES Key Findings

	0% (2011)	20% (2017)	40% (2022)	60% (2030)	80% (2035)	100% (2042)
Non-Compliant Customers [%]	0	0	0	0	0	2
Max Voltage [p.u]	1.052	1.064	1.076	1.09	1.098	1.11
Max HV Conductor Utilization [%]	71	59	48	45	67	91
Congested HV Conductors [km]	0	0	0	0	0	0
Max LV Conductor Utilization [%]	57	53	79	81	81	83
Congested LV Conductors [km]	0	0	0	0	0	0
Max LV TX Utilization [%]	89	95	98	95	97	100
Congested LV TXs [#,%]	[0, 0]	[0, 0]	[0, 0]	[0, 0]	[0, 0]	[0, 0]
Annual Curtailment [MWh,%]	[0, 0]	[0, 0.02]	[1, 0.01]	[1, 0.01]	[3, 0.02]	[5, 0.02]
HV Conductors Replaced [km]	0	0	0	0	0	0
LV Conductors Replaced [km]	0	0	0	0	0	0
LV TXs Replaced [#,%]	[0, 0]	[0, 0]	[2, 2]	[0, 0]	[2, 2]	[7, 8]
LV TXs Replaced per Capacity**	[0, 0, 0, 0, 0, 0, 0, 0]	[0, 0, 0, 0, 0, 0, 0, 0]	[0, 0, 1, 1, 0, 0, 0, 0]	[0, 0, 0, 0, 0, 0, 0, 0]	[0, 0, 0, 0, 0, 0, 2, 0]	[0, 0, 0, 0, 0, 0, 0, 7]
BES Year Mean/Median GDI [%,%]	[100,100]	[11,0]	[11,0]	[11,0]	[11,0]	[11,0]

***The transformer kVA capacities correspond to: [>=10, 10-50, 50-100,100-200, 200-300, 300-400, 400-500, 500-700]*

4.3.2 Single Day Analysis

This section presents a single-day analysis for each of the penetration levels and season for the OTS BES case. As defined previously, these assessments use a clear-sky day (for their corresponding season) as this is expected to result in higher technical problems for the network. It should be noted that all simulation parameters (customer P, Q, phase connections, PV system sizes, etc.) remain the same as the BAU case (Task 3).

Starting first with the customer voltages, shown in Figure 4-28, Page 82, results are observed to have almost the same performance as with the results shown in Task 3 Section 4.2.2 where the adjustment of the off-load tap changers is considered alone. As such, very small overvoltage issues start appearing at 80% penetration onwards during midday. Similar to the BAU case, a “flattening” of voltages appears at when customer voltages start exceeding the 1.10pu limit. This is an effect of the combined Volt-Watt/Volt-var functionality, which has been discussed extensively in the previous sections and Task 3. It is important to note that the adoption of OTS BES systems while slightly reducing the voltages during early generation hours (i.e., 8am-10am), batteries become full before the peak generation hours (i.e., midday) hence the net demand profile continues as if no BES systems were installed. However, while OTS BES systems provide to limited benefits in reducing the voltages during the solar PV generation hours, voltages during load-only hours (early morning and night) are flatten. The latter is the effect of BES systems supplying the household demand locally hence improving the voltage profile.

As seen in Figure 4-29, Page 83 and Figure 4-30, Page 84, similar with the BAU case, the HV and LV lines utilisation remains within limits regardless the penetration level. In fact, the utilisation of the HV lines is slightly reduced due to the following:

- A slight reduction is observed during the early generation hours (i.e., 8am-10am) as the OTS BES systems can slightly reduce reverse power flows before becoming full.
- A slight reduction is observed in general as most customers in the network have lower voltages at the connection point (due to the adjusted off-load tap positions and OLTC actions) hence PV inverters absorb less reactive power which results in a slightly smaller utilisation of the HV lines.

In terms of the LV transformers utilization levels, shown in Figure 4-31, Page 85, all of them operate within their rated capacities without facing congestion issues. These results, as opposed to the BAU and adjustment of off-load tap changers alone (see Task 3) where LV transformers start facing congestion issues from as early as 20% of penetration are due the augmentation performed. With augmentation, the LV transformers are upgraded to increase their capacity and therefore increase the hosting capacity of the network. As it can be seen in Figure 4-31, Page 85, all LV transformers are now operating within their rated capacity for all penetration levels. The number of LV transformers replaced and corresponding capacities for each PV penetration can be seen in Figure 4-34, Page 88 and Figure 4-35, Page 88, respectively. It should be noted that once a transformer has been upgraded, the new capacity is used in the next penetration level assessment.

To understand how the adoption of OTS BES systems might influence the operation of solar PV operate for the assessed PV generations and seasons, the active power of PV inverters is shown in Figure 4-32, Page 86. Results show to have the same performance as with the solution of adjusting the off-load taps alone (see Task 3 section 4.2), where only some customers experience curtailment from 80% penetration onwards. Considering this performance, it can be concluded that the adoption of OTS BES provided limited to no benefits in this matter.

From the households' perspective, Figure 4-36, Page 89 which presents the households' GDI, shows that the adoption of the OTS BES systems is an excellent investment as it allows them to significantly reduce their grid dependence, hence electricity bills. For example, the median GDI of customers regardless the season was around 1%. While these results highlight the benefits provided to the customers when adopting an OTS BES, it should be noted that in this case sunny days are considered for all seasons hence results might overestimate the GDI performance. To realistically assess the GDI performance the analyses performed (i.e., seasonal analysis) in the following section should be considered.

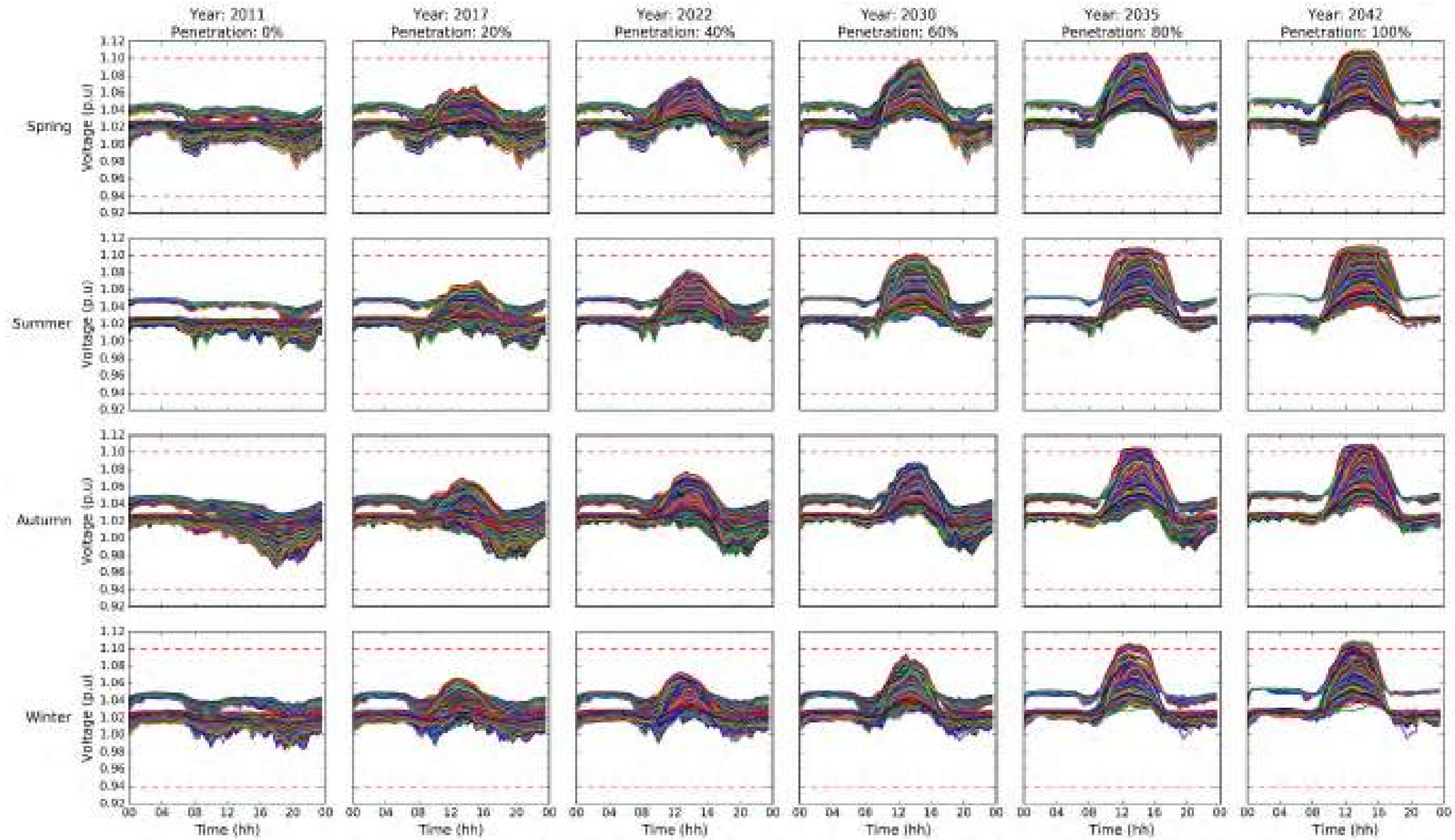


Figure 4-28 CRE21 OTS BES Daily Customer Voltages

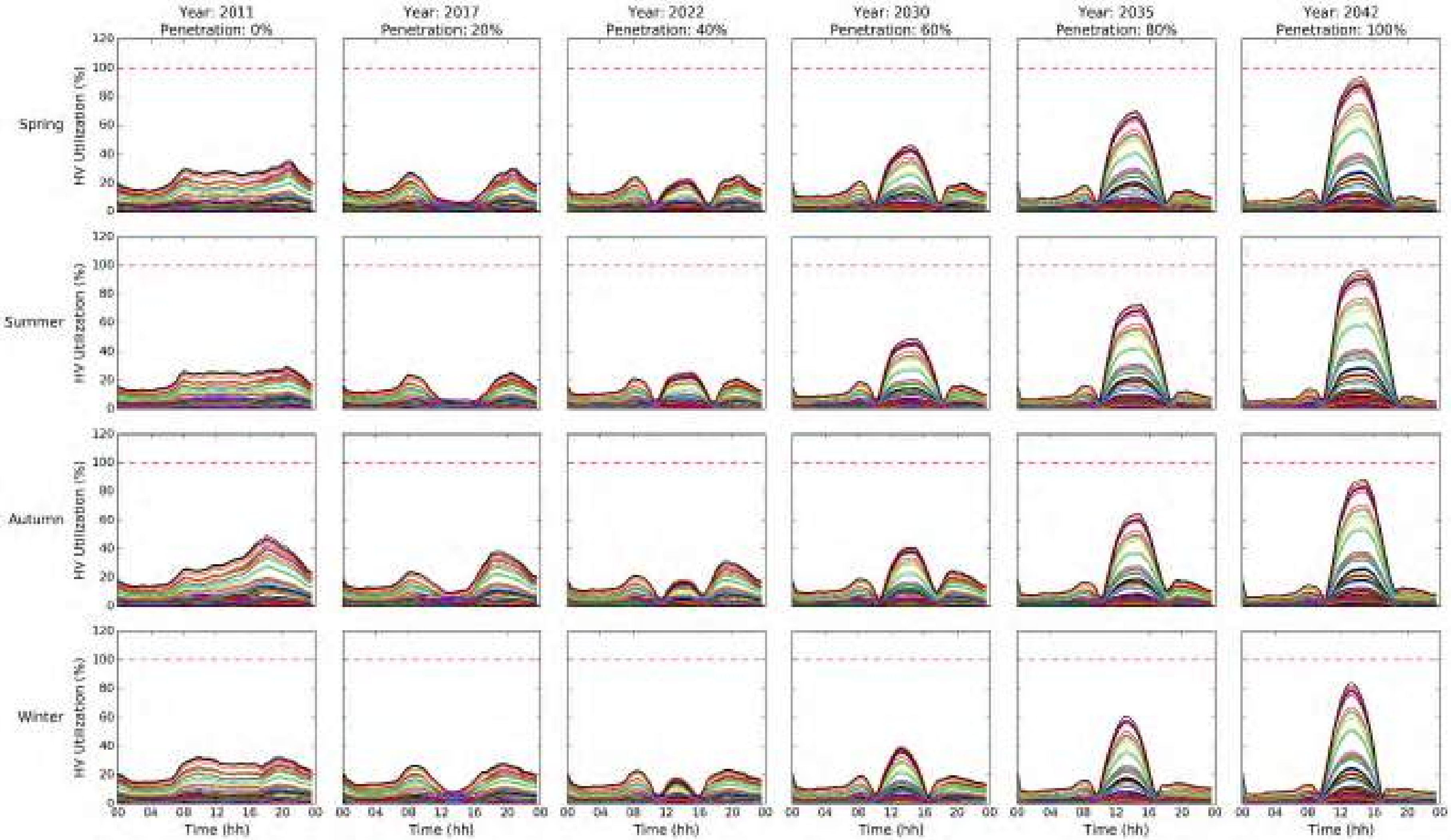


Figure 4-29 CRE21 OTS BES Daily HV Line Utilisation

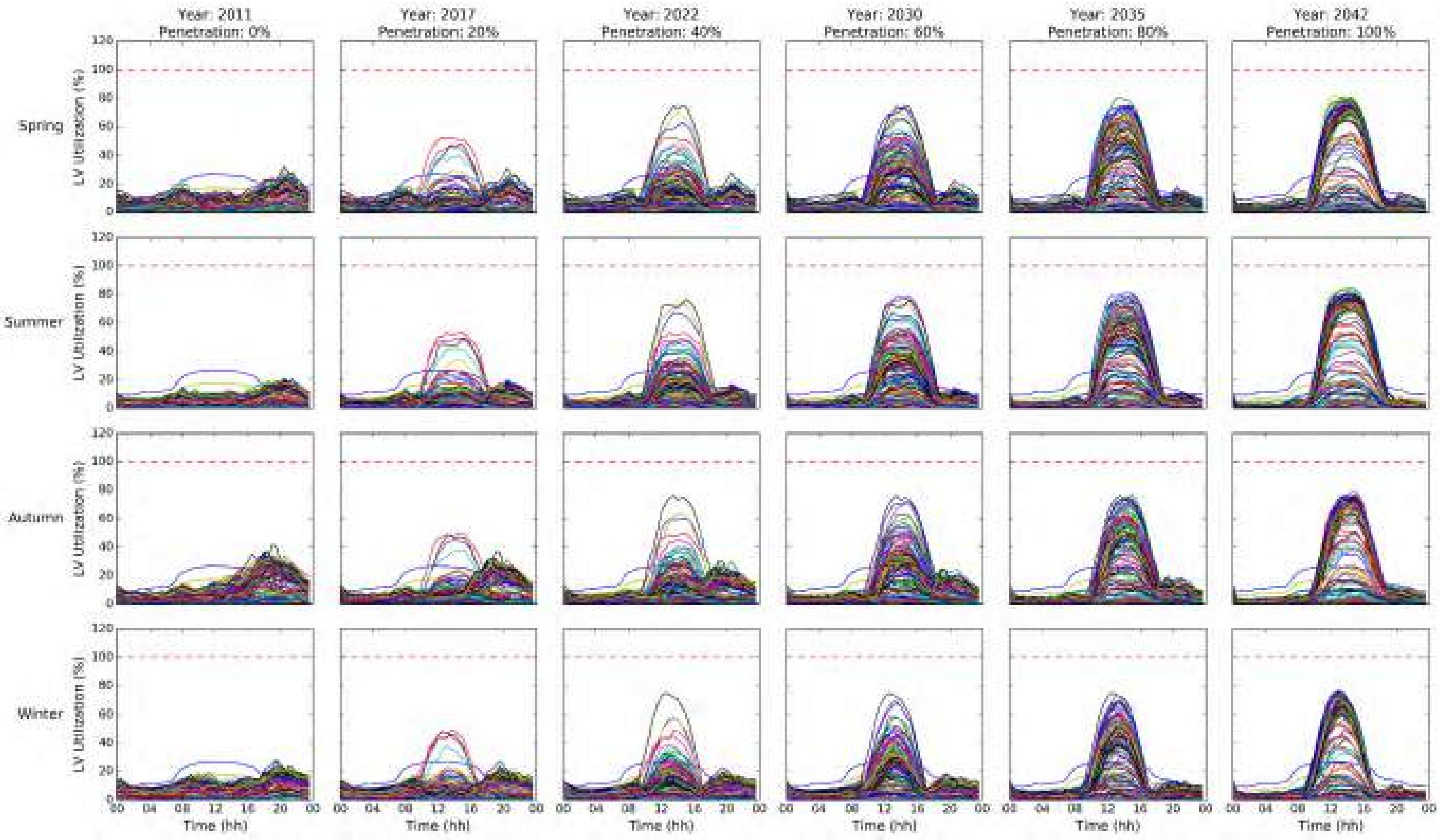


Figure 4-30 CRE21 OTS BES Daily LV Line Utilisation

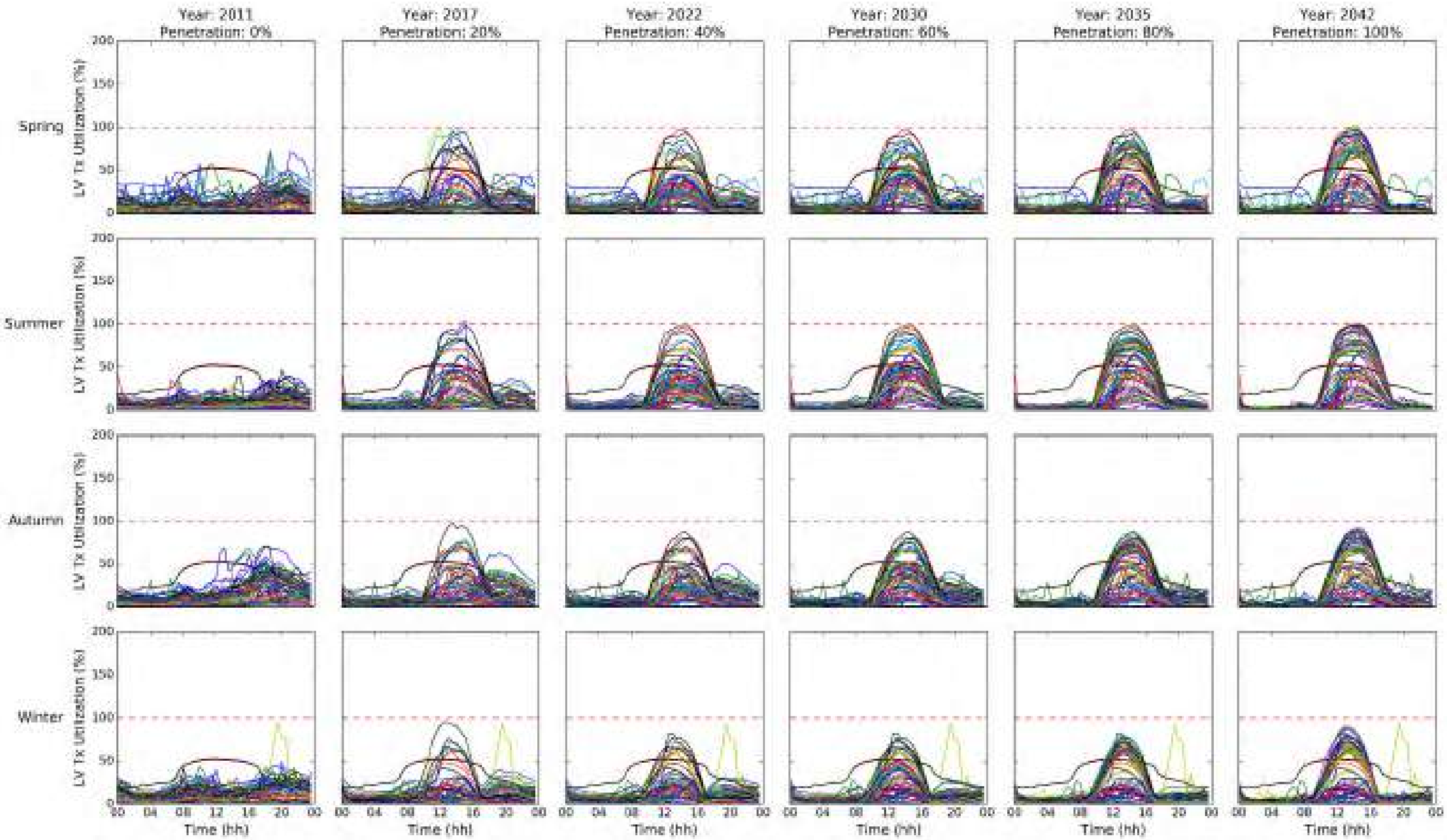


Figure 4-31 CRE21 OTS BES Daily LV Transformer Utilisation

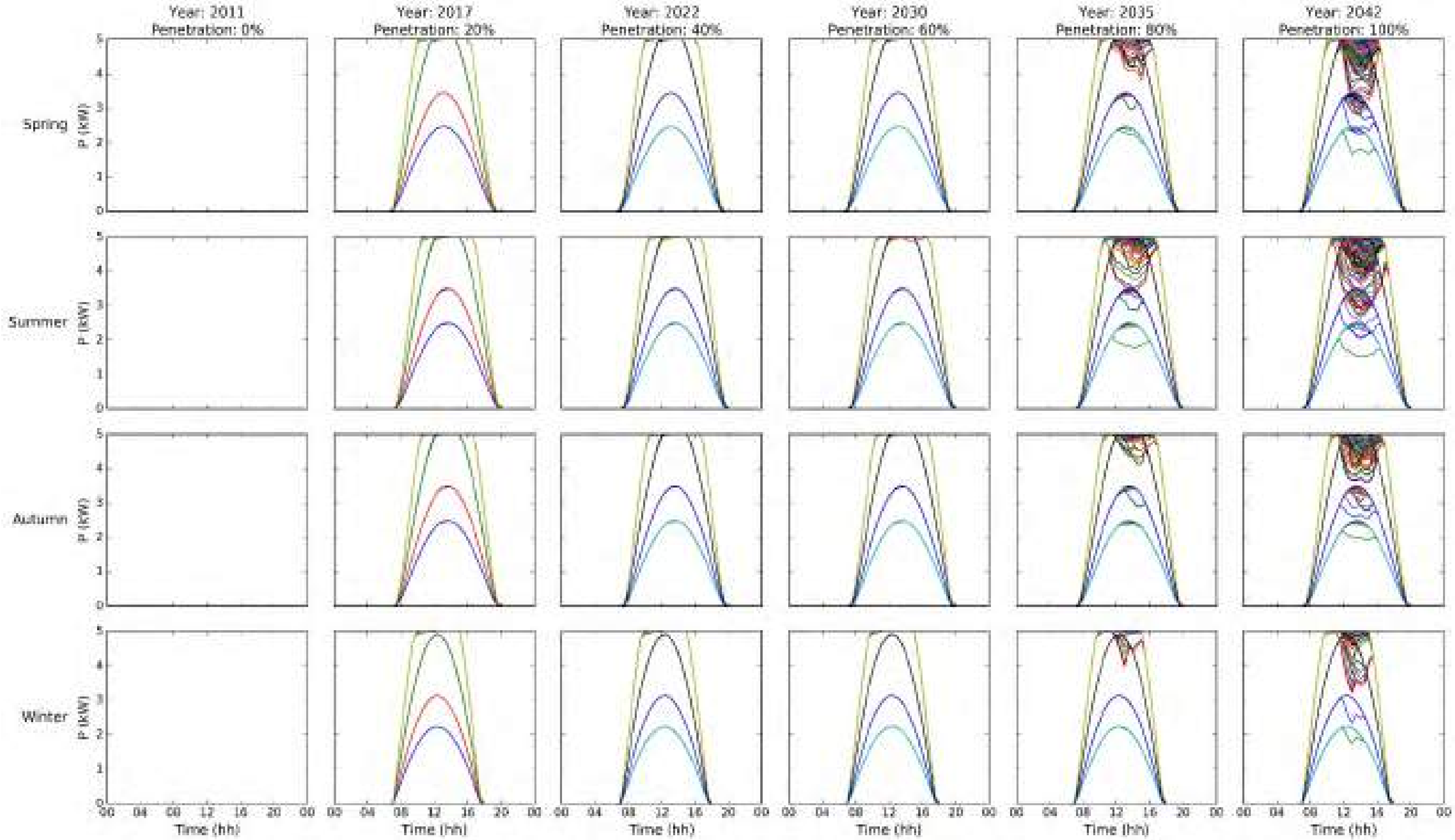


Figure 4-32 CRE21 OTS BES Daily PV System Active Power Output

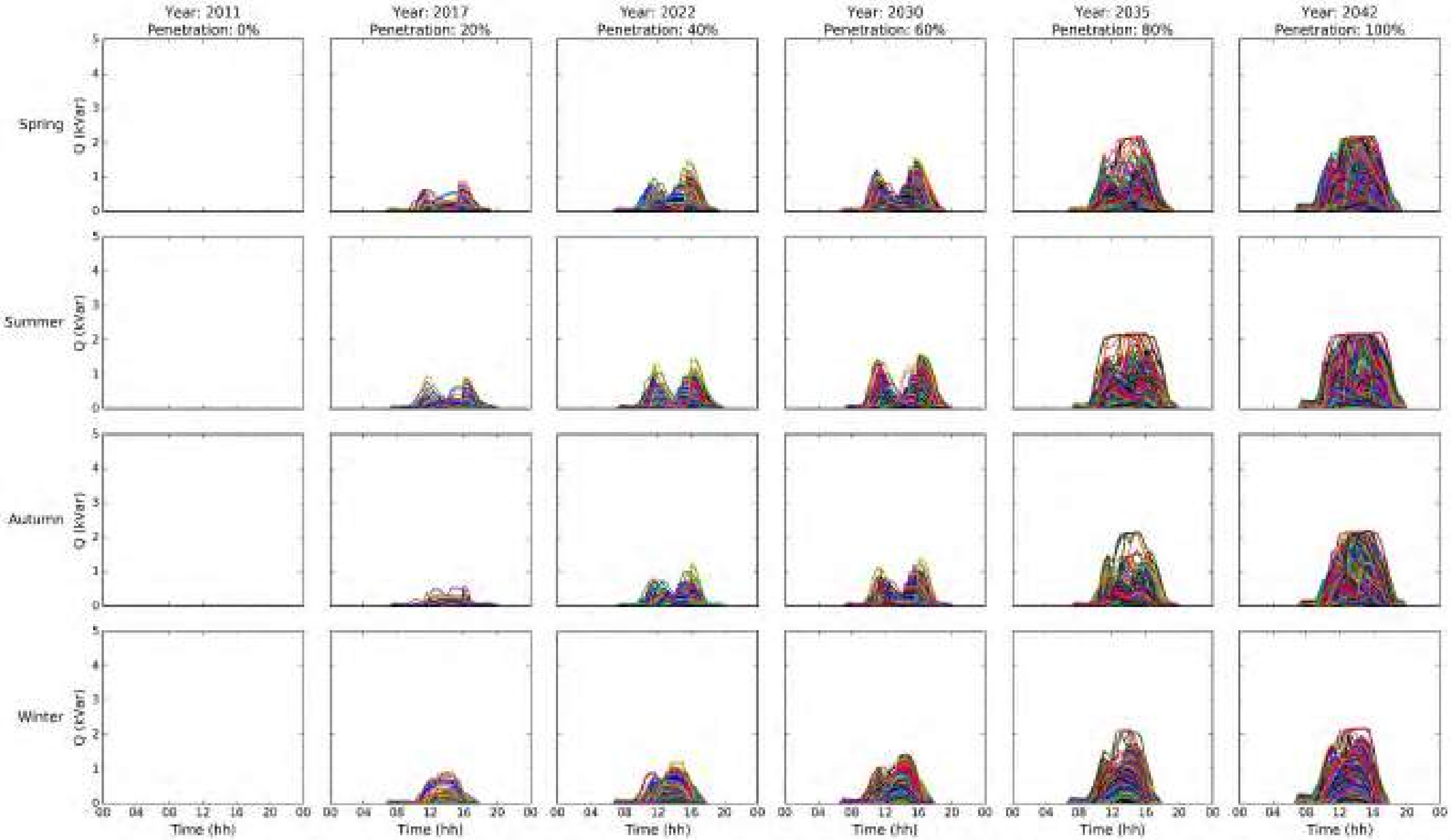


Figure 4-33 CRE21 OTS BES Daily PV System Reactive Power Absorption

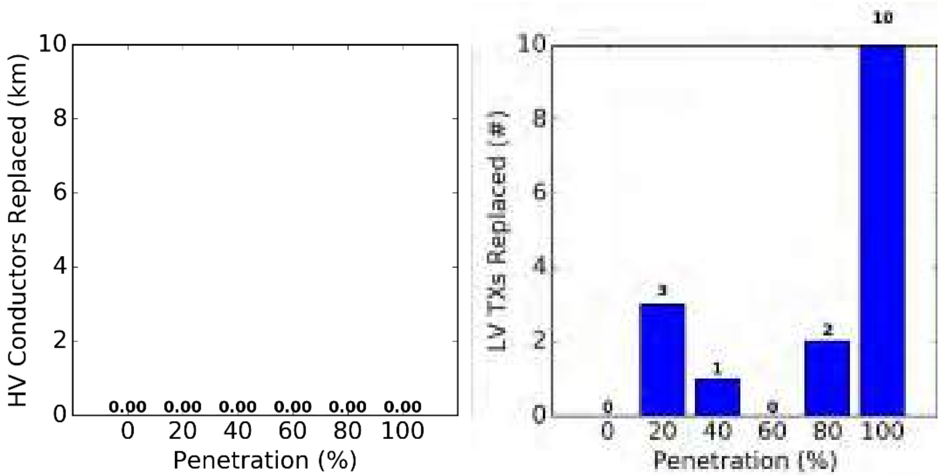


Figure 4-34 CRE21 OTS BES Conductor and Transformer Replacement Information

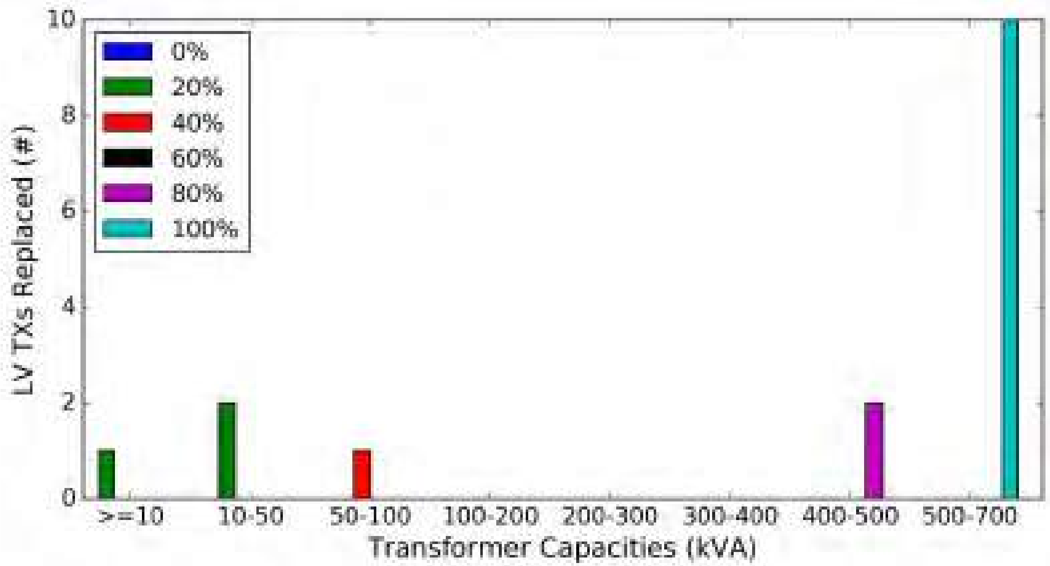


Figure 4-35 CRE21 OTS BES Transformer Replacement Capacities

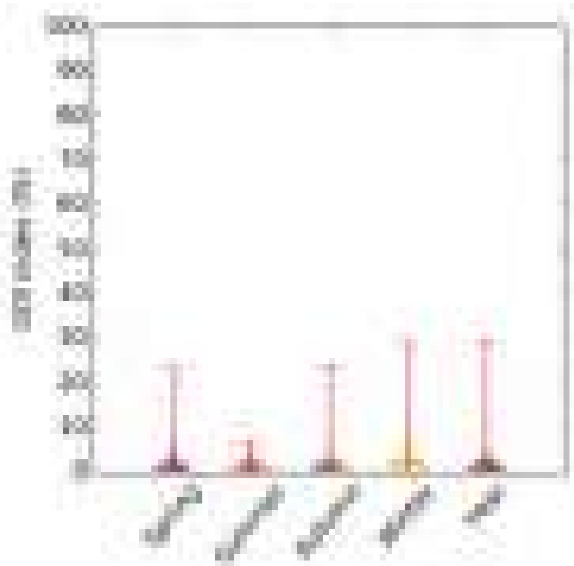


Figure 4-36 CRE21 OTS Grid Dependence Index

4.3.3 Seasonal Analysis

The results for the seasonal analysis for the OTS BES case are demonstrated in this section. Starting with Figure 4-37, the two most constraining factors in this network (as defined by the BAU case), customer voltages and transformer utilisation, are shown. Considering the percentage of non-compliant customers, results show to have almost the same performance with those corresponding to the solution of adjusting the off-load tap changers alone (Task 3, section 4.2 [1]). For example, voltage problems only occur at very high PV penetration levels (>80%), and for a very small number of customers (2%). Considering the aforementioned, results highlight that the adoption of OTS BES systems do not provide any further benefit to this technical issue.

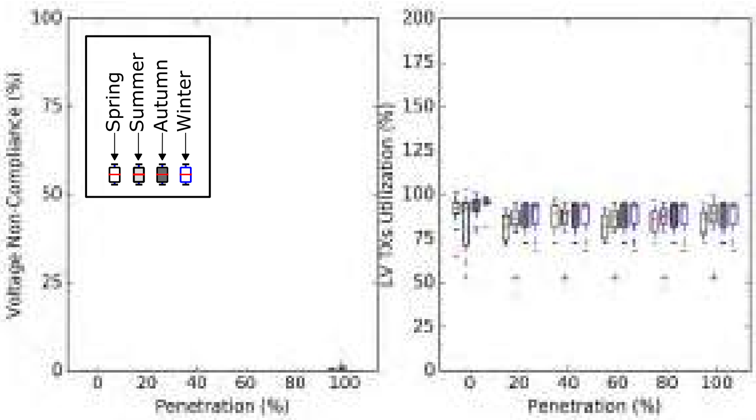


Figure 4-37 CRE21 OTS BES Percentage of Voltage Non-Compliant Customers (left) and Maximum LV Transformer Utlisation (right)

Considering the utilization of LV transformers results also show that the performance was almost the same as with the results when adjusting the off-load taps alone, hence augmentation was required to alleviate all congestion issues. Indeed, as observed in Figure 4-37 (right) and Figure 4-38, augmentation is very effective in keeping the utilization of all assets within their limits across all penetration levels. To understand the level of augmentations necessary to keep the HV lines and LV transformers within their limits, Figure 4-39 shows the length of HV conductors replaced (left) and number of LV transformers replaced (right). As it can be seen, no reinforcements required on the HV network, however, transformers require replacement as the PV penetration increases. In the case of LV transformers, 2 transformers need to be replaced for the 40 and 80% penetration levels. At 100%, on the other hand, 7 transformers need to be replaced. In total, this results in 11 out of 79 LV transformers in the network required to be replaced for the network to allow 100% PV penetration. For more clarity, the capacities of the transformers replaced are provided in Figure 4-40. Augmentation results were found to be aligned and almost the same as those presented in Task 3. Again, given that the utilization of assets found to have the same performance as with the adjustment of off-load taps alone, highlights that the that the adoption of OTS BES systems does not provide any further benefit to this technical issue.

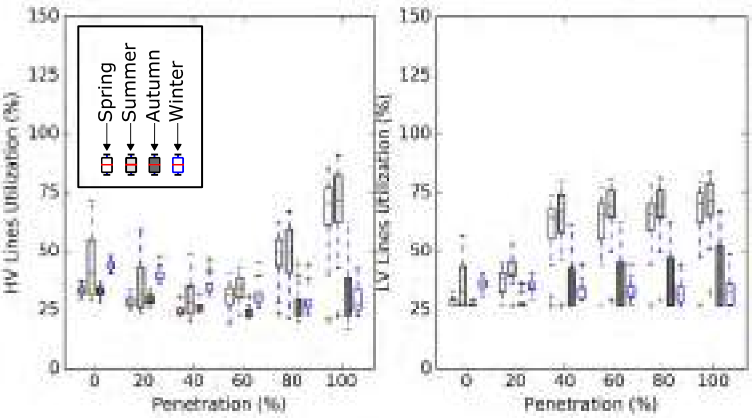


Figure 4-38 CRE21 OTS BES HV and LV Lines Utilisation (Seasonal)

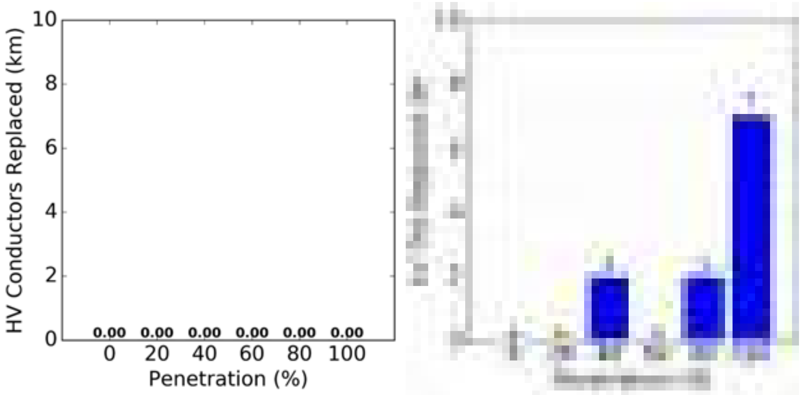


Figure 4-39 CRE21 OTS BES Conductor and Transformer Replacement Information (Seasonal)

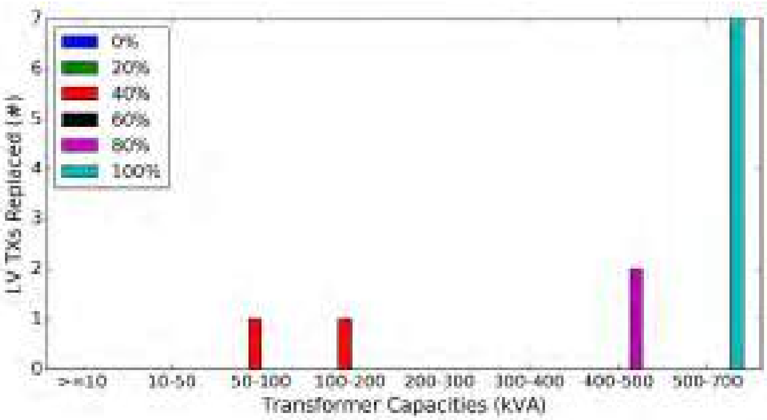


Figure 4-40 CRE21 OTS BES Transformer Replacement Capacities (Seasonal)

In terms of the effects the investigated solution has on the customers, Figure 4-25 shows the curtailment recorded across all penetration levels and seasons, both for individual customers and in the aggregate. As it can be seen, there is no curtailment for customers below the 80% PV penetration level. At 100% PV penetration a very small number of customers experiences curtailment, with the most penalised customer having 18% annual curtailment (extreme case). Considering the entire HV feeder, only 0.02% of the total PV generated energy is curtailed. Once again, it should be noted that the same performance is achieved with the adjustment of off-load tap changers alone, hence the benefits provided with the adoption of OTS BES to this matter are not obvious and limited.

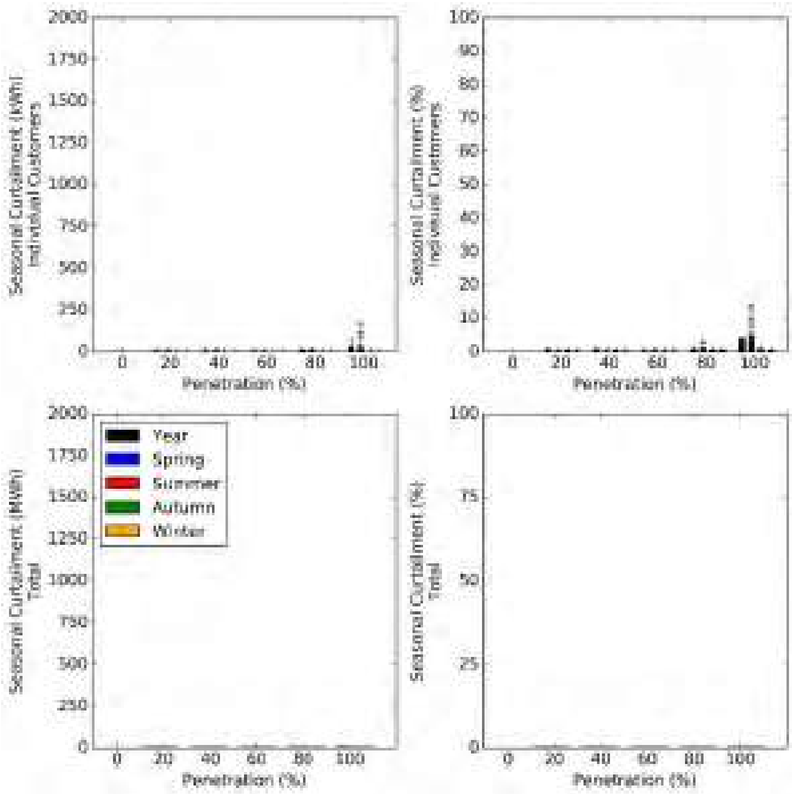


Figure 4-41 CRE21 OTS BES PV Generation Curtailment Information (Seasonal)

Figure 4-42, presents the households' GDI considering the results from the whole seasonal analysis. These results which in comparison to the single-day analysis consider multiple days, different demand and generation conditions allow capturing the true effects that OTS BES might have on customers. Indeed, and as previously stated results highlight that the adoption of the OTS BES systems is an excellent investment (from the customer's perspective) as it allows them to significantly reduce their grid dependence, hence electricity bills. For example, the mean and median GDI for customers during Spring and Summer was found to be just 1 and 2%, respectively. Considering Autumn, while the mean GDI increases to 18% the median remains up to 2%. During Winter, the mean and median values increase to 25 and 18%, respectively. The increment of the GDI during Autumn and Winter can be explained due to the fact that sunny days are less prominent hence the BES systems do not sufficiently charge, and the stored energy might not be adequate enough to cover the household demand. As a result, the dependence to the grid increases given that the uncovered demand (by the battery) has to come from the grid. However, when considering the GDI throughout the whole year, the mean and median values were found to be around 15% and 2%. Given that OTS BES systems are designed and operate for the sole benefit of their owners (i.e., reduce grid energy imports) these results and values can be considered as a benchmark when different BES control approaches, are adopted.

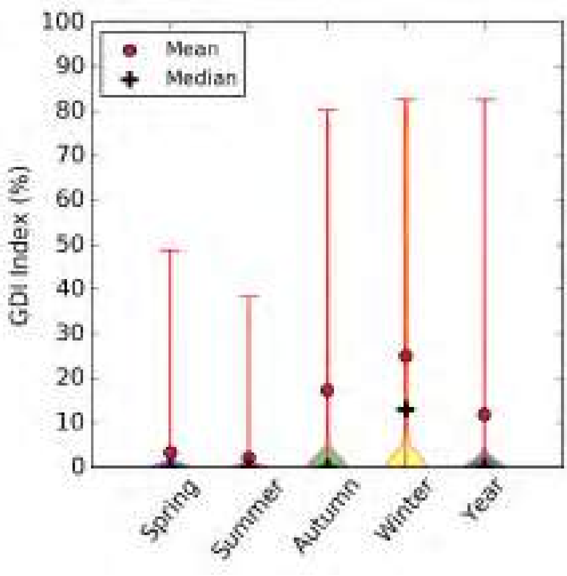


Figure 4-42 CRE21 OTS BES Grid Dependence Index (Seasonal)

4.4 Network Smart BES Systems

This section presents the results obtained from the operation of the CRE21 HV feeder considering the adoption of commercially available residential-scale BES systems embedded with the network smart control logic proposed and detailed in section 2.4.2. Such analysis will allow understand the extent to which advanced battery management strategies can provide benefits not only 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. The analysis follows the methodology specified in section 2.4.4 and results are collected across different penetration levels for different seasons. The presentation of results follows a similar format as presented in the previous sections. It is important to highlight that this solution considers the adjustment of off-load tap changers and augmentation where assets (i.e., conductors, transformers) are congested.

4.4.1 Key Findings

A summary of the key findings is listed below.

- The adoption of this solution (i.e., off-load taps, NS BES, augmentation) can effectively manage all technical issues and shift the Hosting capacity to 100% (compared to 40% when off-load taps are considered alone, see Task 3 section 5.2 [1]).
- Compared to the results obtained when OTS BES systems are adopted, the performance in terms of voltage and asset utilization is significantly increased.
- It has been observed that voltages further reduce during the peak generation period and are always kept below the maximum voltage statutory limit (<1.10p.u), regardless the penetration level and season. This is achieved due to the network smart control logic that enables BES systems charge throughout the whole generation period, hence significantly reduce household exports.
- The adoption of BES systems with the proposed network smart control logic shows to be highly effective in significantly reducing the utilization level of all assets and more importantly alleviate all transformer congestion issues for all penetration and seasons. This is achieved due to the network smart control logic that enables BES systems charge throughout the whole generation period, hence significantly reduce household exports.
- There was no curtailment of PV generation when adopting this solution. This effect is due to the ability to keep all customer voltages always below 1.10p.u, hence the volt-watt function not triggering. Compared to the OTS BES results, the adoption of the network smart control logic contributes significantly to this performance.
- From the households' perspective, the adoption of the network smart BES systems shows to slightly affect customers' GDI when compared to the results with OTS BES systems. For example, the average and median yearly GDI of customers was found to be 15% and 2%, respectively. These values correspond to an increase of 4 and 2%, respectively, when compared to the OTS BES. While the adoption of the network smart control logic might lead to slightly higher grid imports for customers than with the OTS control, the corresponding expense might be considerably lower than the capital investments required to provide the same network benefits with asset-intensive solutions, such as network reinforcements

A summary of the technical issues (highlighted red), curtailment (highlighted green), and augmentation (highlighted blue) for the different penetration levels is presented in Table 4-4.

Table 4-4 HV Feeder U2 (CRE21) – NS BES Key Findings

	0% (2011)	20% (2017)	40% (2022)	60% (2030)	80% (2035)	100% (2042)
Non-Compliant Customers [%]	0	0	0	0	0	0
Max Voltage [p.u]	1.052	1.054	1.058	1.06	1.064	1.092
Max HV Conductor Utilization [%]	71	60	48	47	47	46
Congested HV Conductors [km]	0	0	0	0	0	0
Max LV Conductor Utilization [%]	57	53	47	42	42	44
Congested LV Conductors [km]	0	0	0	0	0	0
Max LV TX Utilization [%]	89	97	97	97	97	97
Congested LV TXs [#,%]	[0, 0]	[0, 0]	[0, 0]	[0, 0]	[0, 0]	[0, 0]
Annual Curtailment [MWh,%]	[0, 0]	[0, 0]	[0, 0]	[0, 0]	[0, 0]	[0, 0]
HV Conductors Replaced [km]	0	0	0	0	0	0
LV Conductors Replaced [km]	0	0	0	0	0	0
LV TXs Replaced [#,%]	[0, 0]	[0, 0]	[0, 0]	[0, 0]	[0, 0]	[0, 0]
LV TXs Replaced per Capacity**	[0, 0, 0, 0, 0, 0, 0, 0]	[0, 0, 0, 0, 0, 0, 0, 0]	[0, 0, 0, 0, 0, 0, 0, 0]	[0, 0, 0, 0, 0, 0, 0, 0]	[0, 0, 0, 0, 0, 0, 0, 0]	[0, 0, 0, 0, 0, 0, 0, 0]
BES Year Mean/Median GDI [%,%]	[100,100]	[15,2]	[15,2]	[15,2]	[15,2]	[15,2]

***The transformer kVA capacities correspond to: [>=10, 10-50, 50-100,100-200, 200-300, 300-400, 400-500, 500-700]*

4.4.2 Single Day Analysis

This section presents a single-day analysis for each of the penetration levels and season for the NS BES case. As defined previously, these assessments use a clear-sky day (for their corresponding season) as this is expected to result in higher technical problems for the network. It should be noted that all simulation parameters (customer P, Q, phase connections, PV system sizes, etc.) remain the same as the BAU case (Task 3).

Starting first with the customer voltages, shown in Figure 4-43, Page 97, results highlight the effectiveness of the BES systems with a network smart control logic to alleviate all issues while also further reducing the magnitude of the daily maximum voltage of each customer (with BES and solar PV). For example, the maximum voltage among all customers is always kept well below the voltage limits (i.e., <1.08p.u) for all penetrations until 80% of penetration. Even at the worst-case scenario the maximum voltage is never above the statutory limit (i.e., 1.10p.u.). This effect is observed in all penetration levels and seasons. This improved behaviour seen in the voltage profiles is the result of household exports being significantly reduced and, hence, the voltage profiles. It is also important to highlight that the network smart control logic leads to small exports in morning hours in order to ensure available capacity during the generation period in the next day. As expected, the latter leads in higher voltages during night and early morning hours than the OTS BES case. However, these values are far from the statutory limit.

Considering the congestion of assets, Figure 4-44, Page 98, Figure 4-45, Page 99 and Figure 4-46, Page 100 present the utilization level of the HV lines, LV lines and the LV transformers, respectively. Interestingly and compared to all other solutions investigated, none of the assets is facing any congestion issues and more importantly their maximum daily utilization levels are almost halved. For example, considering the worst-case scenarios (i.e., 100% penetration in Summer) the utilization level of all HV and LV feeders never goes above 50% (up to 90% with other solutions) and the utilization of the LV transformers never goes above 90% (up to 200% with other solutions). As previously explained, this improved behaviour is the result of household exports being significantly reduced and, hence, the utilization level of assets. It is also important to note that the reduction achieved in customer voltages is leading to significantly less absorption of reactive power which contributes to the lower utilisation levels of assets.

Ultimately, given the improved performance in terms of utilization of assets, as shown in Figure 4-49, Page 103, none of the assets had to be augmented. This highlights the significant benefits that could be provided with the adoption of smarter control logics for BES systems, that could potentially become an alternative to otherwise required costly network reinforcements, saving billions of dollars in investments.

The adoption of BES systems with a network smart control logic shows to also have significant benefits in terms of reducing the required amount of solar PV curtailment. As shown in Figure 4-47, Page 101, none of the customers had to curtail any generation regardless the penetration level and season. These findings show that a smarter BES control logic can provide added value to their owners it can help keep their voltage below the volt-watt triggering point, hence have less exposure to curtailment.

Considering this particular single-day analysis, Figure 4-50, Page 103, shows that the almost the same performance in terms of GDI is achieved (i.e., mean GDI of 1%) as with the OTS BES case; hence showing that the adoption of the network smart control logic does not significantly impact customers profitability (i.e., reduced grid energy imports). While these results highlight the adoption of BES systems with a network smart control logic do not impact the GDI of customers, it should be noted that in this case sunny days are considered for all seasons hence results might overestimate the GDI performance. To realistically assess the GDI performance the analyses performed in the following section (i.e., seasonal analysis) should be considered.

Figure 4-55, presents the households' GDI considering the results from the whole seasonal analysis. The adoption of the network smart BES systems shows to slightly affect customers' GDI when compared to the results obtained with OTS BES systems. For example, the average and median yearly GDI of customers was found to be 15% and 2%, respectively. These values correspond to an increase of 4 and 2%, respectively, when compared to the OTS BES. While the adoption of the network smart control logic might lead to slightly higher grid imports for customers than with the OTS control, the corresponding expense might be considerably lower than the capital investments required to provide the same network benefits with asset-intensive solutions, such as network reinforcements.

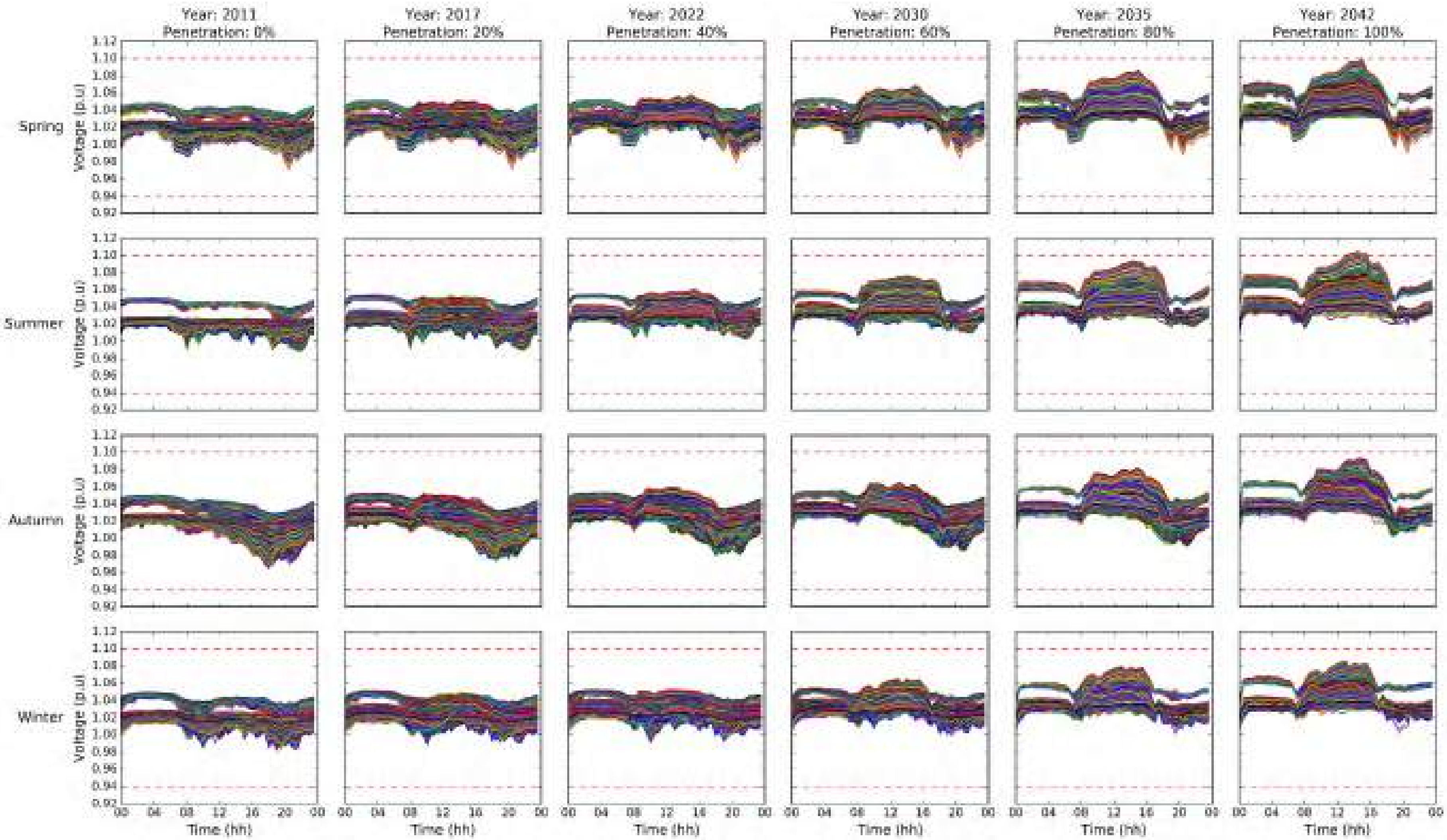


Figure 4-43 CRE21 NS BES Daily Customer Voltages

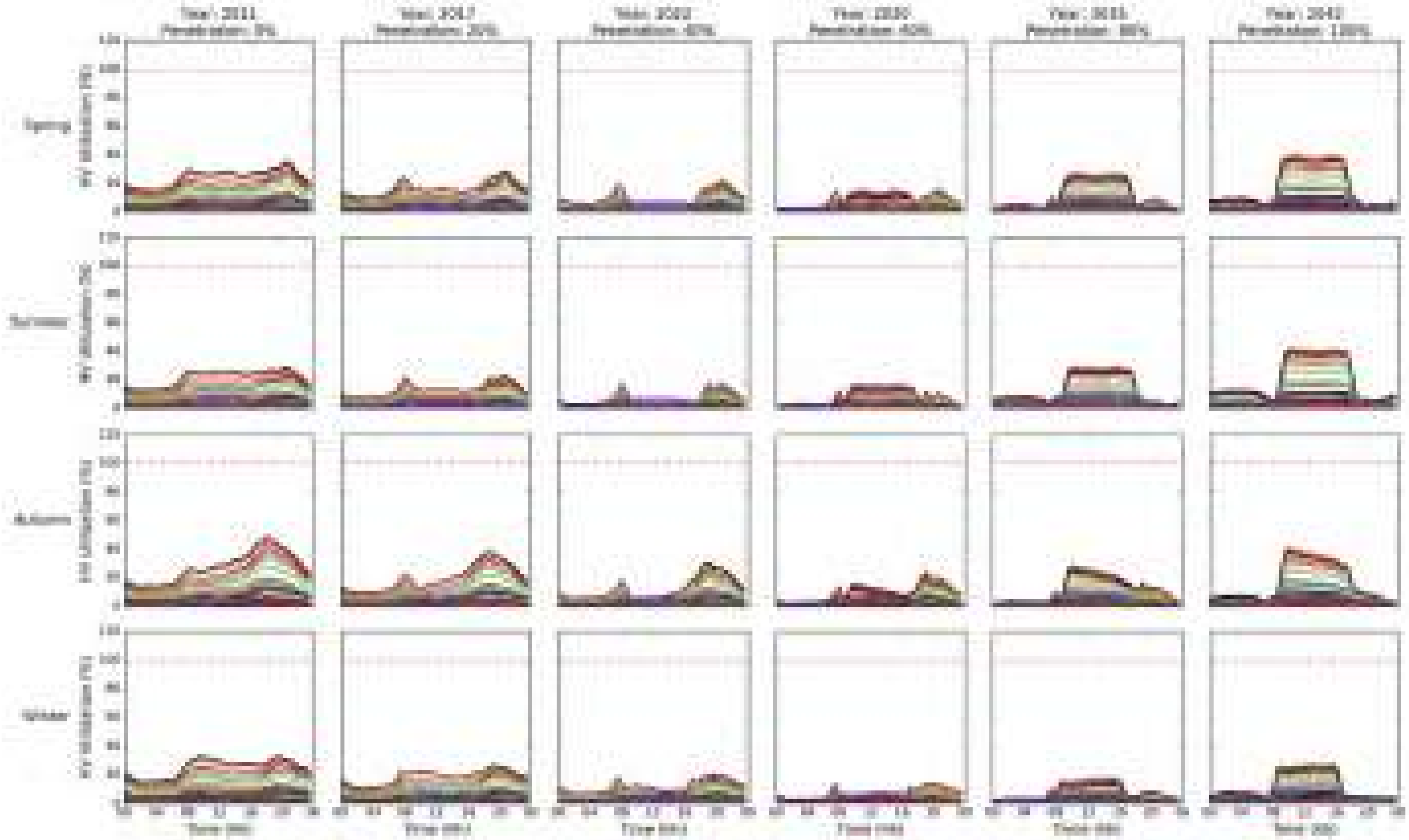


Figure 4-44 CRE21 NS BES Daily HV Line Utilisation

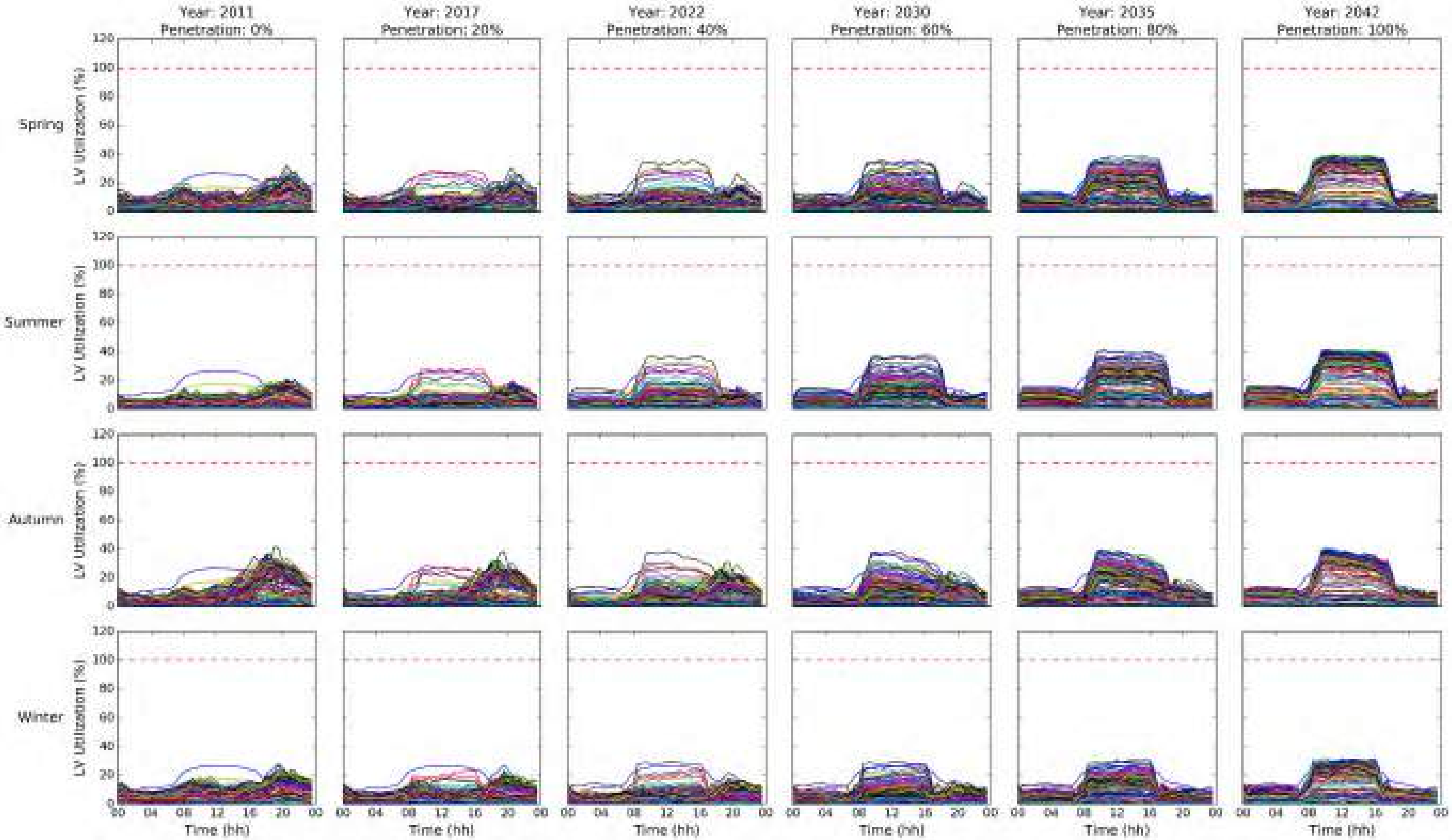


Figure 4-45 CRE21 NS BES Daily LV Line Utilisation

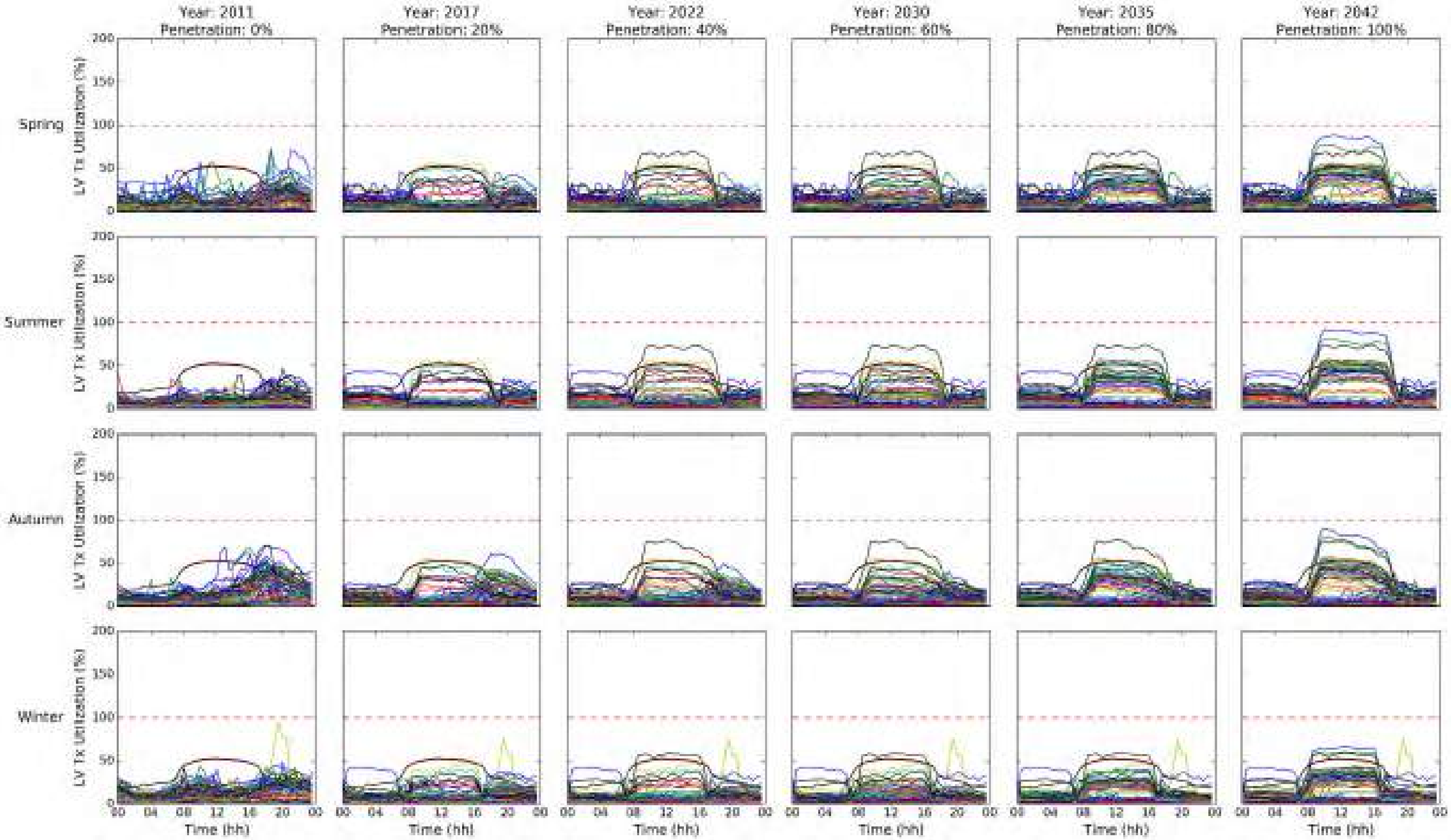


Figure 4-46 CRE21 NS BES Daily LV Transformer Utilisation

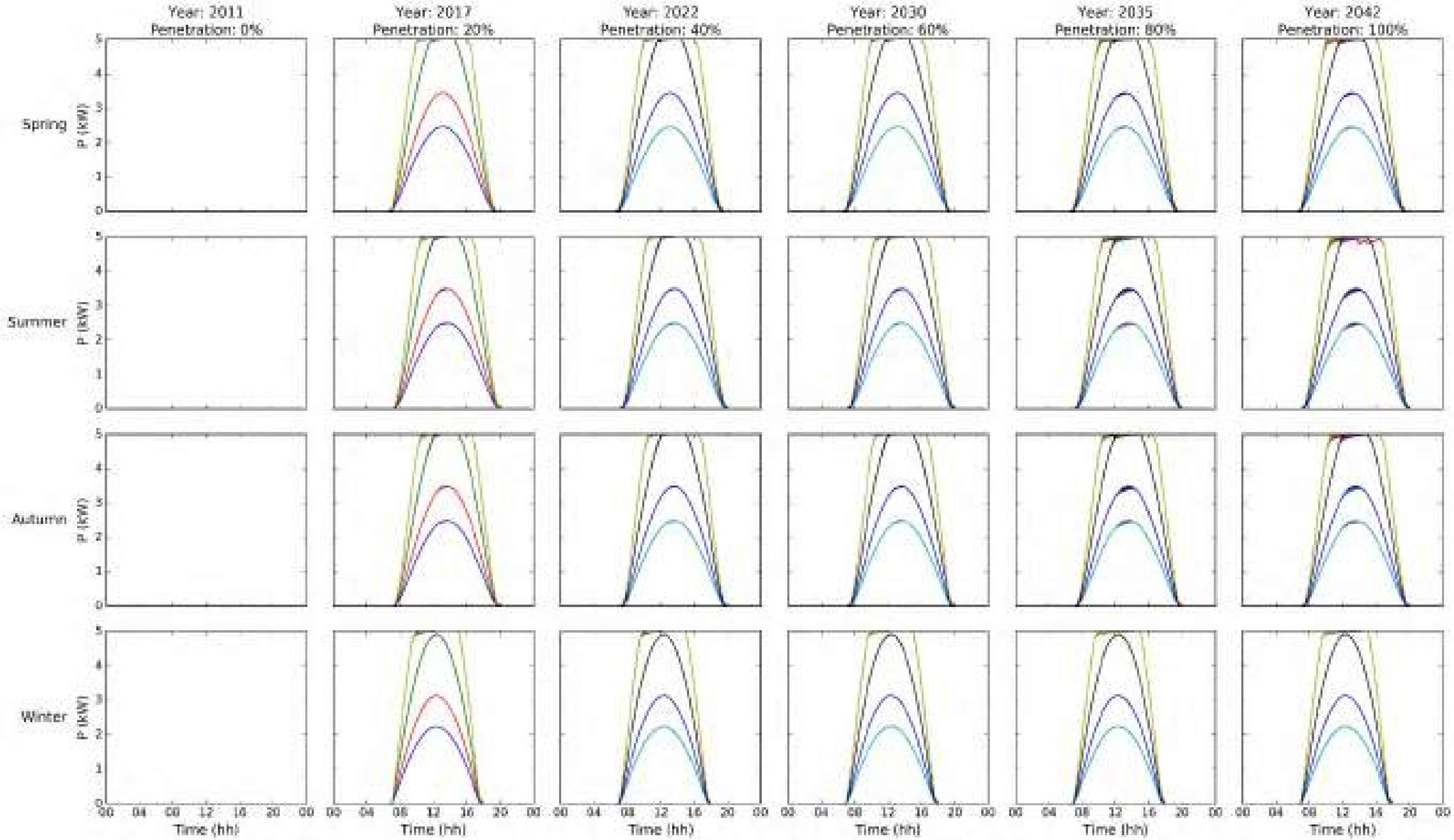


Figure 4-47 CRE21 NS BES Daily PV System Active Power Output

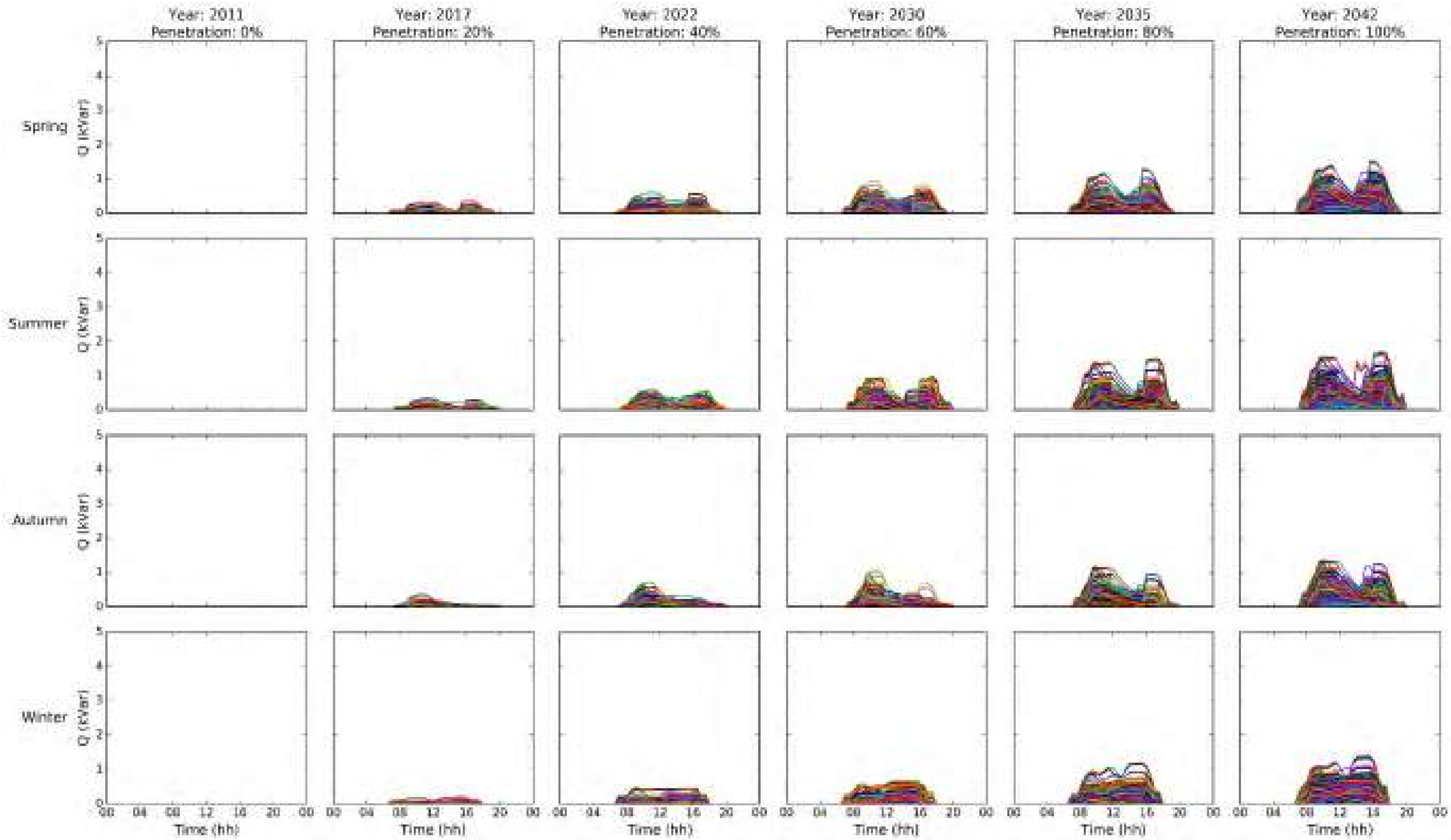


Figure 4-48 CRE21 NS BES Daily PV System Reactive Power Absorption

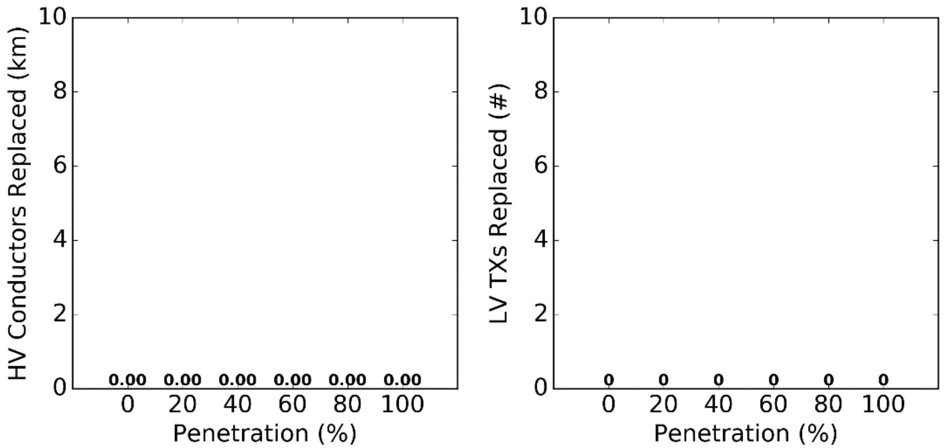


Figure 4-49 CRE21 NS BES Conductor and Transformer Replacement Information

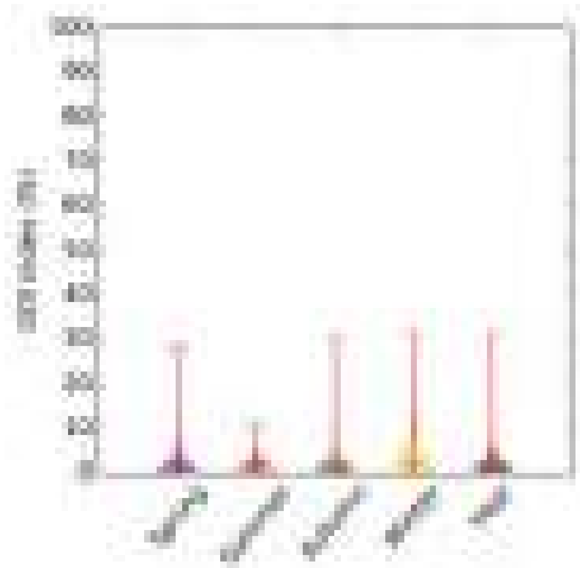


Figure 4-50 CRE21 NS BES Grid Dependence Index

4.4.3 Seasonal Analysis

The results for the seasonal analysis for the OTS BES case are demonstrated in this section. Starting with Figure 4-51, the two most constraining factors in this network (as defined by the BAU case), customer voltages and transformer utilisation, are shown. Considering the percentage of non-compliant customers, results show that none of the customers will ever face voltage issues regardless the penetration and season. Considering the aforementioned, results highlight that the adoption of NS BES systems can provide significant benefits to this technical issue.

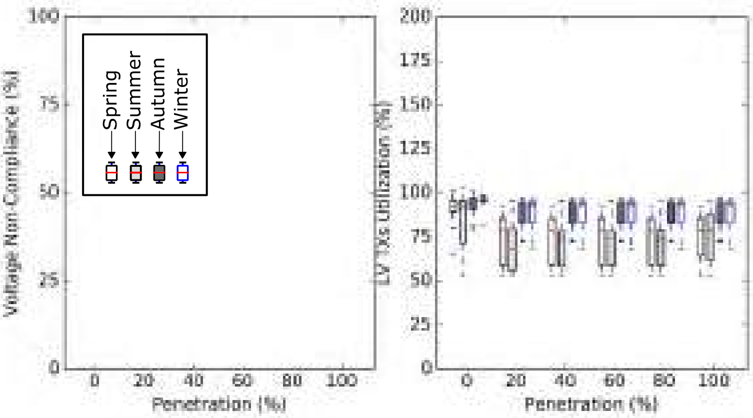


Figure 4-51 CRE21 NS BES Percentage of Voltage Non-Compliant Customers (left) and Maximum LV Transformer Utlisation (right)

Considering the utilization of LV transformers results also show that the performance was almost the same as with the results when considering OTS BES, where none of the transformers is overloaded. However, it should be noted that this performance is achieved due to the operation of the NS BES systems alone and not by augmentation. As a matter of fact, and compared to the results of the OTS BES case, Figure 4-53 (right) shows that no augmentation was required at any penetration level or season when BES systems operate with the NS control logic. Moreover, considering the utilization of HV and LV lines shown in Figure 4-52, a significantly lower utilization level is observed in all lines. As previously explained, this improved behaviour is the result of household exports being significantly reduced and, hence, the utilization level of assets. It is also important to note that the reduction achieved in customer voltages is leading to significantly less absorption of reactive power which contributes to the lower utilisation levels of assets. As such, results show that the adoption of BES systems with network a smart control logic can be an effective solution in keeping the utilization of all assets within their limits across all penetration levels and seasons.

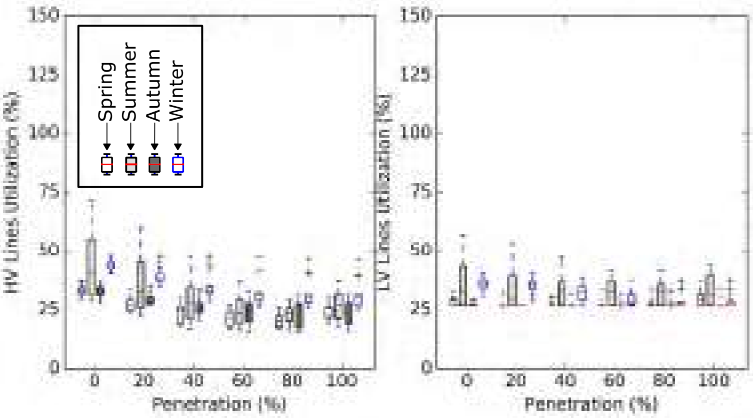


Figure 4-52 CRE21 NS BES HV and LV Lines Utilisation (Seasonal)

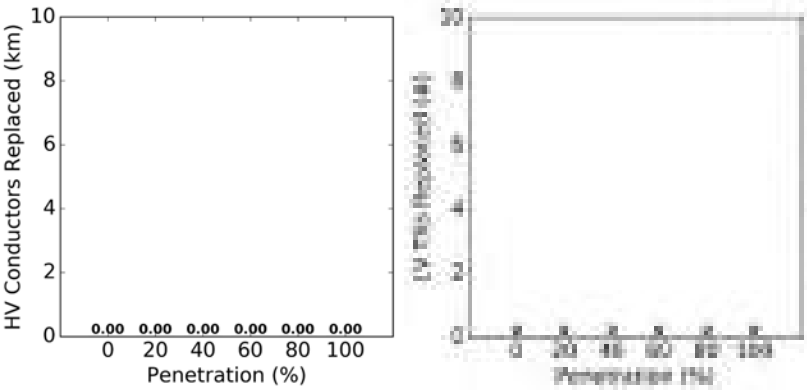


Figure 4-53 CRE21 NS BES Conductor and Transformer Replacement Information (Seasonal)

In terms of the effects the investigated solution has on curtailment, Figure 4-54 shows the curtailment recorded across all penetration levels and seasons, both for individual customers and in the aggregate. As it can be seen and aligned with the results shown in the single case analysis, none of the customers had to curtail any generation regardless the penetration level and season. These findings validate that a smarter BES control logic can provide added value to their owners it can help keep their voltage below the volt-watt triggering point, hence have less exposure to curtailment.

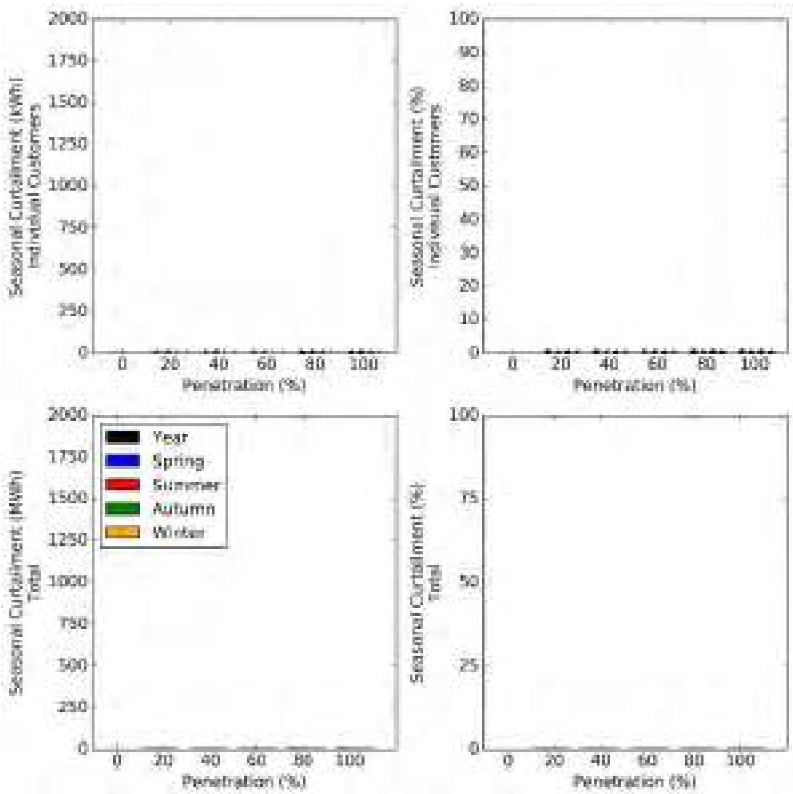


Figure 4-54 CRE21 NS BES PV Generation Curtailment Information (Seasonal)

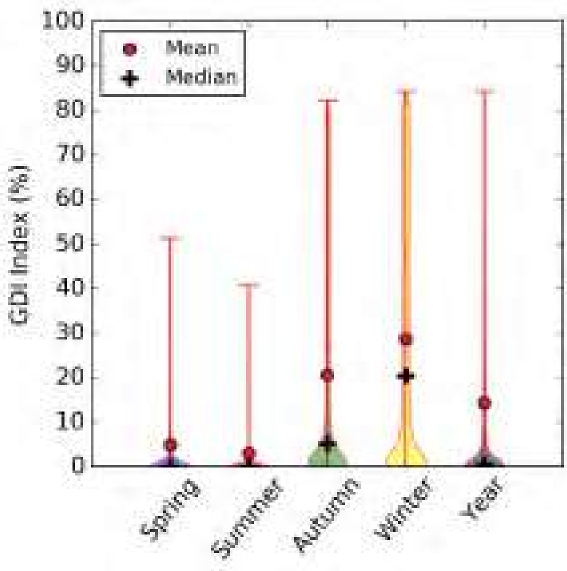


Figure 4-55 CRE21 NS BES Grid Dependence Index (Seasonal)

4.5 Dynamic Voltage Target at Zone Substation OLTC

This section presents the simulation results from the operation of the CRE21 HV feeder with a Dynamic Voltage Target at the Zone Substation (DVT-ZS) across different penetration levels (0 to 100% in 20% steps) and for different seasons (i.e., Spring, Summer, Autumn, Winter).

4.5.1 Adopted Settings

The tailored response curve for this network is shown in Figure 4-56. As discussed in the Section 2.5.1, the selection of (P1, V1) and (P2, V2) depends on the characteristics of each network. Here, the minimum statutory limit is considered for V1 to maximise the headroom and P1 is set to 0MW for simplicity. With CRE21 being an urban distribution network, V1 is set to 0.94 pu. Additionally, the minimum demand is found to be 1.4MW (based on the results in Task 3 for the BAU case with 0% PV penetration) and this value is used for P2. Overall, this configuration ensures that the maximum voltage headroom is reached when there is a net active power export to the upstream network through the zone substation.

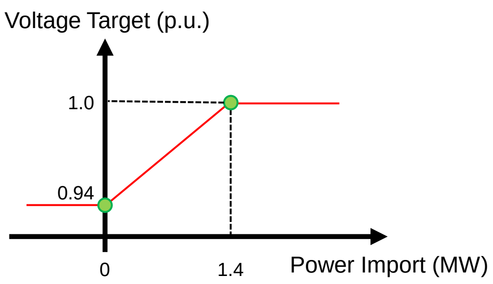


Figure 4-56 OLTC Response Curve for CRE21

4.5.2 Key Findings

A summary of the key findings is listed below.

- A dynamic voltage target is at the Zone Substation is shown to be effective in mitigating voltage violations in LV feeders. While minor violations are still recorded for several penetrations, the magnitude is negligible (less than 0.6% above the statutory limit).
- The main bottleneck in this case is the thermal capacity of LV distribution transformers, asset congestion occurred as early as 20% PV penetration. A main contributing factor is due to the extra PV generation as a result of the lower voltages across the network, and thus less curtailment from the Volt-Watt function in PV inverters.
- Thanks to the increased voltage headroom, total curtailment (due to the Volt-Watt function in inverters) is significantly reduced when compared with the BAU case.

Furthermore, a summary of the analysis (technical issues highlighted in red and curtailment highlighted in green) for the different penetration levels is presented in Table 4-5.

Table 4-5 HV Feeder U2 (CRE21) – DVT-ZS Key Findings

	0% (2011)	20% (2017)	40% (2022)	60% (2030)	80% (2035)	100% (2042)
Non-Compliant Customers [%]	0	0	0	0	0	0
Max Voltage [p.u]	1.082	1.103	1.106	1.097	1.095	1.106
Max HV Conductor Utilization [%]	71	65	62	60	77	103
Congested HV Conductors [km]	0	0	0	0	0	0
Max LV Conductor Utilization [%]	54	52	80	83	83	86
Congested LV Conductors [km]	0	0	0	0	0	0
Max LV TX Utilization [%]	92	105	159	159	160	204
Congested LV TXs [#,%]	[0, 0]	[2, 2]	[2, 2]	[2, 2]	[4, 5]	[14, 17]
Annual Curtailment [MWh,%]	[0, 0]	[2, 0.02]	[2, 0.02]	[1, 0.01]	[3, 0.01]	[5, 0.01]

4.5.3 Single-Day Analysis

This section presents a single-day analysis for each of the penetration levels and seasons for the DVT-ZS case. As mentioned in Section 3.6.2, these assessments use a clear-sky day (for their corresponding season) as this is expected to result in higher technical problems for the network.

The daily assessments demonstrate the operation of the network through:

1. Customer voltages (Figure 4-57, Page 110);
2. HV line utilisation (Figure 4-58, Page 111);
3. LV line utilisation (Figure 4-59, Page 112); and,
4. LV transformer utilisation (Figure 4-60, Page 113).

Furthermore, to understand the effects of seasonality and PV penetration on the operation of PV inverters, this analysis also demonstrates:

5. the daily active power output of PV systems (Figure 4-61, Page 114); and,
6. the reactive power of PV systems (Figure 4-62, Page 115).

Finally, to understand the underlying mechanism behind a dynamic voltage target, the analysis also shows:

7. the daily active power import (Figure 4-63, Page 116);
8. the tap position (Figure 4-64, Page 117); and,
9. the busbar voltage at the secondary terminal (Figure 4-65, Page 118).

Starting with the customer voltages (Figure 4-57, Page 110), it can be seen that there is a noticeable reduction in network voltages during daylight hours. In fact, voltage violations did not occur until 80% PV penetration is reached. This finding can be further validated by examining the behaviour of the Substation OLTC (Figure 4-63, Page 116 and Figure 4-64, Page 117) where the tap position is incrementally lowered as the total power import through the zone substation decreases. Nonetheless, voltage issues are still observed beyond 80% PV penetration, which are contributed by the limited number of tap positions available to reduce the supply voltage even higher. As shown in Figure 4-64 and Figure 4-65, the voltage at the secondary terminal of the zone substation transformer did not reach the desired 0.94 pu even after exhausting all available tap positions.

By analysing the operation of PV inverters (Figure 4-61, Page 114), it can be reaffirmed that curtailment has indeed reduced substantially compared to the BAU case (in Task 3). For instance, noticeable curtailment is only observed starting from 80% penetration; in contrast, curtailment is already apparent at 20% penetration for the BAU case. Furthermore, thanks to the additional voltage headroom created by the zone substation OLTC, lower reactive power absorption is recorded across the board (Figure 4-62, Page 115) compared with the BAU case.

Finally, in terms of the utilisation level of network assets (Figure 4-58 to Figure 4-60), it can be seen that, due to the higher total PV generation, more severe congestion is observed across the network when compared with the BAU case.

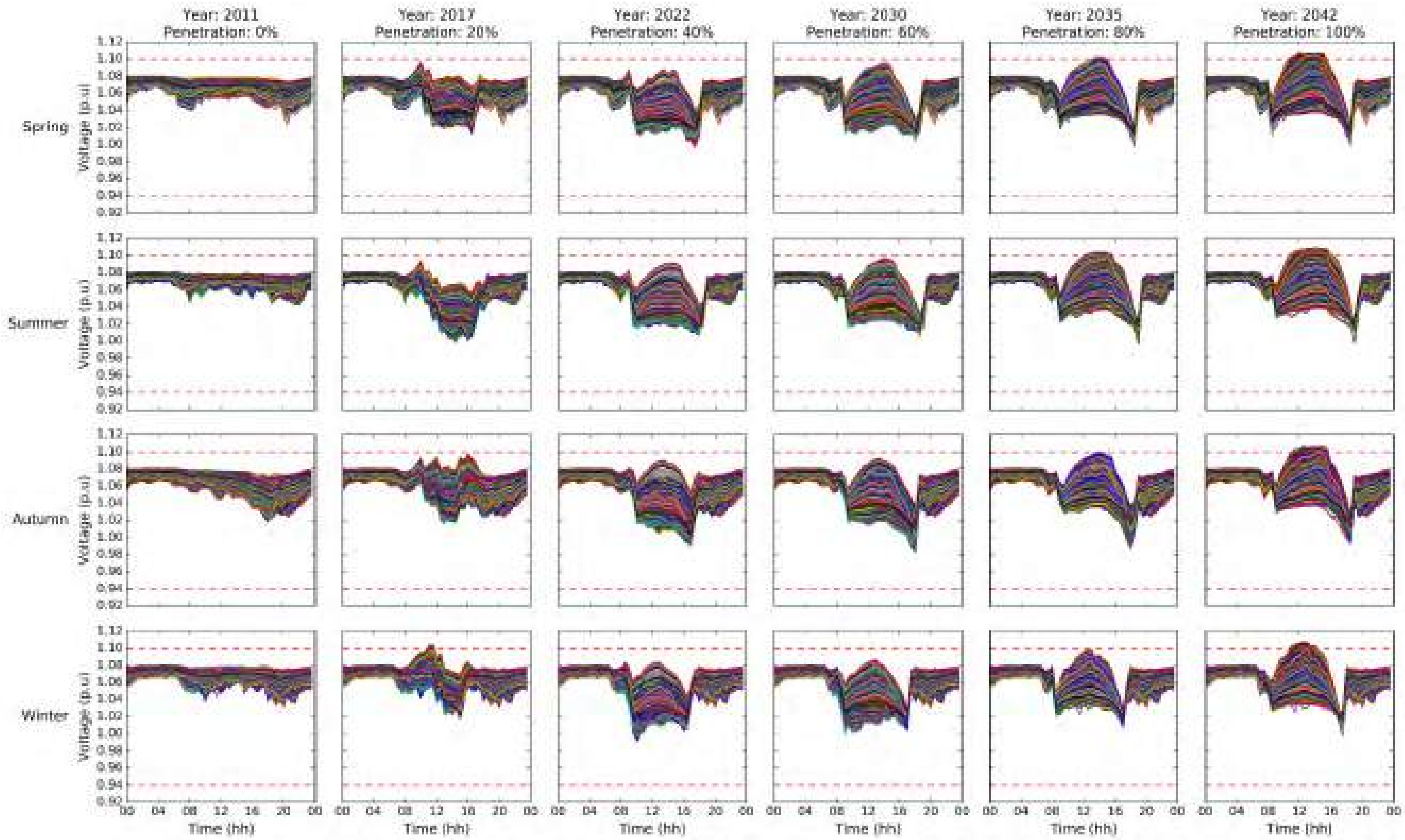


Figure 4-57 CRE21 DVT-ZS Daily Customer Voltages

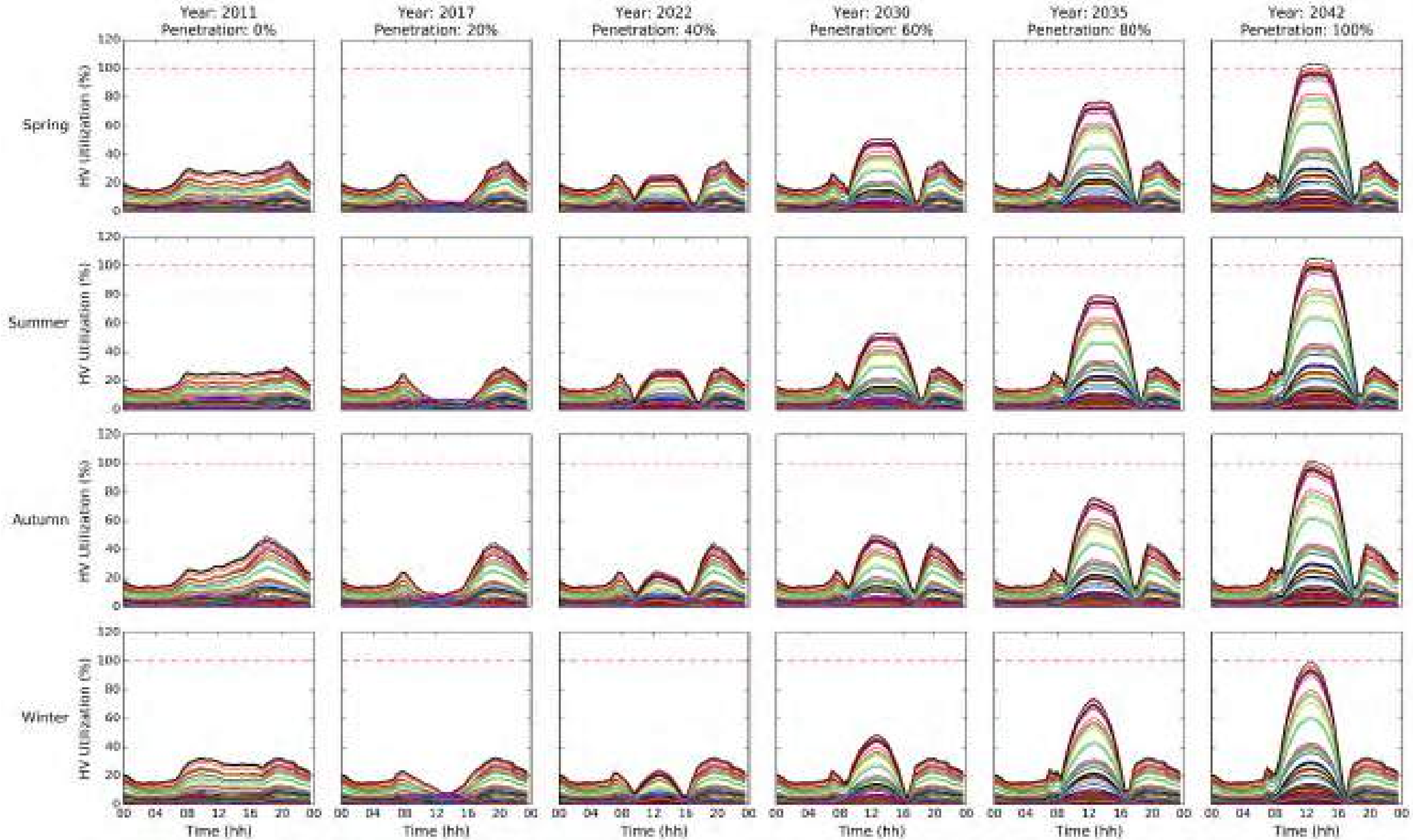


Figure 4-58 CRE21 DVT-ZS Daily HV Line Utilisation

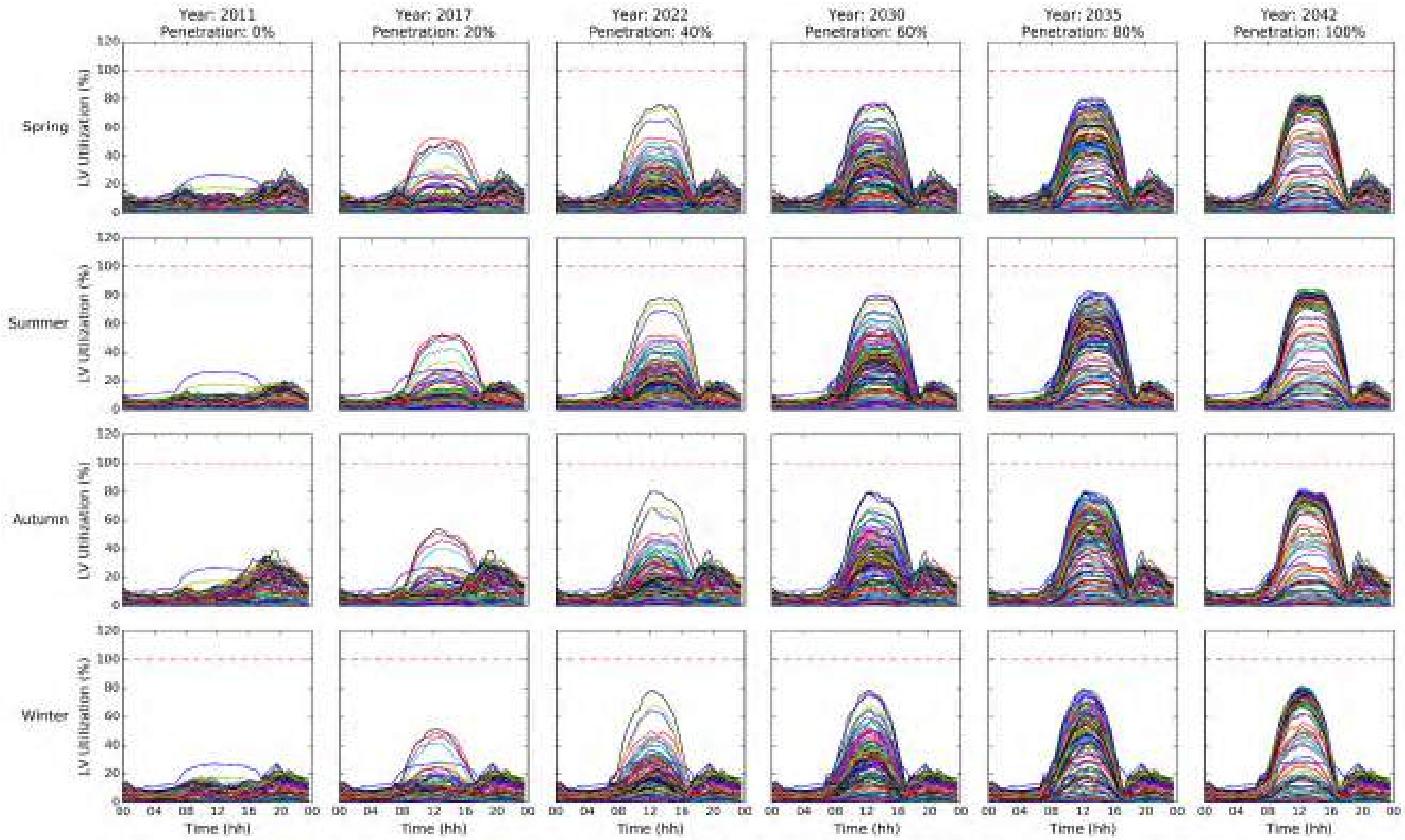


Figure 4-59 CRE21 DVT-ZS Daily LV Line Utilisation

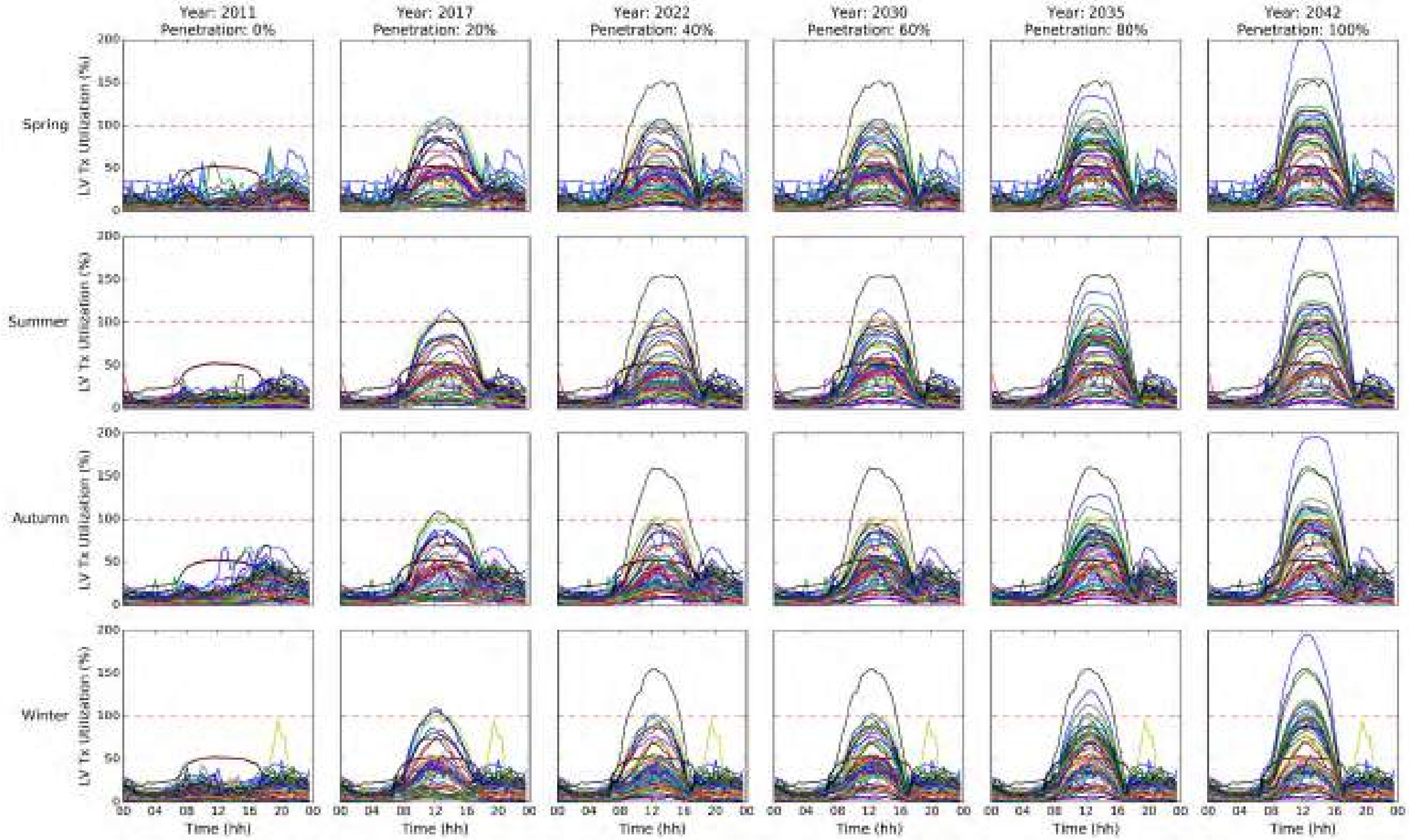


Figure 4-60 CRE21 DVT-ZS Daily LV Transformer Utilisation

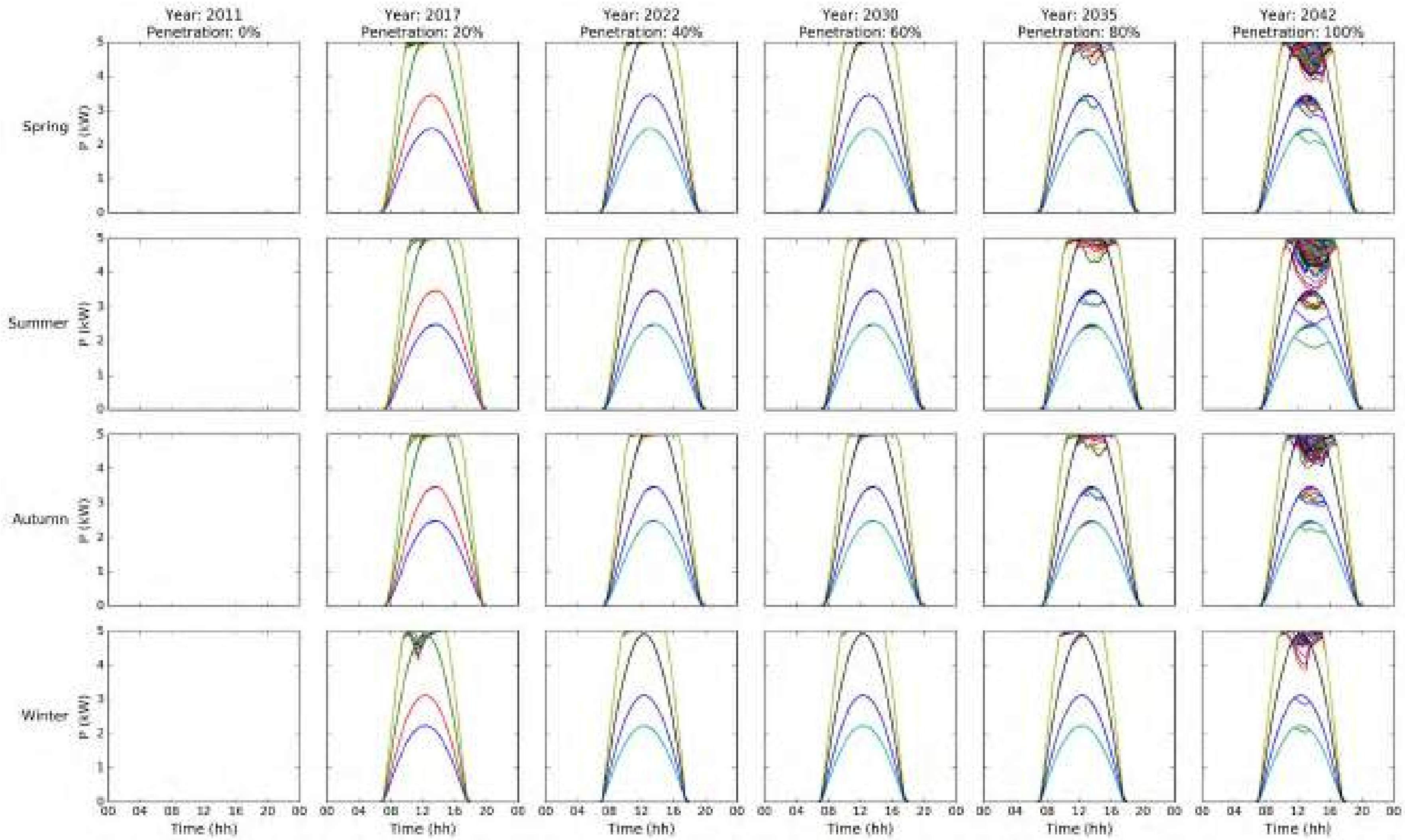


Figure 4-61 CRE21 DVT-ZS Daily PV System Active Power Output

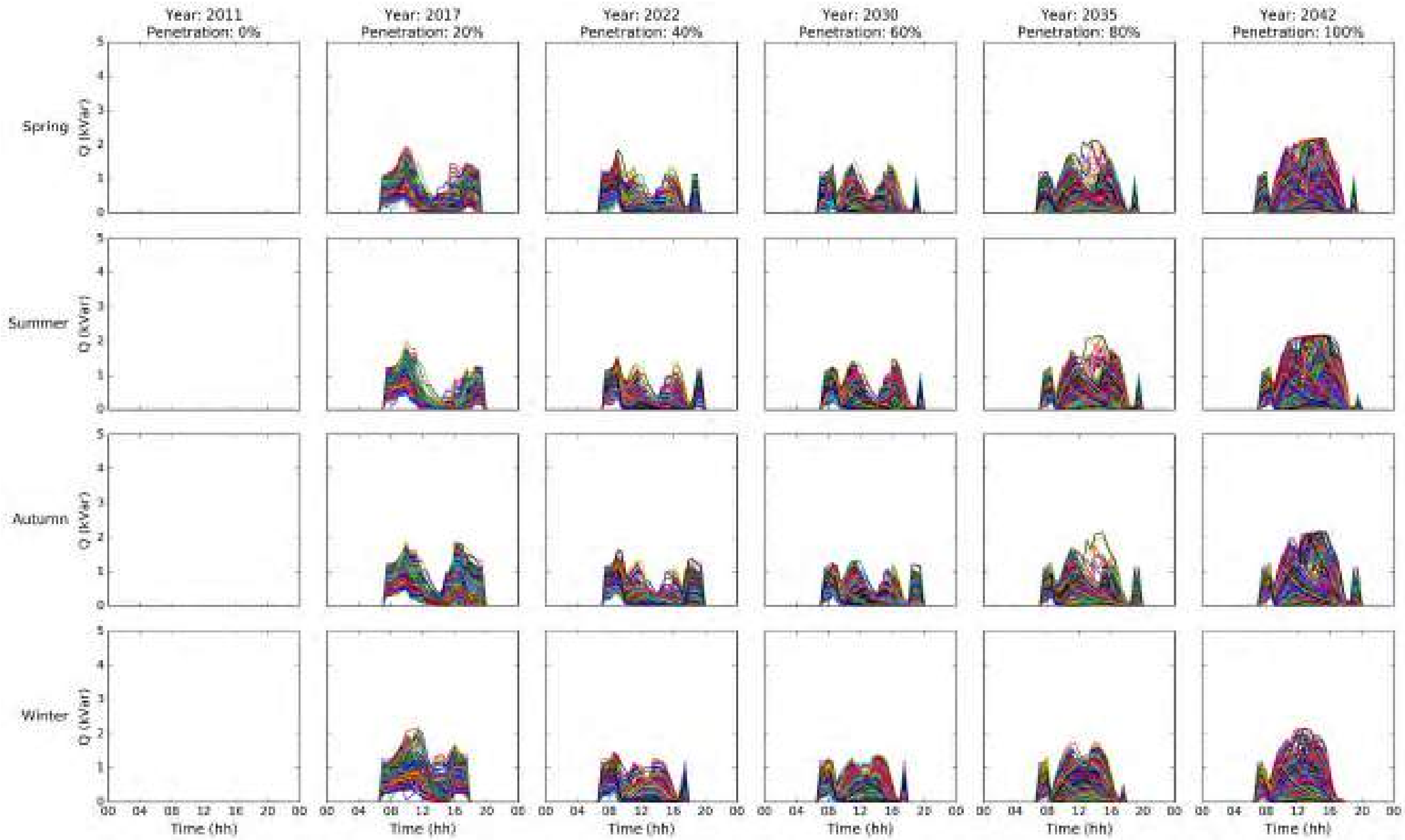


Figure 4-62 CRE21 DVT-ZS Daily PV System Reactive Power Absorption

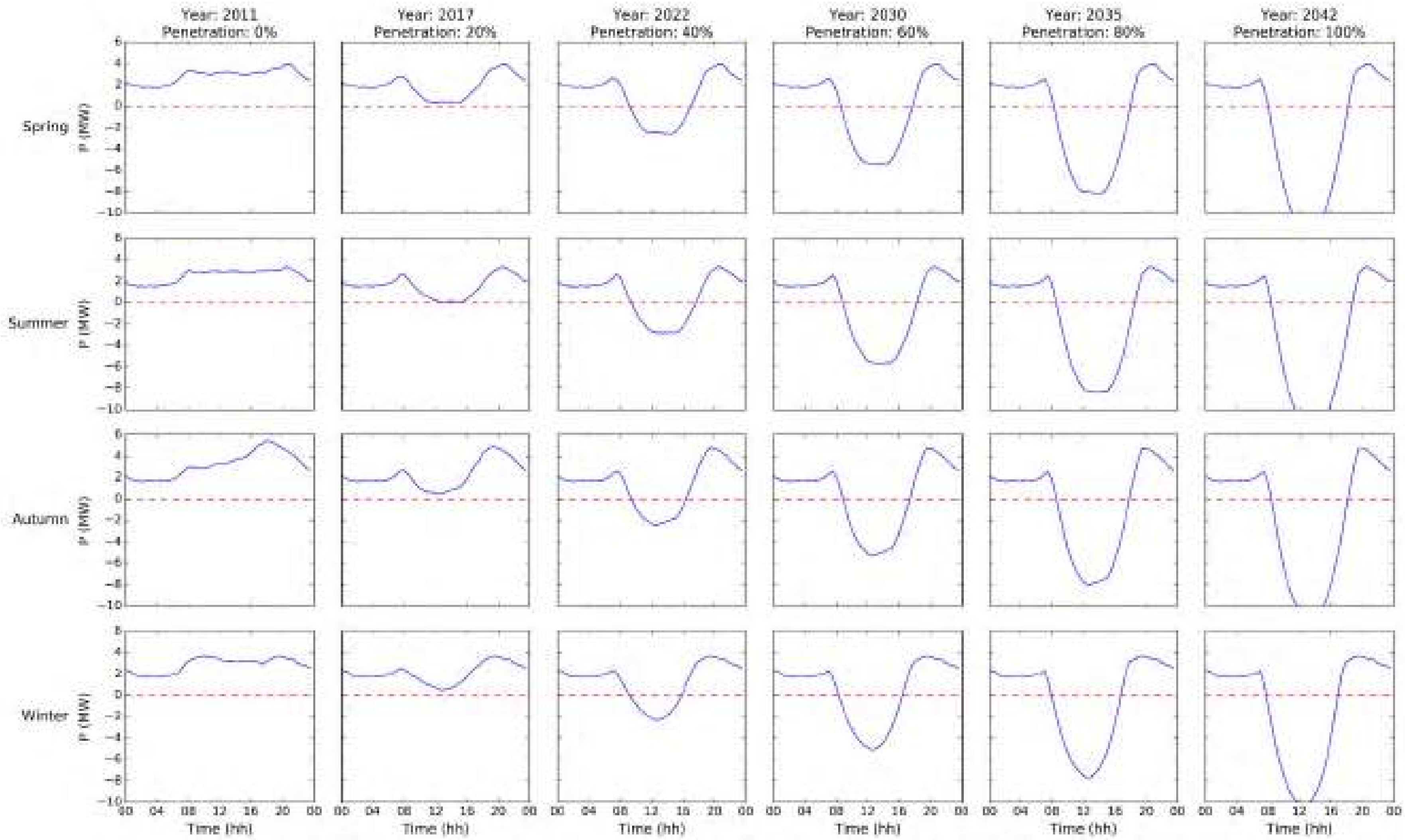


Figure 4-63 CRE21 DVT-ZS Daily Zone Substation Power Import

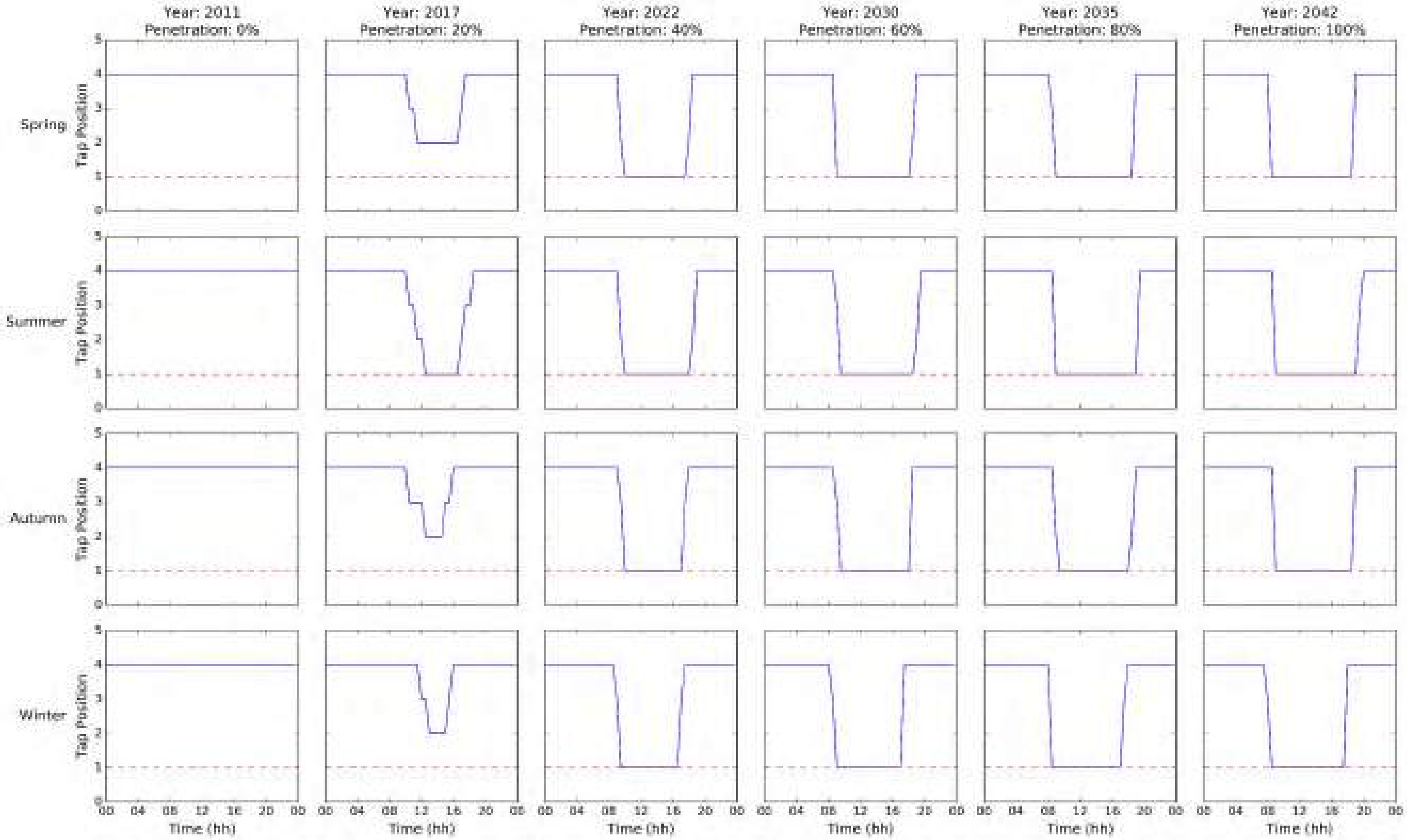


Figure 4-64 CRE21 DVT-ZS Daily Zone Substation Tap Position

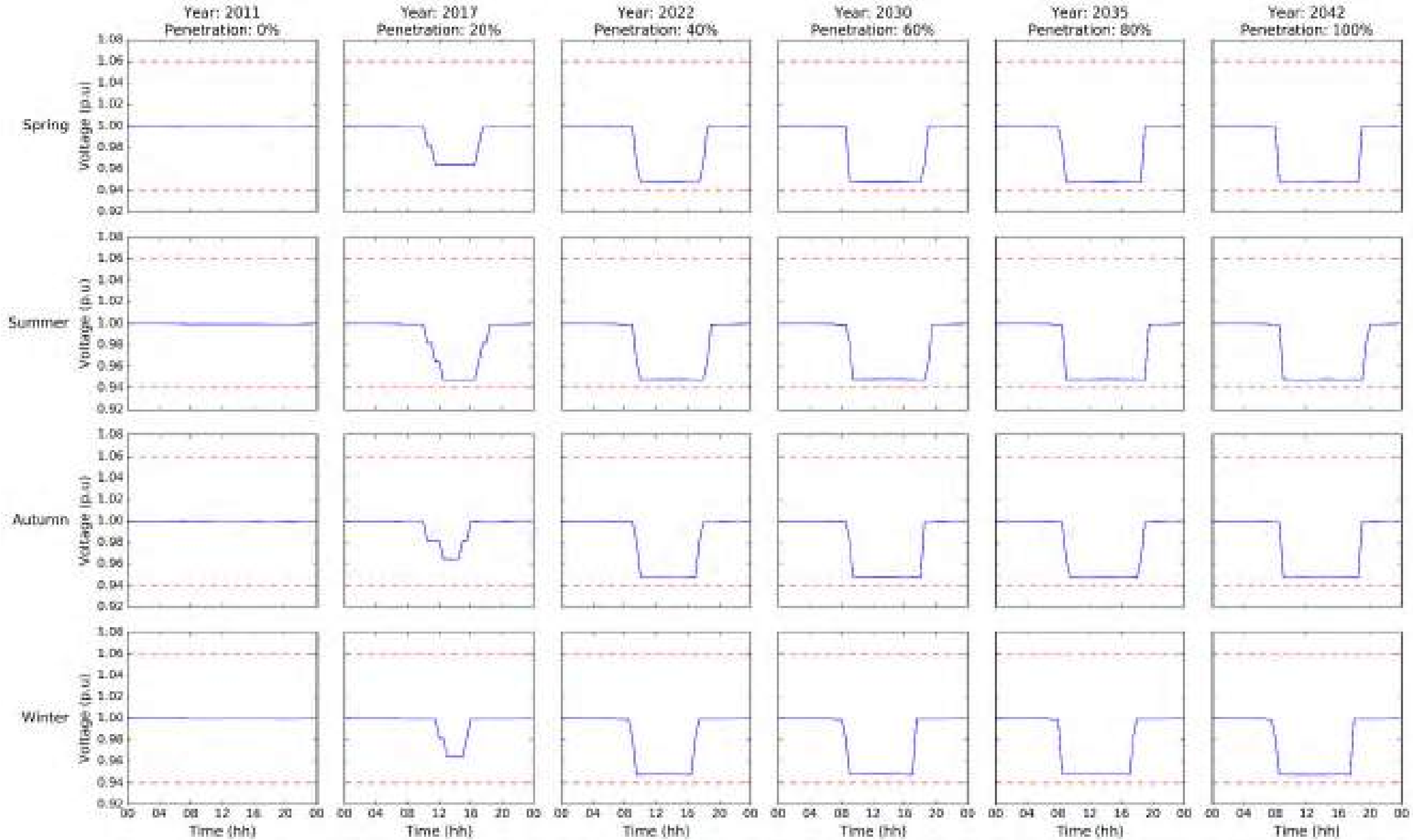


Figure 4-65 CRE21 DVT-ZS Daily Zone Substation Secondary Terminal Voltage

4.5.4 Seasonal Analysis

The results for the seasonal analysis are demonstrated in this section. Starting with Figure 4-66, it is evident that LV transformer utilisation is the main limiting factor for PV penetrations beyond 40%. Furthermore, and aligned with the results in the single-day analysis, the voltage compliance becomes an issue for several customers beyond 80% PV generation.

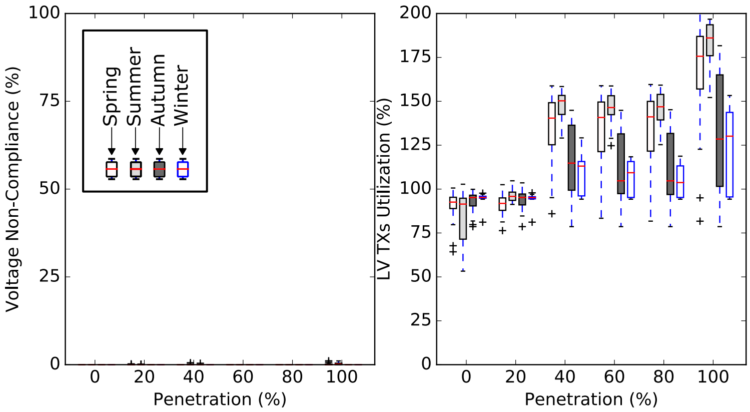


Figure 4-66 CRE21 DVT-ZS Percentage of Voltage Non-Compliant Customers (left) and Maximum LV Transformer Utlisation (right)

In contrast to the issues in LV transformers, both HV and LV lines operated within their thermal limits across all penetration levels and seasons, as shown in Figure 4-67.

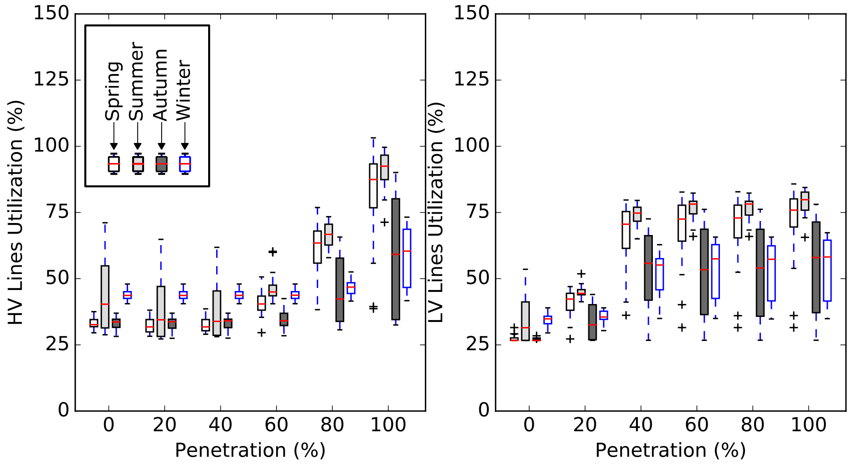


Figure 4-67 CRE21 DVT-ZS HV and LV Lines Utilisation

Finally, PV curtailment is only recorded for a small number for customers, which are assumed to be the customers located in weak parts of the network. Among these customers, the total energy curtailed can be as high as over 10% during summer. Nonetheless, when compared with the BAU case (in Task 3), it is clear that a dynamic voltage target at the zone substation can be very beneficial in terms of reducing the PV curtailment for LV customers.

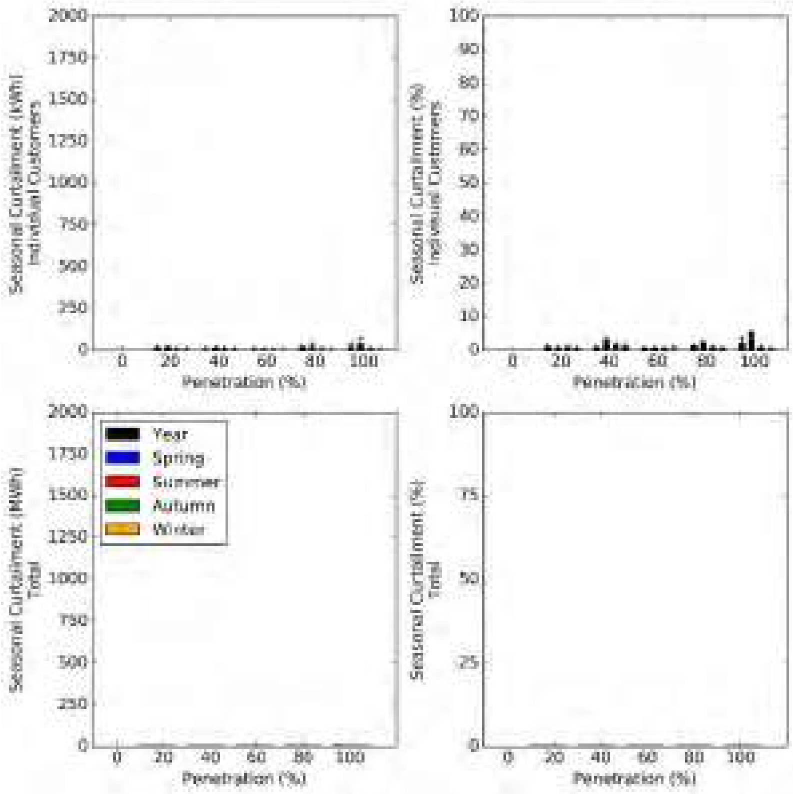


Figure 4-68 CRE21 DVT-ZS PV Generation Curtailment Information

4.6 Summary of Findings

Based on the analyses and solutions investigated for the HV feeder U2 (i.e., CRE21), the following observations/recommendations are listed for this particular feeder.

1. A more tailored set of Volt-Watt and Volt-Var settings is proved to be highly effective in limiting voltage problems in the network. Regardless of PV penetrations ad seasons, the maximum voltage in the network never exceeds above 1.10pu. While the curtailment of PV generation was found to be approximately an additional 1% for each penetration when compared to the BAU case, this can still be considered negligible given the significant benefits provided (i.e., full mitigation of voltage issues). For example, considering the most critical penetration (i.e., 100%) the total curtailment accounts to just 1.2% of the total solar PV generation.

2. The adoption of LV OLTC-fitted transformers in combination with adjustment of off-load tap changers as well as augmentation of congested assets can effectively manage all technical issues and shift the hosting capacity to 100% (compared to 40% when off-load taps are considered alone, see Task 3 section 5.2 [1]). For those LV transformers where their off-load tap capability was not able to mitigate the voltage rise/drop issues, their replacement with an OLTC-fitted LV transformer and adopting the proposed OLTC control logic proves to be highly effective in keeping all customer voltages within the statutory voltage limits, regardless the penetration and season. In terms of PV generation curtailment, it was found to be almost negligible.

3. The adoption of OTS BES systems in combination with adjustment of off-load tap changers as well as augmentation of congested assets can effectively manage all technical issues and shift the hosting capacity to 80% (compared to 40% when off-load taps are considered alone, see Task 3 section 5.2 [1]). From 80% onwards the voltage issues become the bottleneck. Almost the same voltage performance was observed as when the adjustment of off-load tap changers is considered alone. Moreover, almost the same level of augmentation was required when compared to the augmentation results in Task 3. Considering the aforementioned, the results highlighted that he

adoption of OTS BES has limited to no contribution in shifting the corresponding capacity. This is due to the limitations identified on the OTS BES operation where:

a. OTS BES systems do not fully discharge overnight. This is due to insufficient energy consumption of most customers. As a consequence, their ability to store surplus PV generation the following day can be significantly reduced.
b. OTS BES systems reach full SOC very early. With a partially charged BES system, surplus PV generation that occurs early in the morning can lead to a full SOC before or during high PV generation, resulting in PV exports.

4. The adoption of NS BES systems in combination with adjustment of off-load tap changers as well as augmentation of congested assets can effectively manage all technical issues and shift the hosting capacity to 100% (compared to 40% when off-load taps are considered alone, see Task 3 section 5.2 [1]). Compared to the results obtained when OTS BES systems are adopted, the performance in terms of voltage and asset utilization is significantly increased. Results show that NS BES systems are highly effective in significantly reducing the utilization level of all assets and more importantly alleviate all transformer congestion issues for all penetration and seasons. While the adoption of the network smart control logic might lead to slightly higher grid imports for customers than with the OTS control, the corresponding expense might be considerably lower than the capital investments required to provide the same network benefits with asset-intensive solutions, such as network reinforcements.

5. The adoption of a dynamic voltage target at the zone substation OLTC is shown to be very effective in mitigating voltage issues during peak generation hours by creating additional headroom. This resulted in voltage issues only occurring beyond 80% penetration. Nonetheless, due to the nature of OLTCs (i.e., affecting voltages only), this solution is not able to address any congestion issues in the network. In fact, without considering other solutions, it can increase network congestion as a result of less PV curtailment from the Volt-Watt functions in PV inverters. Furthermore, when compared with a permanent setting (e.g., the solutions investigated in Task 3), a dynamic voltage target offers the added benefit of not affecting the voltage legroom during peak demand periods. This can be beneficial for networks that experiences heavy demands at night. Finally, it is worth noting that this analysis did not consider the impact of the investigated solution on other HV feeders that could be connected to the same zone substation.

5 Case Study 2: HV Feeder R1 (Long Rural, SMR8)

5.1 Tailored Volt-Watt and Volt-Var Settings

This section presents the results obtained from the operation of the SMR8 HV feeder with Tailored Volt-Watt and Volt-Var PV inverter settings (T-VW-VV) across different penetration levels (0 to 100% in 20% steps) and for different seasons (i.e., Spring, Summer, Autumn, Winter).

5.1.1 Key Findings

A summary of the key findings is listed below.

- When Tailored PV inverter settings are adopted (compared to those imposed by the DNSPs in Victoria) and without any other solution put in place (e.g., adjustment of off-load taps) the feeder is now able to host up to 20% PV penetration (2022). At this point, the bottleneck becomes the distribution transformers which become overloaded.
- It has been observed that voltage issues are fully mitigated when compared with the BAU case. This highlights that more tailored Volt-Watt and Volt-Var settings can be an effective solution to voltage issues.
- A slight reduction of the HV lines utilisation is observed when compared to the BAU case. This is due to the higher active power curtailment from solar PV due to the more tailored and Tailored Volt-Watt settings. Consequently, the HV lines operate within their thermal limits for all penetration levels.
- A slight reduction of utilisation of LV lines is noticed when compared to the BAU case. This is due to the higher active power curtailment from solar PV due to the more tailored and Tailored Volt-Watt settings.
- A reduced utilisation and number of congested LV transformers is observed when compared to the BAU case. Congestion occurs from 20% PV penetration onwards for a small number of transformers (up to 2 until 60% penetration).
- The curtailment of PV generation was found to be approximately an additional 1% for each penetration when compared to the BAU case. While the amount of curtailment is doubling, this can still be considered negligible given the significant benefits provided (i.e., full mitigation of voltage issues). For example, considering the most critical penetration (i.e., 100%) the total curtailment accounts to just 2% of the total solar PV generation.

Table 5-1 HV Feeder R1 (SMR8) – T-VW-VV Key Findings

	0% (2011)	20% (2017)	40% (2022)	60% (2030)	80% (2035)	100% (2042)
Non-Compliant Customers [%]	0	0	0	0	0	0
Max Voltage [p.u]	1.09	1.09	1.099	1.099	1.099	1.099
Max HV Conductor Utilization [%]	98	106	95	92	89	88
Congested HV Conductors [km]	0	0	0	0	0	0
Max LV Conductor Utilization [%]	58	57	57	57	67	85
Congested LV Conductors [km]	0	0	0	0	0	0
Max LV TX Utilization [%]	89	101	101	110	122	220
Congested LV TXs [#,%]	[0, 0]	[1, 0]	[1, 0]	[2, 0]	[7, 0]	[20, 2]
Annual Curtailment [MWh,%]	[0, 0]	[29, 0.94]	[140, 2.06]	[212, 1.82]	[364, 2.07]	[448, 2.19]

5.2 LV OLTC-fitted Transformers

This section presents the results obtained from the operation of the SMR8 HV feeder considering the solution of replacing off-load tap changer-fitted LV transformers with OLTC-fitted LV transformers according to the methodology specified in section 2.2.5. In the case of an OLTC-fitted LV transformer being installed the corresponding control logic detailed in section 2.2.4 is adopted and the analysis results are collected across different penetration levels for different seasons. The presentation of results follows a similar format as presented in the previous section.

It should be noted, and as stated in section 2.2.5, that this solution (installation of LV OLTC -fitted transformers) is only considered once the off-load capability of a LV transformers is fully utilised and available taps to reduce/increase are exhausted. This allows to utilise – to the extend is possible – any flexibility provided by existing assets (i.e., off-load tap changers), hence reduce the overall investment in new assets (i.e., OLTC). Considering the congestion issues, given that the investigated solution does not manage any power flows, augmentation is considered for congested assets (i.e., conductors, transformers).

5.2.1 Key Findings

A summary of the key findings is listed below.

- The adoption of this solution (i.e., off-load taps, OLTC, augmentation) can effectively manage all technical issues and shift the Hosting capacity to 100% (compared to 20% when off-load taps are considered alone, see Task 3).
- For those LV transformers where their off-load tap capability was not able to mitigate the voltage rise/drop issues, their replacement with an OLTC-fitted LV transformer and adopting the proposed OLTC control logic proves to be highly effective in keeping all customer voltages within the statutory voltage limits, regardless the penetration and season.
    - The total number of OLTC-fitted transformers installed for this Feeder accounts to 47% of the total LV transformers (335 out of 704). While the 47% of total LV transformers were installed an OLTC, most installations (>35%) happened at 20% of penetration.
    - The capacities of the OLTCs correspond to relatively small rating transformers (<100kVA).
    - The average daily number of tap changes was found to around 10 while the maximum number of taps never exceeded 30. These low number of tap changes can lead to a reduced wear and tear of the OLTC hence requiring less maintenance costs.
- No augmentations on the LV and HV conductors were needed regardless the penetration levels. This was aligned with the findings in Task 3.
- Augmentation of transformers was required, and it was found to be very effective for the congested LV networks as it allows host more solar PV penetration. Small number of LV transformers (up to 5) is required to be augmented at penetration levels of up to 80%. Significant increase in transformers that need to be replaced (12) was found at 100% PV penetration.
- Augmentation results, and as expected, were found to be almost the same as those presented in Task 3.
- The curtailment of PV generation was found to be almost negligible when compared to the BAU case shown in Task 3. Furthermore, the level of curtailment was significantly lower than the when the adjustment of off-load taps alone is considered (see Task 3). Considering the most critical penetration (i.e., 100%) the total curtailment accounts to just 0.03% of the total solar PV generation. In other words, the adoption of this solution provides significant benefits to both customers (i.e., minimal curtailment) and network (i.e., voltage and congestion issues).

A summary of the technical issues (highlighted red), curtailment (highlighted green), and augmentation (highlighted blue) for the different penetration levels is presented in Table 5-2.

Table 5-2 HV Feeder R1 (SMR8) - LV OLTC Key Findings

	0% (2011)	20% (2017)	40% (2022)	60% (2030)	80% (2035)	100% (2042)
Non-Compliant Customers [%]	0	0	0	0	0	0
Max Voltage [p.u]	1.09	1.109	1.096	1.102	1.101	1.103
Max HV Conductor Utilization [%]	98	94	83	81	81	80
Congested HV Conductors [km]	0	0	0	0	0	0
Max LV Conductor Utilization [%]	58	57	57	56	66	86
Congested LV Conductors [km]	0	0	0	0	0	0
Max LV TX Utilization [%]	89	100	100	100	100	100
Congested LV TXs [#,%]	[0, 0]	[0, 0]	[0, 0]	[0, 0]	[0, 0]	[0, 0]
Annual Curtailment [MWh,%]	[0, 0]	[1, 0.03]	[2, 0.03]	[3, 0.03]	[5, 0.03]	[5, 0.03]
HV Conductors Replaced [km]	0	0	0	0	0	0
LV Conductors Replaced [km]	0	0	0	0	0	0
LV TXs Replaced [#,%]	[0, 0]	[5, 0]	[0, 0]	[1, 0]	[8, 1]	[12, 1]
LV TXs Replaced per Capacity**	[0, 0, 0, 0, 0, 0, 0, 0]	[4, 0, 0, 1, 0, 0, 0, 0]	[0, 0, 0, 0, 0, 0, 0, 0]	[0, 1, 0, 0, 0, 0, 0, 0]	[0, 1, 0, 7, 0, 0, 0, 0]	[0, 0, 0, 4, 7, 0, 1, 0]
LV OLTC Installed [#,%]	[0, 0]	[275, 39]	[14, 2]	[13, 2]	[21, 3]	[12, 2]
LV OLTC Installed per Capacity**	[0, 0, 0, 0, 0, 0, 0, 0]	[222, 15, 10, 14, 9, 0, 4, 1]	[14, 0, 0, 0, 0, 0, 0, 0]	[7, 1, 3, 1, 1, 0, 0, 0]	[11, 1, 6, 2, 1, 0, 0, 0]	[4, 1, 4, 2, 1, 0, 0, 0]
LV OLTC Mean/Max Daily Taps [#,#]	[0, 0]	[8, 24]	[10, 25]	[10, 26]	[11, 27]	[11, 28]

***The transformer kVA capacities correspond to: [>=10, 10-50, 50-100,100-200, 200-300, 300-400, 400-500, 500-700]*

5.3 Off-the-Shelf BES Systems

This section presents the results obtained from the operation of the SMR8 HV feeder considering the adoption of OTS BES systems by solar PV owners. Such analysis will allow understand the extent to which the widespread adoption of this emerging commercially available residential-scale technology (i.e., OTS BES system) can help reduce the household exports from excess solar PV generation, hence reduce or alleviate the corresponding technical issues. The analysis follows the methodology specified in section 2.3.3 and results are collected across different penetration levels for different seasons. The presentation of results follows a similar format as presented in the previous sections. It is important to highlight that this solution considers the adjustment of off-load tap changers and augmentation where assets (i.e., conductors, transformers) are congested.

5.3.1 Key Findings

A summary of the key findings is listed below.

- The adoption of this solution (i.e., off-load taps, OTS BES, augmentation) was found to provide little to no additional benefits in terms of technical issues as the Hosting capacity remains at 20% (same as the BAU). At this point, the bottleneck becomes the voltage issues.
- Considering the level of technical issues, while results show that voltage problems can be reduced and congestion issues can be alleviated, this performance is only achieved due to the adjustment of the off-load tap changers (i.e., voltage) and the corresponding augmentation performed (i.e., congestion). The adoption of OTS offers limited to almost no benefits for either technical issue. This is due to the following limitations:
    - <u>OTS BES systems do not fully discharge overnight</u>. This is due to insufficient energy consumption of most customers. As a consequence, their ability to store surplus PV generation the following day can be significantly reduced.
    - <u>OTS BES systems reach full SOC very early</u>. With a partially charged BES system, surplus PV generation that occurs early in the morning can lead to a full SOC before or during high PV generation, resulting in PV exports.
- No augmentations on the LV and HV conductors were needed regardless the penetration levels. This was aligned with the findings in Task 3.
- Augmentation of transformers was required, and it was found to be very effective for the congested LV networks as it allows host more solar PV penetration. Seven LV transformers had to be augmented at 20% penetration and 7 and 10 transformers at 80 and 100% penetration.
    - The majority (more than 50%) of transformers required to be augmented correspond to transformers with rated capacity lower than 100kVA.
    - Augmentation results, and as expected, were found to be almost the same as those presented in Task 3.
- The curtailment of PV generation was found to be almost negligible when compared to the BAU case shown in Task 3. In particular, the level of curtailment was almost the same as when the adjustment of off-load taps alone is considered (see Task 3). This effect is primarily due to the adjustment of the off-load tap changers which reduce voltages hence the Volt-Watt function is not triggered. Considering the most critical penetration (i.e., 100%) the total curtailment accounts to just 0.25% of the total solar PV generation. It should be noted that the adoption of OTS BES has limited to no contribution to this effect (i.e., reduction of voltage, hence reduced curtailment).
- From the households' perspective, the adoption of the OTS BES systems shows to be an excellent investment as it allows them to significantly reduce their grid dependence, hence electricity bills. For example, the average and median yearly GDI of customers was found to be 20% and 1%. It is important to note that these numbers are influenced by the seasonality, with Spring and Summer having a much lower GDI (i.e., average of 5%) than Autumn and Winter (i.e., 25 and 31%, respectively).

A summary of the technical issues (highlighted red), curtailment (highlighted green), and augmentation (highlighted blue) for the different penetration levels is presented in Table 5-3.

Table 5-3 HV Feeder R1 (SMR8) – OTS BES Key Findings

	0% (2011)	20% (2017)	40% (2022)	60% (2030)	80% (2035)	100% (2042)
Non-Compliant Customers [%]	0	2	4	5	6	10
Max Voltage [p.u]	1.09	1.114	1.125	1.124	1.122	1.123
Max HV Conductor Utilization [%]	98	96	86	80	76	74
Congested HV Conductors [km]	0	0	0	0	0	0
Max LV Conductor Utilization [%]	58	57	57	57	64	84
Congested LV Conductors [km]	0	0	0	0	0	0
Max LV TX Utilization [%]	89	100	99	99	100	100
Congested LV TXs [#,%]	[0, 0]	[0, 0]	[0, 0]	[0, 0]	[0, 0]	[0, 0]
Annual Curtailment [MWh,%]	[0, 0]	[1, 0.05]	[15, 0.22]	[17, 0.15]	[43, 0.26]	[52, 0.25]
HV Conductors Replaced [km]	0	0	0	0	0	0
LV Conductors Replaced [km]	0	0	0	0	0	0
LV TXs Replaced [#,%]	[0, 0]	[7, 0]	[0, 0]	[1, 0]	[7, 0]	[10, 1]
LV TXs Replaced per Capacity**	[0, 0, 0, 0, 0, 0, 0, 0]	[6, 0, 0, 1, 0, 0, 0, 0]	[0, 0, 0, 0, 0, 0, 0, 0]	[0, 1, 0, 0, 0, 0, 0, 0]	[0, 0, 0, 7, 0, 0, 0, 0]	[0, 0, 0, 3, 6, 0, 1, 0]
BES Year Mean/Median GDI [%,%]	[100,100]	[20,1]	[20,1]	[20,1]	[20,1]	[20,1]

***The transformer kVA capacities correspond to: [>=10, 10-50, 50-100,100-200, 200-300, 300-400, 400-500, 500-700]*

5.4 Network Smart BES Systems

This section presents the results obtained from the operation of the SMR8 HV feeder considering the adoption of commercially available residential-scale BES systems embedded with the network smart control logic proposed and detailed in section 2.4.2. Such analysis will allow understand the extent to which advanced battery management strategies can provide benefits not only 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. The analysis follows the methodology specified in section 2.4.4 and results are collected across different penetration levels for different seasons. The presentation of results follows a similar format as presented in the previous sections. It is important to highlight that this solution considers the adjustment of off-load tap changers and augmentation where assets (i.e., conductors, transformers) are congested.

5.4.1 Key Findings

A summary of the key findings is listed below.

- The adoption of this solution (i.e., off-load taps, NS BES, augmentation) can effectively manage all technical issues and shift the Hosting capacity to 100% (compared to 20% found in the BAU case as well as when off-load taps are considered alone, see Task 3).
- Compared to the results obtained when OTS BES systems are adopted, the performance in terms of voltage and asset utilization is significantly increased.
- It has been observed that voltages significantly reduce during the peak generation period and are always kept below the maximum voltage statutory limit (<1.10p.u), regardless the penetration level and season. This is achieved due to the network smart control logic that enables BES systems charge throughout the whole generation period, hence significantly reduce household exports.
- The adoption of BES systems with the proposed network smart control logic shows to be highly effective in significantly reducing the utilization level of all assets and more importantly alleviate the congestion issues of more than 60% of transformers that were congested in the OTS BES case. Only 8 transformers had to be replaced, instead of 25 in the case of OTS BES. More specifically these transformers correspond to ratings smaller than 100kVA. This excellent performance is achieved due to the network smart control logic that enables BES systems charge throughout the whole generation period, hence significantly reduce household exports.
- There was no curtailment of PV generation when adopting this solution. This effect is due to the ability to keep all customer voltages always below 1.10p.u, hence the volt-watt function not triggering. Compared to the OTS BES results, the adoption of the network smart control logic contributes significantly to this performance.
- From the households' perspective, the adoption of the network smart BES systems shows to slightly affect customers' GDI when compared to the results with OTS BES systems. For example, the average and median yearly GDI of customers was found to be 22% and 5%, respectively. These values correspond to an increase of 5 and 4%, respectively, when compared to the OTS BES. While the adoption of the network smart control logic might lead to slightly higher grid imports for customers than with the OTS control, the corresponding expense might be considerably lower than the capital investments required to provide the same network benefits with asset-intensive solutions, such as network reinforcements

A summary of the technical issues (highlighted red), curtailment (highlighted green), and augmentation (highlighted blue) for the different penetration levels is presented in Table 5-4.

Table 5-4 HV Feeder R1 (SMR8) – NS BES Key Findings

	0% (2011)	20% (2017)	40% (2022)	60% (2030)	80% (2035)	100% (2042)
Non-Compliant Customers [%]	0	0	0	0	0	0
Max Voltage [p.u]	1.09	1.092	1.085	1.086	1.083	1.089
Max HV Conductor Utilization [%]	98	100	90	79	76	74
Congested HV Conductors [km]	0	0	0	0	0	0
Max LV Conductor Utilization [%]	58	57	57	57	57	56
Congested LV Conductors [km]	0	0	0	0	0	0
Max LV TX Utilization [%]	89	100	99	99	99	99
Congested LV TXs [#,%]	[0, 0]	[0, 0]	[0, 0]	[0, 0]	[0, 0]	[0, 0]
Annual Curtailment [MWh,%]	[0, 0]	[1, 0.03]	[2, 0.03]	[4, 0.04]	[5, 0.03]	[7, 0.03]
HV Conductors Replaced [km]	0	0	0	0	0	0
LV Conductors Replaced [km]	0	0	0	0	0	0
LV TXs Replaced [#,%]	[0, 0]	[7, 0]	[0, 0]	[0, 0]	[0, 0]	[1, 0]
LV TXs Replaced per Capacity**	[0, 0, 0, 0, 0, 0, 0, 0]	[6, 0, 0, 1, 0, 0, 0, 0]	[0, 0, 0, 0, 0, 0, 0, 0]	[0, 0, 0, 0, 0, 0, 0, 0]	[0, 0, 0, 0, 0, 0, 0, 0]	[0, 0, 0, 1, 0, 0, 0, 0]
BES Year Mean/Median GDI [%,%]	[100, 100]	[22, 5]	[22, 5]	[22, 5]	[22, 5]	[22, 5]

***The transformer kVA capacities correspond to: [>=10, 10-50, 50-100,100-200, 200-300, 300-400, 400-500, 500-700]*

5.5 Summary of Findings

Based on the analyses and solutions investigated for the HV feeder R1 (i.e., SMR8), the following observations/recommendations are listed for this particular feeder.

1. A more tailored set of Volt-Watt and Volt-Var settings is proved to be highly effective in limiting voltage problems in the network. Regardless of PV penetrations ad seasons, the maximum voltage in the network never exceeds above 1.10pu. While the curtailment of PV generation was found to be approximately increased by 1% for each penetration when compared to the BAU case, this can still be considered negligible given the significant benefits provided (i.e., full mitigation of voltage issues). For example, considering the most critical penetration (i.e., 100%) the total curtailment accounts to just 2% of the total solar PV generation.

2. The adoption of LV OLTC-fitted transformers in combination with adjustment of off-load tap changers as well as augmentation of congested assets can effectively manage all technical issues and shift the hosting capacity to 100% (compared to 0% when off-load taps are considered alone, see Task 3). For those LV transformers where their off-load tap capability was not able to mitigate the voltage rise/drop issues, their replacement with an OLTC-fitted LV transformer and adopting the proposed OLTC control logic proves to be highly effective in keeping all customer voltages within the statutory voltage limits, regardless the penetration and season. In terms of PV generation curtailment, it was found to be almost negligible.

3. The adoption of this solution (i.e., off-load taps, OTS BES, augmentation) was found to provide little to no additional benefits in terms of technical issues as the Hosting capacity remains at 20% (same as the BAU). At this point, the bottleneck becomes the voltage issues. Almost the same voltage performance was observed as when the adjustment of off-load tap changers is considered alone. Moreover, almost the same level of augmentation was required when compared to the augmentation results in Task 3. Considering the aforementioned, the results highlighted that he adoption of OTS BES has limited to no contribution in shifting the corresponding capacity. This is due to the limitations identified on the OTS BES operation where:

    a. OTS BES systems do not fully discharge overnight. This is due to insufficient energy consumption of most customers. As a consequence, their ability to store surplus PV generation the following day can be significantly reduced.
    b. OTS BES systems reach full SOC very early. With a partially charged BES system, surplus PV generation that occurs early in the morning can lead to a full SOC before or during high PV generation, resulting in PV exports.

4. The adoption of NS BES systems in combination with adjustment of off-load tap changers as well as augmentation of congested assets can effectively manage all technical issues and shift the hosting capacity to 100% (compared to 20% when off-load taps are considered alone, see Task 3). Compared to the results obtained when OTS BES systems are adopted, the performance in terms of voltage and asset utilization is significantly increased. Results show that NS BES systems are highly effective in significantly reducing the utilization level of all assets and more importantly alleviate congestion issues for a large number of transformers reducing significantly the augmentation requirements by more than 60% when compared to the OTS BES case. While the adoption of the network smart control logic might lead to slightly higher grid imports for customers than with the OTS control, the corresponding expense might be considerably lower than the capital investments required to provide the same network benefits with asset-intensive solutions, such as network reinforcements.

6 Case Study 3: HV Feeder U1 (Urban, HPK11)

6.1 Tailored Volt-Watt and Volt-Var Settings

This section presents the results obtained from the operation of the HPK11 HV feeder with Tailored Volt-Watt and Volt-Var PV inverter settings (T-VW-VV) across different penetration levels (0 to 100% in 20% steps) and for different seasons (i.e., Spring, Summer, Autumn, Winter).

6.1.1 Key Findings

- When Tailored PV inverter settings are adopted (compared to those imposed by the DNSPs in Victoria) and without any other solution put in place (e.g., adjustment of off-load taps) the feeder is now able to host up to 40% PV penetration (2022). At this point, the bottleneck becomes the distribution transformers which face congestion issues.
- It has been observed that voltage issues are fully mitigated when compared with the BAU case. This highlights that more tailored Volt-Watt and Volt-Var settings can be an effective solution to voltage issues.
- A slight reduction of the HV lines utilisation is observed when compared to the BAU case. This is due to the higher active power curtailment from solar PV due to the more tailored and Tailored Volt-Watt settings. Consequently, the HV lines operate within their thermal limits up to 80% penetration where 1 and 4km of conductors will face congestion issues at 80% (2050) and 100% (2060) of penetration levels.
- While LV lines are not congested regardless the penetration level, a slight reduction (2-3%) of their utilisation is noticed when compared to the BAU case. This is due to the higher active power curtailment from solar PV due to the more tailored and Tailored Volt-Watt settings.
- A reduced utilisation (2-3%) and number of congested LV transformers is observed when compared to the BAU case. Congestion occurs from 40% PV penetration onwards for a small number of transformers and this increases significantly for larger penetrations.
- The curtailment of PV generation was found to be approximately increased by 1% for each penetration when compared to the BAU case. While the amount of curtailment is doubling, this can still be considered negligible given the significant benefits provided (i.e., full mitigation of voltage issues). For example, considering the most critical penetration (i.e., 100%) the total curtailment accounts to just 2.2% of the total solar PV generation.

Furthermore, a summary of the analysis (technical issues highlighted in red and curtailment highlighted in green) for the different penetration levels is presented in Table 6-1.

Table 6-1 HV Feeder U1 (HPK11) – T-VW-VV Key Findings

	0% (2011)	20% (2017)	40% (2022)	60% (2030)	80% (2035)	100% (2042)
Non-Compliant Customers [%]	0	0	0	0	0	0
Max Voltage [p.u]	1.084	1.098	1.099	1.099	1.099	1.099
Max HV Conductor Utilization [%]	92	82	79	94	127	159
Congested HV Conductors [km]	0	0	0	0	1	4
Max LV Conductor Utilization [%]	57	51	78	78	78	79
Congested LV Conductors [km]	0	0	0	0	0	0
Max LV TX Utilization [%]	95	95	128	174	209	210
Congested LV TXs [#,%]	[0, 0]	[0, 0]	[3, 6]	[14, 31]	[22, 50]	[35, 79]
Annual Curtailment [MWh,%]	[0, 0]	[39, 0.53]	[120, 0.81]	[254, 1.15]	[482, 1.64]	[809, 2.21]

6.2 LV OLTC-fitted Transformers

This section presents the results obtained from the operation of the HPK11 HV feeder considering the solution of replacing off-load tap changer-fitted LV transformers with OLTC-fitted LV transformers according to the methodology specified in section 2.2.5. In the case of an OLTC-fitted LV transformer being installed the corresponding control logic detailed in section 2.2.4 is adopted and the analysis results are collected across different penetration levels for different seasons. The presentation of results follows a similar format as presented in the previous section.

It should be noted, and as stated in section 2.2.5, that this solution (installation of LV OLTC -fitted transformers) is only considered once the off-load capability of a LV transformers is fully utilised and available taps to reduce/increase are exhausted. This allows to utilise – to the extend is possible – any flexibility provided by existing assets (i.e., off-load tap changers), hence reduce the overall investment in new assets (i.e., OLTC). Considering the congestion issues, given that the investigated solution does not manage any power flows, augmentation is considered for congested assets (i.e., conductors, transformers).

6.2.1 Key Findings

A summary of the key findings is listed below.

- The adoption of this solution (i.e., off-load taps, OLTC, augmentation) can effectively manage all technical issues and shift the Hosting capacity to 100% (compared to 40% when off-load taps are considered alone, see Task 3).
- For those LV transformers where their off-load tap capability was not able to mitigate the voltage rise/drop issues, their replacement with an OLTC-fitted LV transformer and adopting the proposed OLTC control logic proves to be highly effective in keeping all customer voltages within the statutory voltage limits, regardless the penetration and season.
    - The total number of OLTC-fitted transformers installed for this Feeder accounts to 79% of the total LV transformers (35 out of 44). More than half of the OLTC installations are required up to 40% of penetration.
    - The capacities of the OLTCs correspond to relatively high rating transformers (>300kVA).
    - The average daily number of tap changes was found to around 2 while the maximum number of taps never exceeded 13. These low number of tap changes can lead to a reduced wear and tear of the OLTC hence requiring less maintenance costs.
- No augmentations on the LV conductors were needed regardless the penetration levels. This was aligned with the findings in Task 3.
- HV conductors operate within their thermal limits up to 80% penetration where around 1 and 4km of conductors where augmented at 80% (2050) and 100% (2060) of penetration levels. This was aligned with the findings in Task 3.
- Augmentation of transformers was required, and it was found to be very effective for the congested LV networks as it allows host more solar PV penetration. Almost all transformers had to be augmented at some point of the analysis with more than 50% of those being replaced up to 60% of penetration.
- In general and as expected, augmentation results were found to be almost the same as those presented in Task 3.
- The curtailment of PV generation was found to be almost negligible when compared to the BAU case shown in Task 3. In particular, the level of curtailment was almost the same as when the adjustment of off-load taps alone is considered (see Task 3). Considering the most critical penetration (i.e., 100%) the total curtailment accounts to just 0.04% of the total solar PV generation. In other words, the adoption of this solution provides significant benefits to both customers (i.e., minimal curtailment) and network (i.e., voltage and congestion issues).

A summary of the technical issues (highlighted red), curtailment (highlighted green), and augmentation (highlighted blue) for the different penetration levels is presented in Table 6-2.

Table 6-2 HV Feeder U1 (HPK11) – LV OLTC Key Findings

	0% (2011)	20% (2017)	40% (2022)	60% (2030)	80% (2035)	100% (2042)
Non-Compliant Customers [%]	0	0	0	0	0	0
Max Voltage [p.u]	1.084	1.085	1.084	1.089	1.096	1.09
Max HV Conductor Utilization [%]	92	81	78	91	100	100
Congested HV Conductors [km]	0	0	0	0	0	0
Max LV Conductor Utilization [%]	57	51	81	82	86	86
Congested LV Conductors [km]	0	0	0	0	0	0
Max LV TX Utilization [%]	95	94	99	100	100	99
Congested LV TXs [#,%]	[0, 0]	[0, 0]	[0, 0]	[0, 0]	[0, 0]	[0, 0]
Annual Curtailment [MWh,%]	[0, 0]	[7, 0.1]	[10, 0.07]	[11, 0.05]	[12, 0.04]	[13, 0.04]
HV Conductors Replaced [km]	0	0	0	0	0.71	4.06
LV Conductors Replaced [km]	0	0	0	0	0	0
LV TXs Replaced [#,%]	[0, 0]	[0, 0]	[3, 6]	[11, 25]	[13, 29]	[17, 38]
LV TXs Replaced per Capacity**	[0, 0, 0, 0, 0, 0, 0, 0]	[0, 0, 0, 0, 0, 0, 0, 0]	[0, 0, 0, 0, 3, 0, 0, 0]	[0, 0, 0, 0, 7, 0, 4, 0]	[0, 0, 0, 0, 0, 0, 11, 2]	[0, 0, 0, 0, 0, 0, 0, 17]
LV OLTC Installed [#,%]	[0, 0]	[11, 25]	[5, 11]	[11, 25]	[8, 18]	[0, 0]
LV OLTC Installed per Capacity**	[0, 0, 0, 0, 0, 0, 0, 0]	[0, 0, 0, 2, 4, 0, 4, 1]	[0, 0, 0, 1, 1, 0, 3, 0]	[0, 0, 0, 1, 6, 0, 4, 0]	[0, 0, 0, 0, 1, 0, 7, 0]	[0, 0, 0, 0, 0, 0, 0, 0]
LV OLTC Mean/Max Daily Taps [#,#]	[0, 0]	[1, 7]	[2, 9]	[3, 10]	[2, 13]	[1, 10]

***The transformer kVA capacities correspond to: [>=10, 10-50, 50-100,100-200, 200-300, 300-400, 400-500, 500-700]*

6.3 Off-the-Shelf BES Systems

This section presents the results obtained from the operation of the HPK11 HV feeder considering the adoption of OTS BES systems by solar PV owners. Such analysis will allow understand the extent to which the widespread adoption of this emerging commercially available residential-scale technology (i.e., OTS BES system) can help reduce the household exports from excess solar PV generation, hence reduce or alleviate the corresponding technical issues. The analysis follows the methodology specified in section 2.3.3 and results are collected across different penetration levels for different seasons. The presentation of results follows a similar format as presented in the previous sections. It is important to highlight that this solution considers the adjustment of off-load tap changers and augmentation where assets (i.e., conductors, transformers) are congested.

6.3.1 Key Findings

A summary of the key findings is listed below.

- The adoption of this solution (i.e., off-load taps, OTS BES, augmentation) can effectively manage all technical issues and shift the Hosting capacity to 40% (same hosting capacity as with the adjustment of off-load taps been considered alone, see Task 3). At this point, the bottleneck becomes the voltage issues.
- Despite the ability to increase hosting capacity (compared to the BAU case), this performance is only achieved due to the adjustment of off-load tap changer (i.e., voltage) and the corresponding augmentation (i.e., congestion). The adoption of OTS offers limited to almost no benefits for either technical issue. This is due to the following limitations:
  - OTS BES systems do not fully discharge overnight. This is due to insufficient energy consumption of most customers. As a consequence, their ability to store surplus PV generation the following day can be significantly reduced.
  - OTS BES systems reach full SOC very early. With a partially charged BES system, surplus PV generation that occurs early in the morning can lead to a full SOC before or during high PV generation, resulting in PV exports.
- No augmentations on the LV conductors were needed regardless the penetration levels. This was aligned with the findings in Task 3.
- HV conductors operate within their thermal limits up to 80% penetration where around 1 and 4km of conductors where augmented at 80% (2050) and 100% (2060) of penetration levels. This was aligned with the findings in Task 3.
- Augmentation of transformers was required, and it was found to be very effective for the congested LV networks as it allows host more solar PV penetration. Almost all transformers had to be augmented at some point of the analysis with more than 50% of those being replaced up to 60% of penetration.
- In general, and as expected, augmentation results were found to be almost the same as those presented in Task 3.
- The curtailment of PV generation was found to be almost negligible when compared to the BAU case shown in Task 3. In particular, the level of curtailment was almost the same as when the adjustment of off-load taps alone is considered (see Task 3). This effect is primarily due to the adjustment of the off-load tap changers which reduce voltages hence the Volt-Watt function is not triggered. Considering the most critical penetration (i.e., 100%) the total curtailment accounts to just 0.2% of the total solar PV generation. It should be noted that the adoption of OTS BES has limited to no contribution to this effect (i.e., reduction of voltage, hence reduced curtailment).
- From the households' perspective, the adoption of the OTS BES systems shows to be an excellent investment as it allows them to significantly reduce their grid dependence, hence electricity bills. For example, the average and median yearly GDI of customers was found to be 11% and 1%. It is important to note that these numbers are influenced by the seasonality, with Spring and Summer having a much lower GDI (i.e., average of 2%) than Autumn and Winter (i.e., 18 and 22%, respectively).

A summary of the technical issues (highlighted red), curtailment (highlighted green), and augmentation (highlighted blue) for the different penetration levels is presented in Table 6-3.

Table 6-3 HV Feeder U1 (HPK11) – OTS BES Key Findings

	0% (2011)	20% (2017)	40% (2022)	60% (2030)	80% (2035)	100% (2042)
Non-Compliant Customers [%]	0	0	0	3	7	12
Max Voltage [p.u]	1.084	1.094	1.103	1.106	1.111	1.114
Max HV Conductor Utilization [%]	92	73	58	85	100	100
Congested HV Conductors [km]	0	0	0	0	0	1
Max LV Conductor Utilization [%]	57	47	79	79	82	82
Congested LV Conductors [km]	0	0	0	0	0	0
Max LV TX Utilization [%]	95	86	96	99	100	100
Congested LV TXs [#,%]	[0, 0]	[0, 0]	[0, 0]	[0, 0]	[0, 0]	[0, 0]
Annual Curtailment [MWh,%]	[0, 0]	[7, 0.1]	[10, 0.07]	[13, 0.06]	[27, 0.09]	[72, 0.2]
HV Conductors Replaced [km]	0	0	0	0	0.71	3.54
LV Conductors Replaced [km]	0	0	0	0	0	0
LV TXs Replaced [#,%]	[0, 0]	[0, 0]	[2, 4]	[8, 18]	[14, 31]	[16, 36]
LV TXs Replaced per Capacity**	[0, 0, 0, 0, 0, 0, 0, 0]	[0, 0, 0, 0, 0, 0, 0, 0]	[0, 0, 0, 0, 2, 0, 0, 0]	[0, 0, 0, 0, 6, 0, 2, 0]	[0, 0, 0, 0, 0, 0, 13, 1]	[0, 0, 0, 0, 0, 0, 0, 16]
BES Year Mean/Median GDI [%,%]	[100,100]	[11,0]	[11,0]	[11,0]	[11,0]	[11,0]

***The transformer kVA capacities correspond to: [>=10, 10-50, 50-100,100-200, 200-300, 300-400, 400-500, 500-700]*

6.4 Network Smart BES Systems

This section presents the results obtained from the operation of the HPK11 HV feeder considering the adoption of commercially available residential-scale BES systems embedded with the network smart control logic proposed and detailed in section 2.4.2. Such analysis will allow understand the extent to which advanced battery management strategies can provide benefits not only 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. The analysis follows the methodology specified in section 2.4.4 and results are collected across different penetration levels for different seasons. The presentation of results follows a similar format as presented in the previous sections. It is important to highlight that this solution considers the adjustment of off-load tap changers and augmentation where assets (i.e., conductors, transformers) are congested.

6.4.1 Key Findings

A summary of the key findings is listed below.

- The adoption of this solution (i.e., off-load taps, NS BES, augmentation) can effectively manage all technical issues and shift the Hosting capacity to 100% (compared to 20% found in the BAU case and 40% when off-load taps are considered alone, see Task 3).
- Compared to the results obtained when OTS BES systems are adopted, the performance in terms of voltage and asset utilization is significantly increased.
- It has been observed that voltages significantly reduce during the peak generation period and are always kept below the maximum voltage statutory limit (<1.10p.u), regardless the penetration level and season. This is achieved due to the network smart control logic that enables BES systems charge throughout the whole generation period, hence significantly reduce household exports.
- The adoption of BES systems with the proposed network smart control logic shows to be highly effective in significantly reducing the utilization level of all assets and more importantly alleviate the congestion issues of more than 90% of transformers that were congested in the OTS BES case. Only 3 transformers (in total) had to be replaced at 100% of penetration, instead of 40 in the case of OTS BES. This excellent performance is achieved due to the network smart control logic that enables BES systems charge throughout the whole generation period, hence significantly reduce household exports.
- There was almost no curtailment of PV generation when adopting this solution. This effect is due to the ability to keep all customer voltages always below 1.10p.u, hence the volt-watt function not triggering. Compared to the OTS BES results, the adoption of the network smart control logic contributes significantly to this performance.
- From the households' perspective, the adoption of the network smart BES systems shows to slightly affect customers' GDI when compared to the results with OTS BES systems. For example, the average and median yearly GDI of customers was found to be 15% and 1%, respectively. These values correspond to an increase of 4 and 1%, respectively, when compared to the OTS BES. While the adoption of the network smart control logic might lead to slightly higher grid imports for customers than with the OTS control, the corresponding expense might be considerably lower than the capital investments required to provide the same network benefits with asset-intensive solutions, such as network reinforcements

A summary of the technical issues (highlighted red), curtailment (highlighted green), and augmentation (highlighted blue) for the different penetration levels is presented in Table 6-4.

Table 6-4 HV Feeder U1 (HPK11) – NS BES Key Findings

	0% (2011)	20% (2017)	40% (2022)	60% (2030)	80% (2035)	100% (2042)
Non-Compliant Customers [%]	0	0	0	0	0	0
Max Voltage [p.u]	1.084	1.084	1.068	1.076	1.088	1.095
Max HV Conductor Utilization [%]	92	73	56	55	55	73
Congested HV Conductors [km]	0	0	0	0	0	0
Max LV Conductor Utilization [%]	57	47	43	39	43	44
Congested LV Conductors [km]	0	0	0	0	0	0
Max LV TX Utilization [%]	95	86	77	71	90	99
Congested LV TXs [#,%]	[0, 0]	[0, 0]	[0, 0]	[0, 0]	[0, 0]	[0, 0]
Annual Curtailment [MWh,%]	[0, 0]	[8, 0.11]	[11, 0.08]	[14, 0.06]	[16, 0.06]	[19, 0.05]
HV Conductors Replaced [km]	0	0	0	0	0	0
LV Conductors Replaced [km]	0	0	0	0	0	0
LV TXs Replaced [#,%]	[0, 0]	[0, 0]	[0, 0]	[0, 0]	[0, 0]	[3, 6]
LV TXs Replaced per Capacity**	[0, 0, 0, 0, 0, 0, 0, 0]	[0, 0, 0, 0, 0, 0, 0, 0]	[0, 0, 0, 0, 0, 0, 0, 0]	[0, 0, 0, 0, 0, 0, 0, 0]	[0, 0, 0, 0, 0, 0, 0, 0]	[0, 0, 0, 0, 2, 0, 0, 1]
BES Year Mean/Median GDI [%,%]	[100,100]	[15,1]	[15,1]	[15,1]	[15,1]	[15,1]

***The transformer kVA capacities correspond to: [>=10, 10-50, 50-100,100-200, 200-300, 300-400, 400-500, 500-700]*

6.5 Summary of Findings

Based on the analyses and solutions investigated for the HV feeder U1 (i.e., HPK11), the following observations/recommendations are listed for this particular feeder.

1. A more tailored set of Volt-Watt and Volt-Var settings is proved to be highly effective in limiting voltage problems in the network. Regardless of PV penetrations ad seasons, the maximum voltage in the network never exceeds above 1.10pu. While the curtailment of PV generation was found to be approximately 1% higher for each penetration when compared to the BAU case, this can still be considered negligible given the significant benefits provided (i.e., full mitigation of voltage issues). For example, considering the most critical penetration (i.e., 100%) the total curtailment accounts to just 2% of the total solar PV generation.

2. The adoption of LV OLTC-fitted transformers in combination with adjustment of off-load tap changers as well as augmentation of congested assets can effectively manage all technical issues and shift the hosting capacity to 100% (compared to 0% when off-load taps are considered alone, see Task 3). For those LV transformers where their off-load tap capability was not able to mitigate the voltage rise/drop issues, their replacement with an OLTC-fitted LV transformer and adopting the proposed OLTC control logic proves to be highly effective in keeping all customer voltages within the statutory voltage limits, regardless the penetration and season. In terms of PV generation curtailment, it was found to be almost negligible.

3. The adoption of this solution (i.e., off-load taps, OTS BES, augmentation) was found to provide little to no additional benefits in terms of technical issues as the Hosting capacity increases to 40% (same hosting capacity as with the adjustment of off-load taps been considered alone, see Task 3). At this point, the bottleneck becomes the voltage issues. Almost the same voltage performance was observed as when the adjustment of off-load tap changers is considered alone. Moreover, almost the same level of augmentation was required when compared to the augmentation results in Task 3. Considering the aforementioned, the results highlighted that he adoption of OTS BES has limited to no contribution in shifting the corresponding capacity. This is due to the limitations identified on the OTS BES operation where:

    a. OTS BES systems do not fully discharge overnight. This is due to insufficient energy consumption of most customers. As a consequence, their ability to store surplus PV generation the following day can be significantly reduced.
    b. OTS BES systems reach full SOC very early. With a partially charged BES system, surplus PV generation that occurs early in the morning can lead to a full SOC before or during high PV generation, resulting in PV exports.

4. The adoption of NS BES systems in combination with adjustment of off-load tap changers as well as augmentation of congested assets can effectively manage all technical issues and shift the hosting capacity to 100% (compared to 20% found in the BAU case and 40% when off-load taps are considered alone, see Task 3). Compared to the results obtained when OTS BES systems are adopted, the performance in terms of voltage and asset utilization is significantly increased. Results show that NS BES systems are highly effective in significantly reducing the utilization level of all assets and more importantly alleviate congestion issues for a large number of transformers reducing significantly the augmentation requirements by more than 90% when compared to the OTS BES case. While the adoption of the network smart control logic might lead to slightly higher grid imports for customers than with the OTS control, the corresponding expense might be considerably lower than the capital investments required to provide the same network benefits with asset-intensive solutions, such as network reinforcements.

7 Case Study 4: HV Feeder R2 (Short Rural, KLO14)

7.1 Tailored Volt-Watt and Volt-Var Settings

This section presents the results obtained from the operation of the KLO14 HV feeder with Tailored Volt-Watt and Volt-Var PV inverter settings (T-VW-VV) across different penetration levels (0 to 100% in 20% steps) and for different seasons (i.e., Spring, Summer, Autumn, Winter).

7.1.1 Key Findings

- When Tailored PV inverter settings are adopted (compared to those imposed by the DNSPs in Victoria) and without any other solution put in place (e.g., adjustment of off-load taps) the feeder is able to host up to 20% PV penetration. This is the same penetration level achieved as with the BAU case. After 20% penetration, the congestion of distribution transformers and HV conductors are the bottleneck.
- It has been observed that voltage issues are fully mitigated when compared with the BAU case. This highlights that more tailored Volt-Watt and Volt-Var settings can be an effective solution to voltage issues.
- While a slight reduction of the HV lines maximum utilisation levels is observed when compared to the BAU case, the same amount of kilometres is congested as with the BAU case. For example, around 5km of conductors will face congestion issues from 20% of penetration level.
- While LV lines are not congested regardless the penetration level, a slight reduction (2-3%) of their utilisation is noticed when compared to the BAU case. This is due to the higher active power curtailment from solar PV due to the more tailored and Tailored Volt-Watt settings.
- A reduced utilisation (2-3%) and number (at least one less) of congested LV transformers is observed when compared to the BAU case. Congestion occurs at the same penetration level as with the BAU (i.e., 20%).
- The curtailment of PV generation was found to be approximately 1% higher each penetration when compared to the BAU case. While the amount of curtailment is doubling, this can still be considered negligible given the significant benefits provided (i.e., full mitigation of voltage issues). For example, considering the most critical penetration (i.e., 100%) the total curtailment accounts to just 1.63% of the total solar PV generation.

Furthermore, a summary of the analysis (technical issues highlighted in red and curtailment highlighted in green) for the different penetration levels is presented in Table 7-1.

Table 7-1 HV Feeder R2 (KLO14) – T-VW-VV Key Findings

	0% (2011)	20% (2017)	40% (2022)	60% (2030)	80% (2035)	100% (2042)
Non-Compliant Customers [%]	0	0	0	0	0	0
Max Voltage [p.u]	1.099	1.099	1.099	1.099	1.099	1.099
Max HV Conductor Utilization [%]	92	135	126	121	120	149
Congested HV Conductors [km]	0	5	5	5	2	5
Max LV Conductor Utilization [%]	65	65	61	70	75	79
Congested LV Conductors [km]	0	0	0	0	0	0
Max LV TX Utilization [%]	90	107	170	169	169	175
Congested LV TXs [#,%]	[0, 0]	[3, 0]	[6, 0]	[20, 2]	[27, 3]	[30, 4]
Annual Curtailment [MWh,%]	[0, 0]	[4, 0.11]	[45, 0.5]	[208, 1.37]	[314, 1.45]	[457, 1.63]

7.2 LV OLTC-fitted Transformers

This section presents the results obtained from the operation of the KLO14 HV feeder considering the solution of replacing off-load tap changer-fitted LV transformers with OLTC-fitted LV transformers according to the methodology specified in section 2.2.5. In the case of an OLTC-fitted LV transformer being installed the corresponding control logic detailed in section 2.2.4 is adopted and the analysis results are collected across different penetration levels for different seasons. The presentation of results follows a similar format as presented in the previous section.

It should be noted, and as stated in section 2.2.5, that this solution (installation of LV OLTC -fitted transformers) is only considered once the off-load capability of a LV transformers is fully utilised and available taps to reduce/increase are exhausted. This allows to utilise – to the extend is possible – any flexibility provided by existing assets (i.e., off-load tap changers), hence reduce the overall investment in new assets (i.e., OLTC). Considering the congestion issues, given that the investigated solution does not manage any power flows, augmentation is considered for congested assets (i.e., conductors, transformers).

7.2.1 Key Findings

A summary of the key findings is listed below.

- The adoption of this solution (i.e., off-load taps, OLTC, augmentation) can effectively manage all technical issues and shift the Hosting capacity to 100% (compared to 20% when off-load taps are considered alone, see Task 3).
- For those LV transformers where their off-load tap capability was not able to mitigate the voltage rise/drop issues, their replacement with an OLTC-fitted LV transformer and adopting the proposed OLTC control logic proves to be highly effective in keeping all customer voltages within the statutory voltage limits, regardless the penetration and season.
    - The total number of OLTC-fitted transformers installed for this Feeder accounts to 79% of the total LV transformers (553 out of 700). More than half of the OLTC installations are required up to 20% of penetration.
    - The capacities of most OLTCs correspond to relatively low rating transformers (<50kVA).
    - The average daily number of tap changes was found to around 7 while the maximum number of taps never exceeded 23. These low number of tap changes can lead to a reduced wear and tear of the OLTC hence requiring less maintenance costs.
- No augmentations on the LV conductors were needed regardless the penetration levels. This was aligned with the findings in Task 3.
- Around 4km of HV conductors will need to be augmented at 20% penetration. This was aligned with the findings in Task 3.
- Augmentation of transformers was required, and it was found to be very effective for the congested LV networks as it allows host more solar PV penetration. Around 5% of transformers had to be augmented at some point of the analysis with most of them corresponding to low rated capacities (<50kVA)
- In general and as expected, augmentation results were found to be almost the same as those presented in Task 3.
- The curtailment of PV generation was found to be almost negligible when compared to the BAU case shown in Task 3. In particular, the level of curtailment was almost the same as when the adjustment of off-load taps alone is considered (see Task 3). Considering the most critical penetration (i.e., 100%) the total curtailment accounts to just 0.03% of the total solar PV generation. In other words, the adoption of this solution provides significant benefits to both customers (i.e., minimal curtailment) and network (i.e., voltage and congestion issues).

A summary of the technical issues (highlighted red), curtailment (highlighted green), and augmentation (highlighted blue) for the different penetration levels is presented in Table 7-2.

Table 7-2 HV Feeder R2 (KLO14) – LV OLTC Key Findings

	0% (2011)	20% (2017)	40% (2022)	60% (2030)	80% (2035)	100% (2042)
Non-Compliant Customers [%]	0	0	0	0	0	0
Max Voltage [p.u]	1.09	1.093	1.093	1.094	1.096	1.098
Max HV Conductor Utilization [%]	92	96	87	85	83	100
Congested HV Conductors [km]	0	0	0	0	0	0
Max LV Conductor Utilization [%]	65	62	59	74	84	84
Congested LV Conductors [km]	0	0	0	0	0	0
Max LV TX Utilization [%]	90	100	100	100	100	100
Congested LV TXs [#,%]	[0, 0]	[0, 0]	[0, 0]	[0, 0]	[0, 0]	[0, 0]
Annual Curtailment [MWh,%]	[0, 0]	[2, 0.05]	[2, 0.03]	[6, 0.04]	[7, 0.04]	[8, 0.03]
HV Conductors Replaced [km]	0	4.56	0	0	0	0
LV Conductors Replaced [km]	0	0	0	0	0	0
LV TXs Replaced [#,%]	[0, 0]	[11, 1]	[2, 0]	[13, 1]	[7, 1]	[4, 0]
LV TXs Replaced per Capacity**	[0, 0, 0, 0, 0, 0, 0, 0]	[10, 1, 0, 0, 0, 0, 0, 0]	[2, 0, 0, 0, 0, 0, 0, 0]	[1, 10, 2, 0, 0, 0, 0, 0]	[1, 1, 0, 5, 0, 0, 0, 0]	[0, 0, 0, 0, 1, 0, 0, 3]
LV OLTC Installed [#,%]	[0, 0]	[365, 52]	[10, 1]	[138, 20]	[27, 4]	[13, 2]
LV OLTC Installed per Capacity**	[0, 0, 0, 0, 0, 0, 0, 0]	[289, 33, 18, 8, 7, 0, 9, 1]	[6, 0, 4, 0, 0, 0, 0, 0]	[81, 33, 13, 2, 5, 0, 4, 0]	[11, 6, 0, 0, 0, 0, 10, 0]	[9, 4, 0, 0, 0, 0, 0, 0]
LV OLTC Mean/Max Daily Taps [#,#]	[0, 0]	[4, 16]	[6, 21]	[7, 23]	[8, 23]	[8, 23]

***The transformer kVA capacities correspond to: [>=10, 10-50, 50-100,100-200, 200-300, 300-400, 400-500, 500-700]*

7.3 Off-the-Shelf BES Systems

This section presents the results obtained from the operation of the KLO14 HV feeder considering the adoption of OTS BES systems by solar PV owners. Such analysis will allow understand the extent to which the widespread adoption of this emerging commercially available residential-scale technology (i.e., OTS BES system) can help reduce the household exports from excess solar PV generation, hence reduce or alleviate the corresponding technical issues. The analysis follows the methodology specified in section 2.3.3 and results are collected across different penetration levels for different seasons. The presentation of results follows a similar format as presented in the previous sections. It is important to highlight that this solution considers the adjustment of off-load tap changers and augmentation where assets (i.e., conductors, transformers) are congested.

7.3.1 Key Findings

A summary of the key findings is listed below.

- The adoption of this solution (i.e., off-load taps, OTS BES, augmentation) can effectively manage all technical issues and shift the Hosting capacity to 40% (same hosting capacity as with the adjustment of off-load taps been considered alone, see Task 3). At this point, the bottleneck becomes the voltage issues.
- Despite the ability to increase hosting capacity (compared to the BAU case), this performance is only achieved due to the adjustment of off-load tap changer (i.e., voltage) and the corresponding augmentation (i.e., congestion). The adoption of OTS offers limited to almost no benefits for either technical issue. This is due to the following limitations:
  - o <u>OTS BES systems do not fully discharge overnight</u>. This is due to insufficient energy consumption of most customers. As a consequence, their ability to store surplus PV generation the following day can be significantly reduced.
  - o <u>OTS BES systems reach full SOC very early</u>. With a partially charged BES system, surplus PV generation that occurs early in the morning can lead to a full SOC before or during high PV generation, resulting in PV exports.
- No augmentations on the LV conductors were needed regardless the penetration levels. This was aligned with the findings in Task 3.
- HV conductors operate within their thermal limits and around 4km of conductors where augmented at 20% of penetration. This was aligned with the findings in Task 3.
- Augmentation of transformers was required, and it was found to be very effective for the congested LV networks as it allows host more solar PV penetration. Around 5% of transformers had to be augmented at some point of the analysis with most of them corresponding to low rated capacities (<50kVA). In general, and as expected, augmentation results were found to be almost the same as those presented in Task 3.
- The curtailment of PV generation was found to be almost negligible when compared to the BAU case shown in Task 3. In particular, the level of curtailment was almost the same as when the adjustment of off-load taps alone is considered (see Task 3). This effect is primarily due to the adjustment of the off-load tap changers which reduce voltages hence the Volt-Watt function is not triggered. Considering the most critical penetration (i.e., 100%) the total curtailment accounts to just 0.11% of the total solar PV generation. It should be noted that the adoption of OTS BES has limited to no contribution to this effect (i.e., reduction of voltage, hence reduced curtailment).
- From the households' perspective, the adoption of the OTS BES systems shows to be an excellent investment as it allows them to significantly reduce their grid dependence, hence electricity bills. For example, the average and median yearly GDI of customers was found to be 18% and 1%. It is important to note that these numbers are influenced by the seasonality, with Spring and Summer having a much lower GDI (i.e., average of 4%) than Autumn and Winter (i.e., average of 25 and 35%, respectively).

A summary of the technical issues (highlighted red), curtailment (highlighted green), and augmentation (highlighted blue) for the different penetration levels is presented in Table 7-3.

Table 7-3 HV Feeder R2 (KLO14) – OTS BES Key Findings

	0% (2011)	20% (2017)	40% (2022)	60% (2030)	80% (2035)	100% (2042)
Non-Compliant Customers [%]	0	0	1	7	8	16
Max Voltage [p.u]	1.09	1.086	1.11	1.118	1.122	1.123
Max HV Conductor Utilization [%]	92	95	75	69	67	91
Congested HV Conductors [km]	0	0	0	0	0	0
Max LV Conductor Utilization [%]	65	65	58	68	79	79
Congested LV Conductors [km]	0	0	0	0	0	0
Max LV TX Utilization [%]	90	99	96	98	99	100
Congested LV TXs [#,%]	[0, 0]	[0, 0]	[0, 0]	[0, 0]	[0, 0]	[0, 0]
Annual Curtailment [MWh,%]	[0, 0]	[2, 0.05]	[2, 0.03]	[8, 0.06]	[18, 0.08]	[31, 0.11]
HV Conductors Replaced [km]	0	4.56	0	0	0	0
LV Conductors Replaced [km]	0	0	0	0	0	0
LV TXs Replaced [#,%]	[0, 0]	[11, 1]	[2, 0]	[11, 1]	[5, 0]	[4, 0]
LV TXs Replaced per Capacity**	[0, 0, 0, 0, 0, 0, 0, 0]	[10, 1, 0, 0, 0, 0, 0, 0]	[2, 0, 0, 0, 0, 0, 0, 0]	[0, 9, 2, 0, 0, 0, 0, 0]	[0, 0, 0, 5, 0, 0, 0, 0]	[0, 0, 0, 0, 1, 0, 1, 2]
BES Year Mean/Median GDI [%,%]	[100,100]	[18,0]	[18,0]	[18,0]	[18,0]	[18,0]

***The transformer kVA capacities correspond to: [>=10, 10-50, 50-100,100-200, 200-300, 300-400, 400-500, 500-700]*

7.4 Network Smart BES Systems

This section presents the results obtained from the operation of the KLO14 HV feeder considering the adoption of commercially available residential-scale BES systems embedded with the network smart control logic proposed and detailed in section 2.4.2. Such analysis will allow understand the extent to which advanced battery management strategies can provide benefits not only 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. The analysis follows the methodology specified in section 2.4.4 and results are collected across different penetration levels for different seasons. The presentation of results follows a similar format as presented in the previous sections. It is important to highlight that this solution considers the adjustment of off-load tap changers and augmentation where assets (i.e., conductors, transformers) are congested.

7.4.1 Key Findings

A summary of the key findings is listed below.

- The adoption of this solution (i.e., off-load taps, NS BES, augmentation) can effectively manage all technical issues and shift the Hosting capacity to 100% (compared to 20% found in the BAU case and when off-load taps are considered alone, see Task 3).
- Compared to the results obtained when OTS BES systems are adopted, the performance in terms of voltage and asset utilization is significantly increased.
- It has been observed that voltages significantly reduce during the peak generation period and are always kept below or up to the maximum voltage statutory limit (<1.10p.u), regardless the penetration level and season. This is achieved due to the network smart control logic that enables BES systems charge throughout the whole generation period, hence significantly reduce household exports.
- The adoption of BES systems with the proposed network smart control logic shows to be highly effective in significantly reducing the utilization level of all assets and more importantly alleviate the congestion issues of more than 60% of transformers that were congested in the OTS BES case. Only 14 transformers (in total) had to be replaced up to 100% of penetration, instead of 35 in the case of OTS BES. This excellent performance is achieved due to the network smart control logic that enables BES systems charge throughout the whole generation period, hence significantly reduce household exports.
- There was almost no curtailment of PV generation when adopting this solution. This effect is due to the ability to keep all customer voltages always below 1.10p.u, hence the volt-watt function not triggering. Compared to the OTS BES results, the adoption of the network smart control logic contributes significantly to this performance.
- From the households' perspective, the adoption of the network smart BES systems shows to slightly affect customers' GDI when compared to the results with OTS BES systems. For example, the average and median yearly GDI of customers was found to be 20% and 3%, respectively. These values correspond to an increase of 2 and 3%, respectively, when compared to the OTS BES. While the adoption of the network smart control logic might lead to slightly higher grid imports for customers than with the OTS control, the corresponding expense might be considerably lower than the capital investments required to provide the same network benefits with asset-intensive solutions, such as network reinforcements

A summary of the technical issues (highlighted red), curtailment (highlighted green), and augmentation (highlighted blue) for the different penetration levels is presented in Table 7-4.

Table 7-4 HV Feeder R2 (KLO14) – NS BES Key Findings

	0% (2011)	20% (2017)	40% (2022)	60% (2030)	80% (2035)	100% (2042)
Non-Compliant Customers [%]	0	0	0	0	0	0
Max Voltage [p.u]	1.09	1.086	1.087	1.098	1.1	1.1
Max HV Conductor Utilization [%]	92	95	74	72	71	71
Congested HV Conductors [km]	0	0	0	0	0	0
Max LV Conductor Utilization [%]	65	65	58	51	47	47
Congested LV Conductors [km]	0	0	0	0	0	0
Max LV TX Utilization [%]	90	99	96	96	96	96
Congested LV TXs [#,%]	[0, 0]	[0, 0]	[0, 0]	[0, 0]	[0, 0]	[0, 0]
Annual Curtailment [MWh,%]	[0, 0]	[1, 0.05]	[3, 0.04]	[5, 0.04]	[7, 0.04]	[11, 0.04]
HV Conductors Replaced [km]	0	4.56	0	0	0	0
LV Conductors Replaced [km]	0	0	0	0	0	0
LV TXs Replaced [#,%]	[0, 0]	[11, 1]	[2, 0]	[1, 0]	[0, 0]	[0, 0]
LV TXs Replaced per Capacity**	[0, 0, 0, 0, 0, 0, 0, 0]	[10, 1, 0, 0, 0, 0, 0, 0]	[2, 0, 0, 0, 0, 0, 0, 0]	[0, 1, 0, 0, 0, 0, 0, 0]	[0, 0, 0, 0, 0, 0, 0, 0]	[0, 0, 0, 0, 0, 0, 0, 0]
BES Year Mean/Median GDI [%,%]	[100,100]	[20, 3]	[20, 3]	[20, 3]	[20, 3]	[20, 3]

***The transformer kVA capacities correspond to: [>=10, 10-50, 50-100,100-200, 200-300, 300-400, 400-500, 500-700]*

7.5 Summary of Findings

Based on the analyses and solutions investigated for the HV feeder R2 (i.e., KLO14), the following observations/recommendations are listed for this particular feeder.

1. A more tailored set of Volt-Watt and Volt-Var settings is proved to be highly effective in limiting voltage problems in the network. Regardless of PV penetrations ad seasons, the maximum voltage in the network never exceeds above 1.10pu. While the curtailment of PV generation was found to be approximately 1% higher for each penetration when compared to the BAU case, this can still be considered negligible given the significant benefits provided (i.e., full mitigation of voltage issues). For example, considering the most critical penetration (i.e., 100%) the total curtailment accounts to just 1.6% of the total solar PV generation.

2. The adoption of LV OLTC-fitted transformers in combination with adjustment of off-load tap changers as well as augmentation of congested assets can effectively manage all technical issues and shift the hosting capacity to 100% (compared to 0% when off-load taps are considered alone, see Task 3). For those LV transformers where their off-load tap capability was not able to mitigate the voltage rise/drop issues, their replacement with an OLTC-fitted LV transformer and adopting the proposed OLTC control logic proves to be highly effective in keeping all customer voltages within the statutory voltage limits, regardless the penetration and season. In terms of PV generation curtailment, it was found to be almost negligible.

3. The adoption of this OTS BES in combination with off-load taps and augmentation was found to provide little to no additional benefits in terms of technical issues as the Hosting capacity increases to 40% (same hosting capacity as with the adjustment of off-load taps been considered alone, see Task 3). At this point, the bottleneck becomes the voltage issues. Almost the same voltage performance was observed as when the adjustment of off-load tap changers is considered alone. Moreover, almost the same level of augmentation was required when compared to the augmentation results in Task 3. Considering the aforementioned, the results highlighted that he adoption of OTS BES has limited to no contribution in shifting the corresponding capacity. This is due to the limitations identified on the OTS BES operation where:

    a. OTS BES systems do not fully discharge overnight. This is due to insufficient energy consumption of most customers. As a consequence, their ability to store surplus PV generation the following day can be significantly reduced.
    b. OTS BES systems reach full SOC very early. With a partially charged BES system, surplus PV generation that occurs early in the morning can lead to a full SOC before or during high PV generation, resulting in PV exports.

4. The adoption of NS BES systems in combination with adjustment of off-load tap changers as well as augmentation of congested assets can effectively manage all technical issues and shift the hosting capacity to 100% (compared to 40% found in both the BAU case and when off-load taps are considered alone, see Task 3). Compared to the results obtained when OTS BES systems are adopted, the performance in terms of voltage and asset utilization is significantly increased. Results show that NS BES systems are highly effective in significantly reducing the utilization level of all assets and more importantly alleviate congestion issues for a large number of transformers reducing significantly the augmentation requirements by at least 60% when compared to the OTS BES case. While the adoption of the network smart control logic might lead to slightly higher grid imports for customers than with the OTS control, the corresponding expense might be considerably lower than the capital investments required to provide the same network benefits with asset-intensive solutions, such as network reinforcements.

8 Conclusions

This document corresponds to the *"Deliverable 4: Non-Traditional Solutions"* 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 led by the University of Melbourne in collaboration with AusNet Services. It focuses on the investigation of "non-traditional solutions" in combination with "traditional solutions" aiming at increasing the solar PV hosting capacity (HC) of Distribution Networks considering the new Victorian Volt-Watt and Volt-var settings which mandates that both power quality response modes are enabled.

8.1 Key Findings

Chapter 1 introduced the current state of residential PV system installations in Australia and the technical and operation challenges the widespread adoption of these might bring to the Distribution Network Service Providers (DNSPs).

Chapter 2 presented the non-traditional solutions considered in this report. Here, the term "Non-Traditional Solutions", refers to solutions not commonly adopted (today) by DNSPs in Australia (and internationally) in order to alleviate technical issues related to voltage and asset congestion. Such non-traditional solutions are based on the combined use of 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 that leverage existing controllable elements such as off-load or on-load tap changers as well as replacing or upgrading conductors and/or transformers. The following five non-traditional solutions were considered in this Task. It is worth noting that the fifth solution has been added for completeness.

- Tailored Volt-Watt and Volt-Var PV Inverter Settings. This solution considers the adoption of tailored (stricter) Volt-Watt and Volt-Var PV inverter settings compared to the ones imposed by the Victorian DNSPs and investigated in Task 3 "Traditional Solutions" [1]. This will help understand the extent to which a tailored set of settings aiming at fully mitigating voltage rise issues can help further increase the HC as well as understand the corresponding effects on customers (i.e., solar PV curtailment). For this purpose, the adopted stricter set of PV inverter settings involve the full curtailment of PV generation when reaching the upper voltage limit (as detailed in section 2.1.1). To truly understand the corresponding effects and benefits when compared to the those imposed by the Victorian DNSPs, this solution will not consider any other traditional solution.
- LV OLTC-fitted Transformers with Adaptive Control. This solution considers the replacement of off-load tap changer-fitted LV transformers with OLTC-fitted LV transformers considering an adaptive control logic. The main idea of this approach is to leverage smart meter data to actively calculate a voltage target (at the busbar) that brings contrasting voltages issues (rise and drop) closer to a middle point, thus satisfying voltage limits. Crucially, this provides the significant benefit of easily adapting to network changes (i.e., additional PV system installations or loads) without the need of reconfiguring OLTC settings. This solution (installation of LV OLTC-fitted transformers) is adopted and combined with the traditional solutions (i.e., adjustment of off-load tap changers and augmentation) and is only considered once the off-load capability of a LV transformers is fully utilised, i.e., available taps to reduce/increase are exhausted. Considering the congestion issues and given that the investigated solution does not manage any power flows, augmentation is considered for congested assets (i.e., conductors, transformers).
- Off-the-Shelf (OTS) Battery Energy Storage (BES) Systems. This solution considers the case where households with solar PV adopt residential "off-the-shelf" (OTS) BES systems and their corresponding effects on the solar PV HC. Such analysis allows to understand the extent to which the widespread adoption of this emerging commercially available technology can help reduce the household exports from excess solar PV generation, and, hence, reduce or alleviate

network issues. It is important to highlight that this solution is investigated in combination with adjusted off-load tap changers as well as with network augmentation (for congested assets).
- Network Smart (NS) Battery Energy Storage (BES) Systems. This solution considers the adoption of commercially available residential-scale BES systems embedded with an advanced controller aiming at reducing high PV exports. In particular, the "Network Smart" (NS) controller proposed by The University of Melbourne is investigated. This controller adapts the BES charging power proportionally to the PV generation, while ensuring available capacity by discharging overnight. This analysis allows to understand the extent to which advanced BES controllers can provide benefits not only to their owners (lowering electricity bills) but also to the electricity infrastructure, reducing power exports from households with solar PV and, thus, mitigating network impacts. This solution is investigated in combination with adjusted off-load tap changers as well as network augmentation (for congested assets).
- Dynamic Voltage Target at Zone Substation OLTC. This solution is added for completeness, which also complements the current trials of 'Solar Ready Settings' by AusNet Services for in-line voltage regulators in rural networks. It considers a dynamic (and incremental) voltage reduction at the zone substation OLTC based on the volume of reverse power flow as a proxy of the voltage rise in downstream networks. Particularly, the volume of reverse flow is estimated using the net power flow through the zone substation. For simplicity, this solution will not consider other traditional solutions.

Chapter 2.5 detailed the data and considerations used for the analyses performed in this Task. First, the residential and non-residential demand used for the analyses were described. Then, the modelling of solar PV such as irradiance profiles, penetrations, panel sizes and inverter settings are detailed, followed by the list of transformers and conductors used for the augmentation analyses. Lastly, the case studies performed in this report were presented which consider:
- Four (4) HV Feeders. The selected feeders present significant differences between them (i.e., urban, short rural, long rural etc.) allow demonstrating that the adopted solutions can be applied, to the extent that is possible, across the wide spectrum of HV feeders in the AusNet Services area and other DNSP areas across Australia.
- Single-Day Analysis. For each feeder and solution, a single-day analysis is performed considering progressive solar PV penetration. This analysis provides a time-series demonstration of the network performance. This analysis represents the "worst-case" scenario of peak generation combined with low demand.
- Seasonal Analysis. For each feeder and solution, a seasonal analysis (multiple days per season) is performed considering progressive solar PV penetration. This analysis provides a more realistic representation of the network performance considering seasonality. PV generation is modelled considering real PV irradiance profiles and residential demand is modelled considering real smart meter data.

Chapter 4 presented the results from each case study and the main findings are summarised below:

Tailored Volt-Watt and Volt-Var PV Inverter Settings. A more tailored set of Volt-Watt and Volt-Var settings is proved to be highly effective in limiting voltage problems in the network. Regardless of PV penetrations ad seasons, the maximum voltage in the network never exceeds above 1.10pu. While the curtailment of PV generation was found to be approximately 1% higher for each penetration when compared to the BAU case (which had approximately 1% of curtailment), this can still be considered negligible given the significant benefits provided (i.e., full mitigation of voltage issues). For example, with a 100% PV penetration, the total curtailment never exceeds 2% of the total solar PV generation, regardless the type of feeder.

Tailored Volt-Watt and Volt-Var settings could be applied as individual settings, with some customers having more strict settings within the same network, potentially further increasing the benefits. Individualised settings would allow Volt-Watt and Volt-Var curves to change dependent on their location or time. For example, certain LV feeders could have stricter settings than others, or customers towards the end of the LV feeder having stricter settings than those at the head of the feeder.

LV OLTC-fitted Transformers with Adaptive Control. The adoption of LV OLTC-fitted transformers in combination with adjustment of off-load tap changers as well as augmentation of congested assets can effectively manage all technical issues and shift the hosting capacity to 100%. For those LV transformers where their off-load tap capability was not able to mitigate the voltage rise/drop issues, their replacement with an OLTC-fitted LV transformer and adopting the proposed OLTC control logic proves to be highly effective in keeping all customer voltages within the statutory voltage limits, regardless the penetration and season. In terms of PV generation curtailment, it was found to be almost negligible.

Off-the-Shelf (OTS) Battery Energy Storage (BES) Systems. The adoption of OTS BES systems does not help increase the HC further to what it could be achieved with traditional solutions (off-load taps and augmentation) alone. While compared to the BAU case, HC can be increased by at least 20%, this is only achieved due to the adjustment of off-load tap changers (i.e., voltage) and the corresponding augmentations (i.e., congestion). The adoption of OTS BES offers limited to almost no benefits for either technical issue. This is due to the following limitations:

- OTS BES systems do not fully discharge overnight. This is due to insufficient energy consumption of most customers. As a consequence, their ability to store surplus PV generation the following day is significantly reduced.
- OTS BES systems reach full SOC very early. With a partially charged BES system, surplus PV generation that occurs early in the morning can lead to a full SOC before or during high PV generation, resulting in PV exports.

In terms of voltage levels, during generation period were found to be almost the same as with the case of adjusting the off-load tap changers alone (Task 3) and in terms of the augmentation requirements, these were found to be almost the same as with those presented in Task 3. As such, the adoption of OTS BES provides limited to no benefits on either voltage of asset congestion management.

The curtailment of PV generation was found to be almost the same as with the case of adjusting the off-load tap changers alone (Task 3). This effect is primarily due to the adjustment of the off-load tap changers which reduces voltages hence the Volt-Watt function is not triggered. As such, the adoption of OTS BES has limited to no benefits on this effect.

Although the OTS BES system do no bring significant benefits to the network, the results show they are an excellent investment for PV owners as it allows to significantly reduce grid energy imports by at least 80% and, as a consequence, reduce electricity bills.

Network Smart (NS) Battery Energy Storage (BES) Systems. The adoption of NS BES systems in combination with adjustment of off-load tap changers as well as augmentation of congested assets can effectively manage all technical issues and shift the hosting capacity to 100%. Compared to the results obtained when OTS BES systems are adopted, the performance in terms of voltage and asset utilization is significantly increased. Results show that NS BES systems are highly effective in significantly reducing the utilization level of all assets and more importantly alleviate almost all transformer congestion issues for all penetration and seasons. While the adoption of the network smart control logic might lead to slightly higher grid imports for customers than with the OTS control, the corresponding expense might be considerably lower than the capital investments required to provide the same network benefits with asset-intensive solutions, such as network reinforcements. Although not simulated, it is possible for NS BES systems, with modified settings, to absorb reactive power as shown with PV inverters, to further reduce the impact of voltage rise.

Dynamic Voltage Target at Zone Substation OLTC. The adoption of a dynamic voltage target at the zone substation OLTC is shown to be very effective in mitigating voltage issues during peak generation hours by creating additional headroom. This resulted in voltage issues only occurring beyond 80% penetration. Nonetheless, due to the nature of OLTCs (i.e., affecting voltages only), this solution is not able to address any congestion issues in the network. In fact, without considering other solutions, it can increase network congestion due to less PV curtailment from the Volt-Watt functions. Furthermore, when compared with a permanent setting (e.g., the solutions investigated in Task 3), a dynamic voltage target offers the added benefit of not affecting the voltage legroom during peak demand periods. This can be beneficial for networks that experiences heavy demands at night. Finally, it is worth noting that this analysis did not consider the impact of the investigated solution on other HV feeders that could be connected to the same zone substation. Since any adjustment of the voltage target at the zone substation will affect all downstream networks, its adequacy and effectiveness highly depends on the characteristics of all downstream networks. Consequently, a more realistic assessment entails the modelling of all feeders connected to a given zone substation.

8.2 Planning Recommendations

Considering the analyses performed in the previous Task (Traditional Solutions) and this Task 4 (Non-Traditional Solutions), the following planning recommendations are drawn.

Business as Usual (no traditional solution implemented) is 20%

- Without the implementation of traditional solutions, the HC of all HV feeders investigated is approximately <u>20% penetration</u> of solar PV. Depending on the HV feeder, this HC is expected to have been reached between 2017 and 2019.
- The HC is primarily limited by voltage issues, which is experienced by all feeders.
- At the HC, a small number of transformers is expected to face congestion issues.
    - In particular, transformers with small capacities (<=50kVA).
    - More probable in rural feeders as larger number of small transformers exist.
- The analyses highlight that, for all HV feeders, enabling both Volt-Watt and Volt-var functions with the Victorian Volt-Watt and Volt-var settings set as default provides significant benefits to both DNSPs and customers. Voltage rise issues and curtailment are dramatically reduced compared to just having the Volt-Watt function enabled.
    - Regardless of the PV penetration, or solution adopted, the combination of the two functions helps keep the maximum voltage across all feeders up to 1.12pu. This effect can be explained due to the significant absorption of reactive power from multiple solar PV installations which helps reduce voltages.
    - Generation curtailment is always kept to significantly low levels (below 2%) regardless the type of feeder and penetration level. This finding demonstrates the significant value brought to customers (minimal curtailment).
        - Volt-Watt alone (Volt-var not enabled) leads to significant curtailment which can, in turn, affect the profitability of solar PV owners.
    - While significant benefits were found in terms of voltage issues and generation curtailment, the Volt-var function can exacerbate the thermal utilization of assets. The significant amount of reactive power being absorbed results in larger currents flowing through conductors and transformers. Most affected are the low-capacity LV transformers which become overloaded at relatively low penetration levels; at much lower levels than without having the Volt-var function. This can be effectively solved by network augmentation which needs to be planned for.
    - In the aggregate, the Volt-var function significantly increases the reactive power being imported at the head of the HV feeder. This could potentially create issues in maintaining the power factor at the transmission-distribution network interface within the allowed limits. Adequate planning of capacitor banks in the upstream network (i.e., sub-transmission) might be required to compensate for this increase.
- Based on the above, it is recommended that
    - DNSPs across Australia consider in their PV connection requirements that both inverter control functions (Volt-Watt and Volt-var) are enabled and with the same or similar settings to those defined by Victorian DNSPs [2, 3]; and,

    - customer voltages of HV feeders approaching 20% of solar PV penetration are monitored/analyzed, and that further connection requests are approved upon more detailed network studies.
- Simulations have considered homogeneity among the technologies and settings installed by residential customers (e.g., same PV inverter settings, BES with PV, BES capacity). In real networks, different customers can have different technologies installed (some customers with PV might not have BES). Furthermore, as PV penetration increases, some customers will still be operating on older inverter settings whilst only newer installations will operate with the newer standards. This also applies to storage as time progresses, newer BES system installations will have updated connection standards that will have to operate alongside older standards.

Increasing HC with traditional solutions to 40% (extra 20%)

- The HC of all urban and short rural HV feeders can be shifted to 40% (to be reached between 2021 and 2030 depending on the HV feeder) by adjusting the off-load taps of the LV transformers as it significantly reduces voltage issues.
    - This solution is likely to provide limited benefits to long rural HV Feeders due to:
        - The level of voltage rise in SWER connected solar PV customers can be significantly higher than the corresponding voltage reduction of the tap step.
        - The tap capability of SWER transformers can be limited.
    - This solution will also, indirectly, help reduce the level of solar PV curtailment.
- Some additional – but minor – benefits (slightly less voltage issues) can also be achieved by adjusting the voltage target at the zone substation (followed by the adequate adjustment of off-load tap changers).
- Caution should be taken as the adjustment of the OLTC target and/or off-load tap positions may create issues during unexpected peak demand conditions (larger voltage drops) or due to the future adoption of technologies that increase demand (i.e., electric vehicles).
- Based on the above, it is recommended that for urban HV feeders as well as short rural HV feeders, the adjustment of off-load tap changers is exploited (when possible) to make it possible to host up to 40% of houses with solar PV.

Increasing HC with traditional solutions beyond 40%

- Beyond 40% penetration of solar PV, the HC is limited by both congestion issues (experienced by LV transformers and HV conductors) and voltage issues.
- Network augmentation is effective in mitigating congestion issues. However, while it indirectly helps reduce voltages (conductors have smaller impedances), the conductors considered in the analysis did not eliminate voltage issues. Consequently, at high penetrations, voltage issues will still remain (even with the adjustment of off-load tap changers).
- Based on the above, traditional solutions are unable to facilitate high solar PV penetrations. Thus, it is recommended that for such cases, non-traditional solutions are explored.

Increasing HC with traditional and non-traditional solutions beyond 40%

- <u>LV OLTC-fitted Transformers and Traditional Solutions.</u>
    - The <u>HC of all urban and rural HV feeders can be shifted to 100%</u> (to be reached between 2040 and 2060 depending on the HV feeder) by installing OLTC-fitted LV transformers with an adaptive control logic as well as adjusting the off-load taps of LV transformers and augmenting congested assets.
    - OLTC-fitted LV transformers with the proposed control logic are highly effective in regulating voltage issues within the statutory limits in both urban and rural feeders.

        - For those LV transformers where off-load tap capability is not able to mitigate the voltage rise/drop issues, their replacement with an adaptive OLTC-fitted LV transformer is can be considered.
        - The adaptive operation of the OLTC can cater not only for voltage rise issues but for voltage drop issues as well. This highlights a more future proof solution able to cater also for voltage drop issues due to the future adoption of technologies that can increase demand (i.e., electric vehicles).
        - The operation of OLTC-fitted LV transformers in long rural feeders with long SWER connections can be challenging as at high penetration levels (>50%) voltages might still be close to the statutory limit. This effect can be explained due to the fact that the level of voltage rise in SWER connected solar PV customers can be significantly higher than the corresponding voltage reduction of the tap steps.
    - This solution leads to negligible curtailment. This is the effect of significantly reducing voltages, hence, Volt-Watt is not triggered. This finding shows the significant value offered to the customers.
    - This solution requires a significant percentage of LV transformers connected to an HV Feeder to be equipped with OLTC. At least 50% of LV transformers will need to be equipped with OLTC by 60% penetration (2030 and 2040 depending on the HV feeder).
        - For urban networks OLTCs installations correspond to relatively high rating transformers (>300kVA).
        - For rural networks OLTCs installations correspond to relatively low rating transformers (<100kVA).
        - Regardless the type of feeder, penetration and season, the average daily tap changes is not expected to exceed 10. This low number of tap changes can lead to a reduced wear and tear of the OLTC hence requiring less maintenance costs.

- Off-the-Shelf BES systems and Traditional Solutions.
    - If the HC bottleneck for either urban or rural HV feeder are voltage issues the adoption of OTS BES has a limited to no contribution in shifting the hosting capacity further to what can be achieved with the traditional solutions alone. The aforementioned is due to the following limitations:
        - OTS BES systems do not fully discharge overnight. This is due to insufficient energy consumption of most customers. As a consequence, their ability to store surplus PV generation the following day is significantly reduced.
        - OTS BES systems reach full SOC very early. With a partially charged BES system, surplus PV generation that occurs early in the morning can lead to a full SOC before or during high PV generation, resulting in PV exports
    - While compared to the BAU case the HC can be increased by at least 20%, this is only achieved due to the adjustment of off-load tap changers (i.e., voltage) and the corresponding augmentations (i.e., congestion).

- Network Smart BES systems and Traditional Solutions.
    - The HC of all urban and rural HV feeders can be shifted to 100% (to be reached between 2040 and 2060 depending on the HV feeder) by adopting residential BES systems with a network smart controller as well as adjusting the off-load taps of LV transformers and augmenting congested assets.
    - BES systems with a network smart controller can significantly reduce voltages during the generation period while keeping the maximum voltages well below the statutory limit (<1.10p.u), regardless the penetration level and season. This performance is only achieved due to the network smart control logic that enables BES systems charge throughout the whole generation period, hence significantly reduce household exports.

    - The reduction of voltage during PV generation hours provides a significant voltage headroom that can help facilitate the provision of flexibility services from Distribution Networks.
  - BES systems with a network smart controller can significantly reduce the utilization level of all assets and more importantly alleviate congestion issues for the majority of otherwise congested assets. Analyses highlighted that the adoption of BES systems with a network smart controller can reduce augmentation requirements by at least 60%.
  - Curtailment of PV generation is almost negligible when adopting this solution. This effect is due to the ability to keep all customer voltages always below 1.10p.u, hence the volt-watt function not triggering. Compared to the OTS BES analysis, the adoption of the network smart control logic contributes significantly to this performance.
    - The adoption of BES systems with a network smart controller, compared to the OTS BES, increases customers' grid dependence by 2-4%. While the adoption of the network smart control logic might lead to slightly higher grid imports for customers than with the OTS control, the corresponding expense might be considerably lower than the capital investments required to provide the same network benefits with asset-intensive solutions, such as network augmentation.

- Based on the above, it is recommended that for either type of HV feeder, the adjustment of off-load tap changers is exploited (when possible) and for those LV transformers where off-load tap capability is not able to mitigate the voltage rise/drop issues, their replacement with an adaptive OLTC-fitted LV transformer should be considered.
- Given this rapid adoption of BES by households with solar PV, it is crucial for DNSPs to understand as early as possible that the OTS operation of BES systems will not help mitigating solar PV impacts. However, there is a clear opportunity where these emerging technologies can provide an alternative to expensive and time-consuming augmentations. Nonetheless, for this to happen, there are two potential pathways: 1) households can be incentivized to adopt advanced battery management strategies, or 2) such strategies become mandatory.
  - The first pathway acknowledges the fact that households are helping electricity distribution companies deferring network investments. Hence, incentives such as direct payments or subsidized/discounted BES systems with those strategies can stimulate and accelerate the corresponding adoption.
  - The second pathway, on the other hand, follows the philosophy of providing network support through regulation (e.g., standards, technical requirements). This is similar to what has already been seen with PV inverter functions such as Volt-Watt and Volt-Var which are required to be enabled (and with specific settings).

Increasing HC with a dynamic voltage target at zone substation OLTC

- A variable voltage target at the zone substation can be an effective option in creating additional headroom that targets peak generation hours. However, this solution is more applicable to zone substations where all the HV feeders connected to it have similar characteristics (demand/generation). Otherwise, the management of voltage rise issues on one HV feeder can result in voltage drop issues in another.
- Due to the limitation of existing OLTC designs, i.e., predominately targeted at boosting voltages, there are very few tap positions available to reduce voltages. Furthermore, the relatively large deadbands (typically between 2% and 3%) also poses issues to control voltages in a granular way, which can limit the overall flexibility of this solution
- Based on the above, it is recommended that future OLTC investments should consider additional taps to reduce voltages as well as more granular deadbands for more precise control of voltages.

9 Next Steps

The next steps to be carried out by The University of Melbourne for the "Advanced Planning of PV-Rich Distribution Networks" project include:

Task 5 Cost comparison among potential solutions
Task 5 This task will develop and perform a cost comparison assessment among all potential solutions, traditional and non-tradition, considering both the capital and operational expenditures. This will help determining in which cases (e.g., type of network, PV penetration level), certain solutions are more cost-effective and, therefore, should be considered by DNSPs.

Deliverable 9: Cost comparison among potential solutions (Delivery Date: 10th November 2020)
Synopsis: Technical Report presenting the methodology and initial findings corresponding to the comparison of traditional and non-traditional solutions to increase PV hosting capacity.

10 References

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