Appendices

Future grid for distributed energy

JUNE 2020

CitiPower and Powercor is Victoria's largest electricity distribution business, delivering electricity to over 1.1 million residential households and commercial customers across Victoria. CitiPower provides power for more than 330,000 customers in Melbourne's CBD and inner suburbs. Powercor provides electricity for nearly 820,000 customers in central and western Victoria, as well as Melbourne's western suburbs.

CitiPower and Powercor engaged ENEA Consulting to undertake the Distributed Energy Resources Hosting Capacity Study. CitiPower and Powercor supported ENEA Consulting by establishing the low voltage network categories, providing the power flow models of the example networks and technical support.

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ENEA Consulting is a strategy consultancy that maximises energy transition opportunities for public and private organisations globally. Through dedicated consulting services and pro bono support to NGOs and social entrepreneurs, ENEA is also committed to improving energy access, especially in developing countries.

As part of this Distributed Energy Resources (DER) Hosting Capacity Study, CitiPower and Powercor commissioned ENEA Consulting to perform power flow modelling of the example low voltage networks, undertake a techno-economic assessment of mitigation measures and write the DER Hosting Capacity Study report.

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Contents

1 Assumptions

Modelling PV generation

Customer type	PV system size
Residential	5 kW
C&I	25 kW

The PV generation is computed using the open-source Python library pvlib. This library was originally developed at Sandia National Laboratories and generates PV generation values based on the following inputs:

1. The solar irradiance
2. The air temperature
3. The wind speed
4. The geographical coordinates
5. The configuration of the solar panels (tilt and azimuth).

To account for a variety of solar panel implementations (and the fact that every premises will receive a solar installation throughout modelling), PV profiles are generated at azimuths of 90, 180 and 270 degrees. The results for the different configurations are then averaged. As the typical Victorian rooftop shows a tilt between 23 and 38 degrees, the mean value is taken, 30.5 degrees.

Cost-benefit analysis

Mitigation option	CAPEX	Marginal cost	Lifetime
Reconductoring	$57,000	$1,257	50
Transformer upgrade	$57,000	$1,257	50
Combined reconductoring and transformer upgrade	$80,000	$1,764	50
Transformer upgrade and OLTC	$129,069	$3,712	50
Behind-the-meter battery (residential)	$18,900	$18,900	10
Behind-the-meter battery (C&I)	$58,900	$58,900	10
Smart inverter (residential)	$1,250	$0	10
Smart inverter (C&I)	$4,000	$0	15
Low voltage regulator	$10,000	$10,000	10

Investment responsibility	WACC (real)
DNSP (network augmentation)	2.33%
Residential customer (behind-the-meter)	8%
C&I customers (behind-the-meter)	8%

Substation type	Maximum kVA rating (CitiPower)	Maximum kVA rating (Powercor)
Pole type (Three-phase)	500	315
Pole type (Single-phase)	N/A	50
SWER	N/A	25
Kiosk	2,000	2,000
Indoor	2,000	2,000

Reconductoring assumptions	• Low quality conductors replaced with 4-19/3.25 AAC • Underground cables, 19/3.25AAC and ABC were not upgraded

Behind-the-meter battery feature	Assumption
Operation	Operated to maximise self-consumption with no price consideration. Battery only charges from the PV system
Capacity	Residential customer – 13.5 kWh C&I – 67.5 kWh
Roundtrip efficiency	92.5%
Peak and continuous output	When modelling battery behaviour, output ratings are modelled as a hard limit, so essentially, the continuous and peak output ratings are one and the same.

Low voltage regulator feature	Assumption
Voltage regulation	+/- 13%
Regulation accuracy bandwidth	+/-1% (229 V and 231 V)
Capacity	30 kVA per phase per LV street circuit

Dynamic voltage control feature	Assumption
Tapping range	+/- 10%
Tap size	2.5%

2 LV network categories and features

LV network categories

CPPAL has over 80,000 LV networks. These were allocated to 10 categories based on common features that influence hosting capacity. Listed below are the total number of LV networks allocated to each category and the total number of customers in each category.

LV network category	Total number of LV networks	Total number of customers
High-density indoor	3,209	148,651
URD kiosk	1,289	141,116
Mid-density pole	2,381	178,328
C&I pole	2,440	15,671
Urban pole	3,853	390,485
Urban C&I pole A / B	1,052	1,052
Mid-density rural pole	9,401	87,850
Low-density rural single-phase	37,297	88,904
Remote rural SWER	17,438	28,442

Example LV network features

Ten real-world LV networks were chosen from each of the 10 categories. The following table compares features of these specific LV networks, which are not necessarily representative of all LV networks within each example LV network's category but do cover a wide variety of LV network arrangements.

Example LV network	Transformer rating (kVA)	Total customers	% residential customers	Maximum demand (kW)	Conductor	HV feeder type	Average distance from distribution transformer (m)
High-density indoor - 1000kVA - 159mm^2 (0.25 in) 3.5/c Cu	1,000	9	53%	124	159mm cu	CBD	195
C&I pole - 500kVA - 4-19/3.25 AAC	500	9	0%	27	4-19/3.25 AAC	Urban	83
Mid-density pole - 500kVA - 4-19/3.25 AAC	500	23	0%	167	19/3.25 AAC	Urban	93
URD kiosk - 315kVA - 185mm2 4/c lv.sa.x	315	125	98%	108	185mm lv.sa.x	Urban	234
Urban pole - 315kVA - 150mm2 LV ABC	315	57	77%	44	Mainly 150mm LVABC	Rural Long	200
Urban C&I pole A - 315kVA - 150mm^2 LV ABC	315	15	14%	10	Mainly 150mm LVABC	Rural Long	83
Urban C&I pole B - 315kVA - 4-6/.186,7/062 ACSR	315	16	14%	10	4-6/.186, 7/062 ACSR	Rural Long	83
Low-density rural single-phase - 50kVA - 3-7/.064 Cu	50	6	100%	5	.080 cu	Rural Long	83
Mid-density rural pole - 100kVA - 4-6/1/114 ACSR	50	24	100%	23	4-6/1/114 ACSR	Rural Long	283
Remote rural SWER - 10kVA - 2-7/.064 Cu	10	1	0%	4	2-7/.064 cu	Rural Long	70

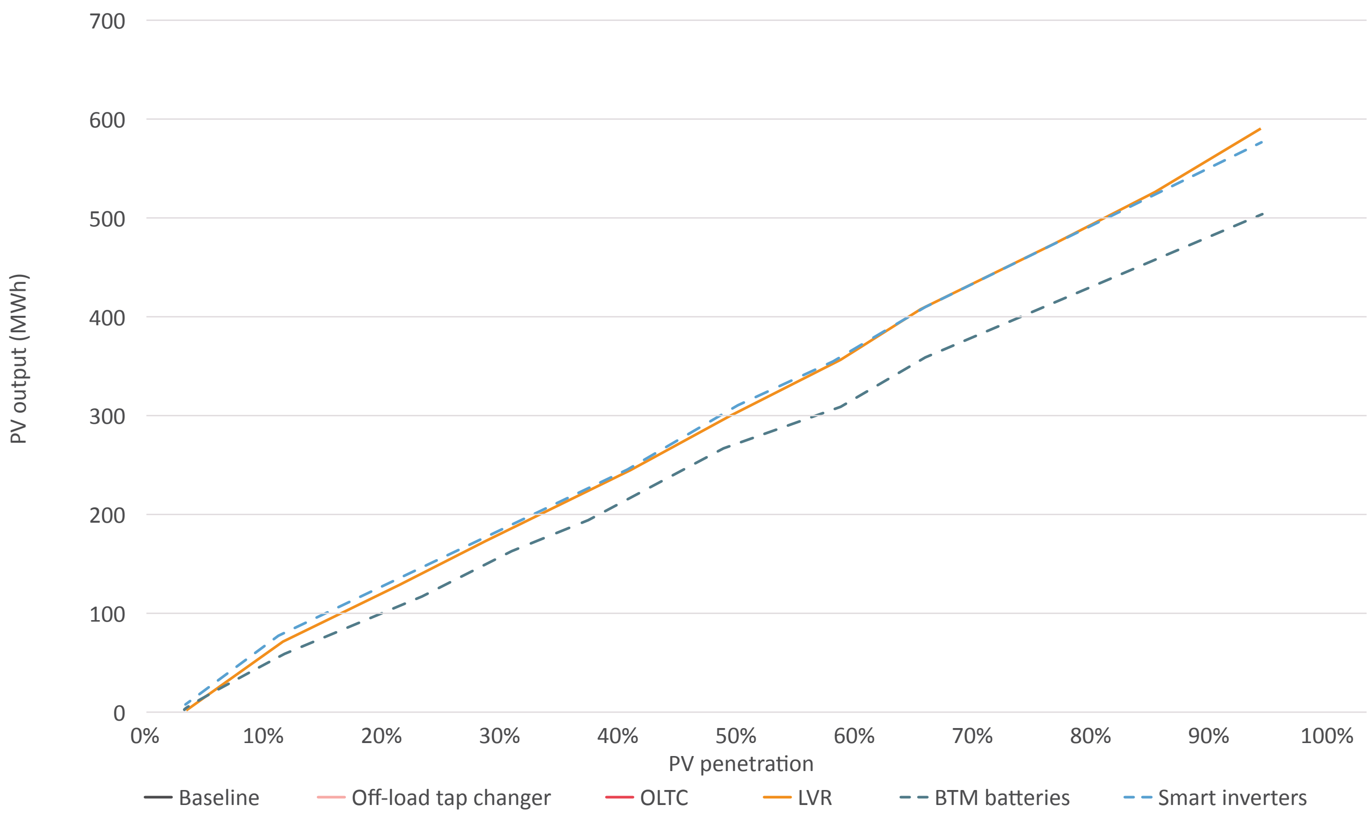
3 Mitigation measures performance

Five mitigation measures were applied to the eight LV networks that were not able to achieve 100% PV penetration without experiencing voltage issues. These included transformer upgrade and/or reconductoring (off-load tap changer, increasing transformer rating, increasing LV conductor quality), OLTC, LVR, smart inverters and behind-the-meter batteries.

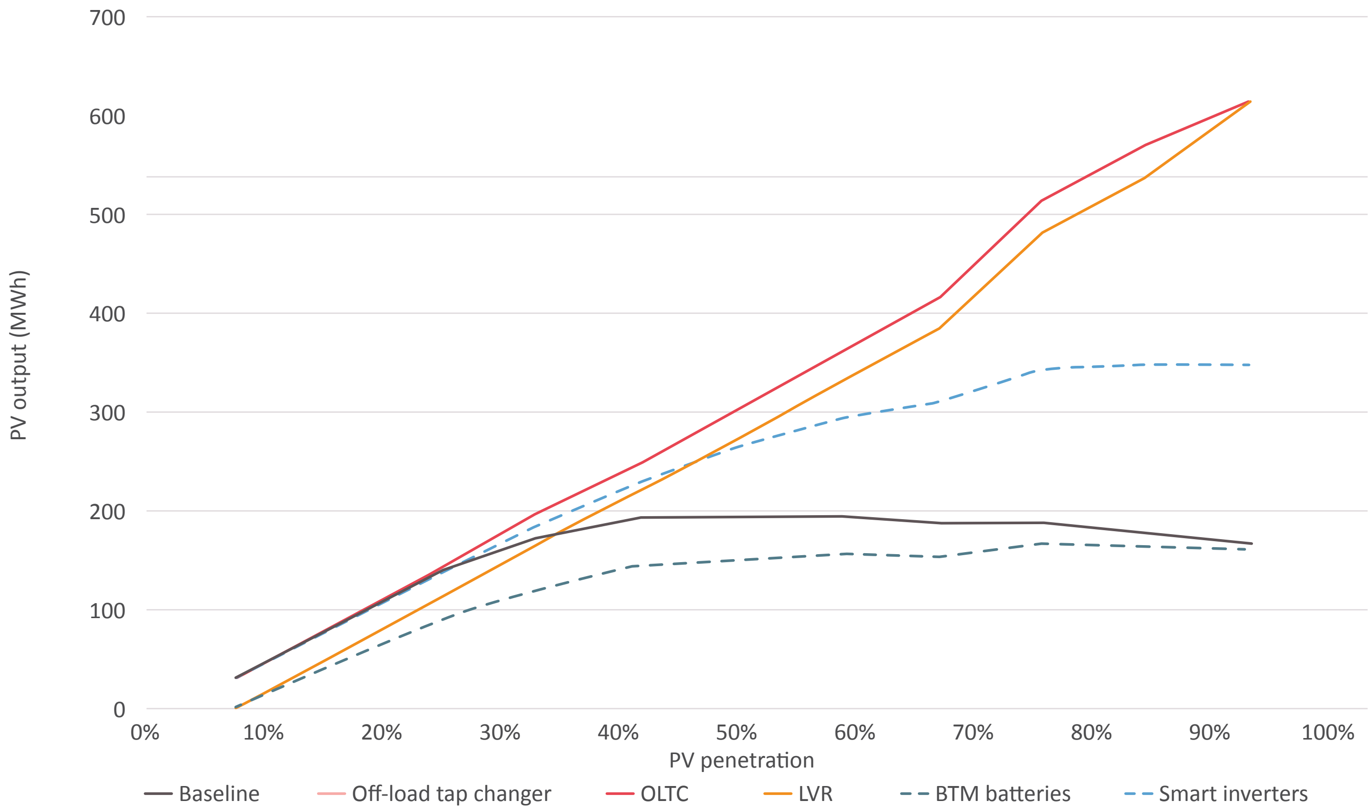
Additional PV generation

The following figures show the amount of non-breaching PV generation (in MWh) enabled by each mitigation measure compared to the baseline scenario for each LV network.

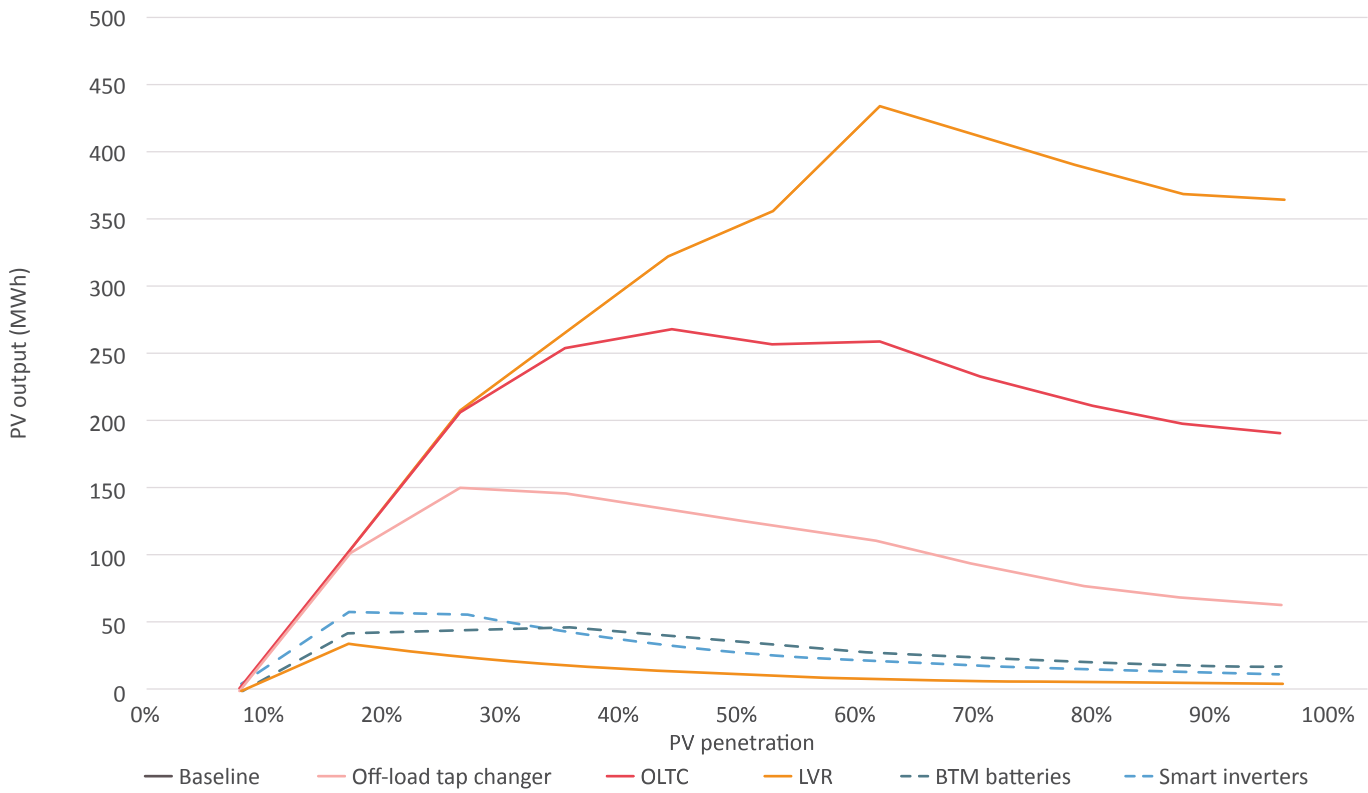
Mid-density pole - 500kVA - 4-19/3.25 AAC



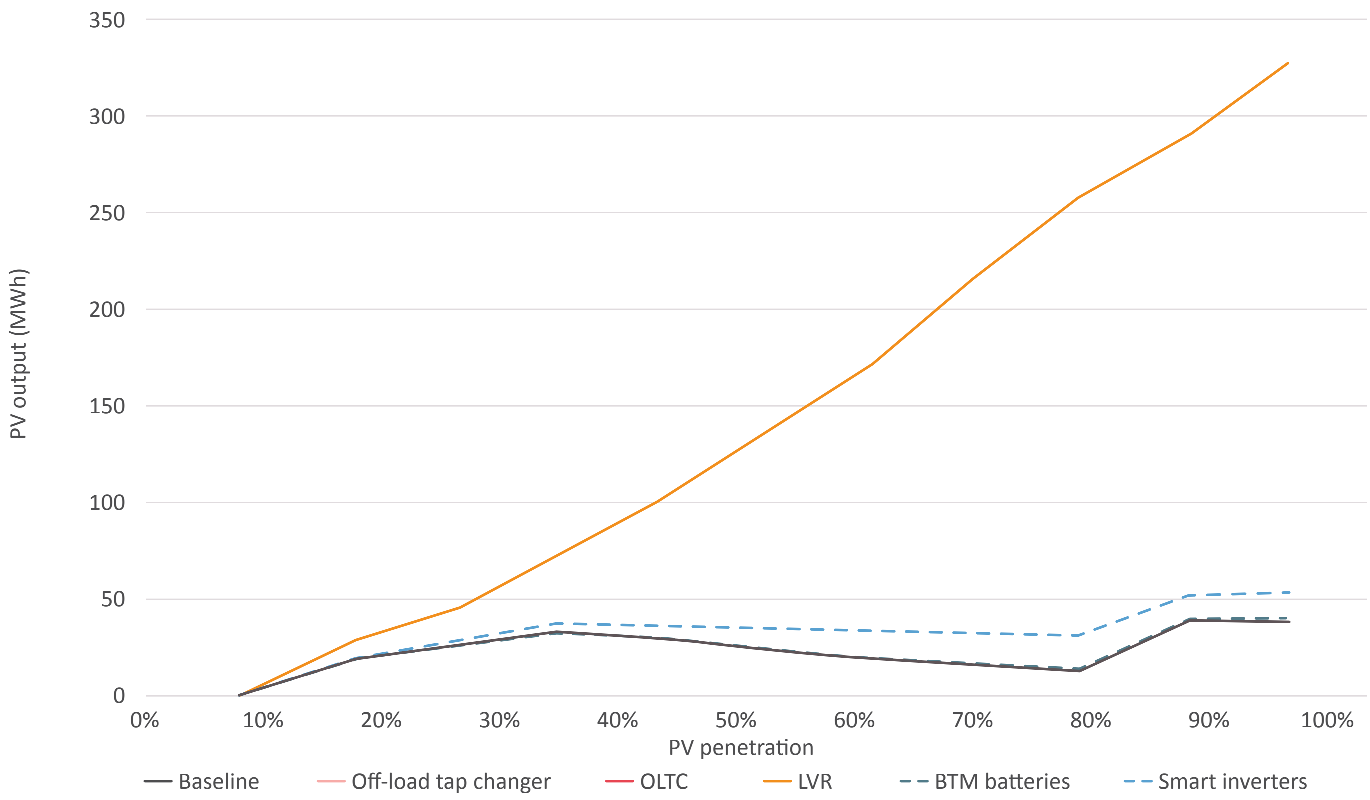
URD kiosk - 315kVA - 185mm² 4/c lv.sa.x



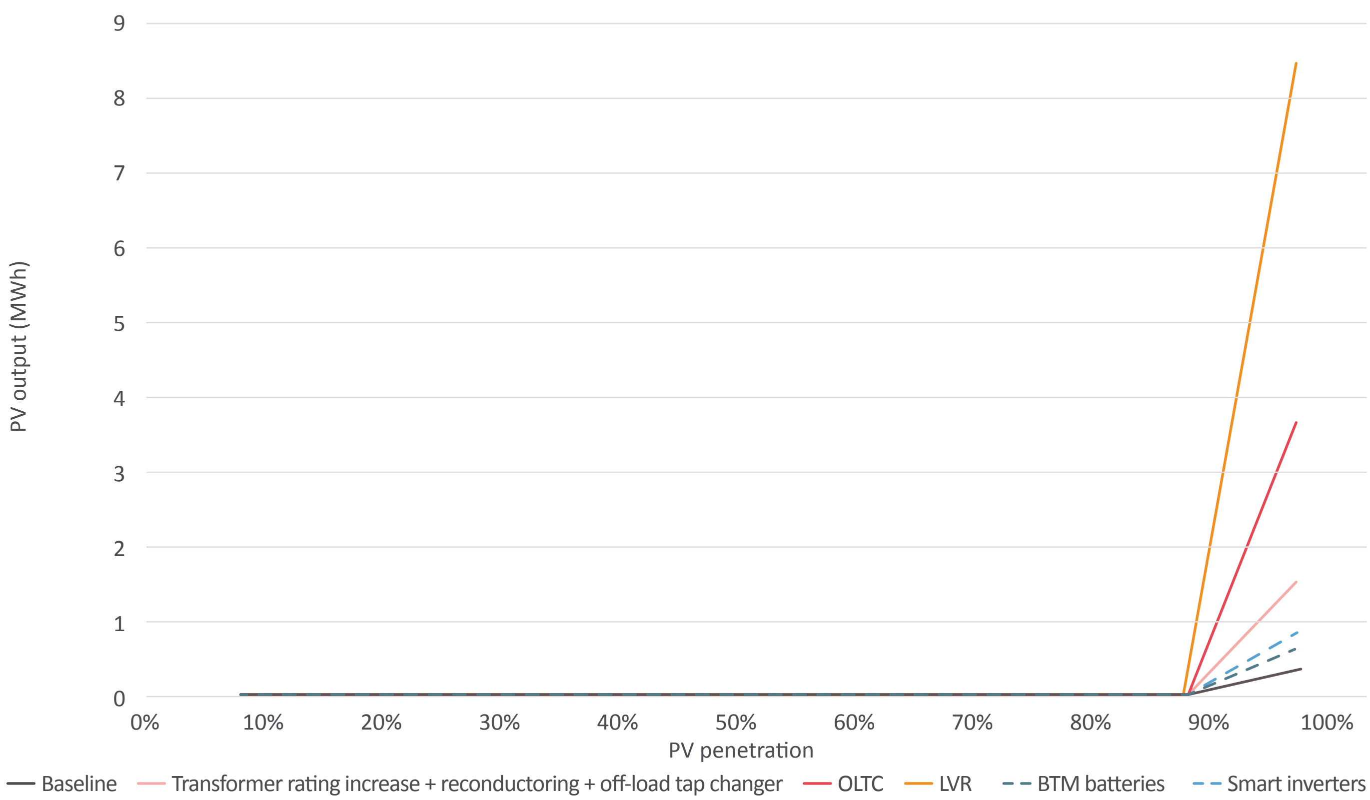
Urban pole - 315kVA - 150mm² LV ABC



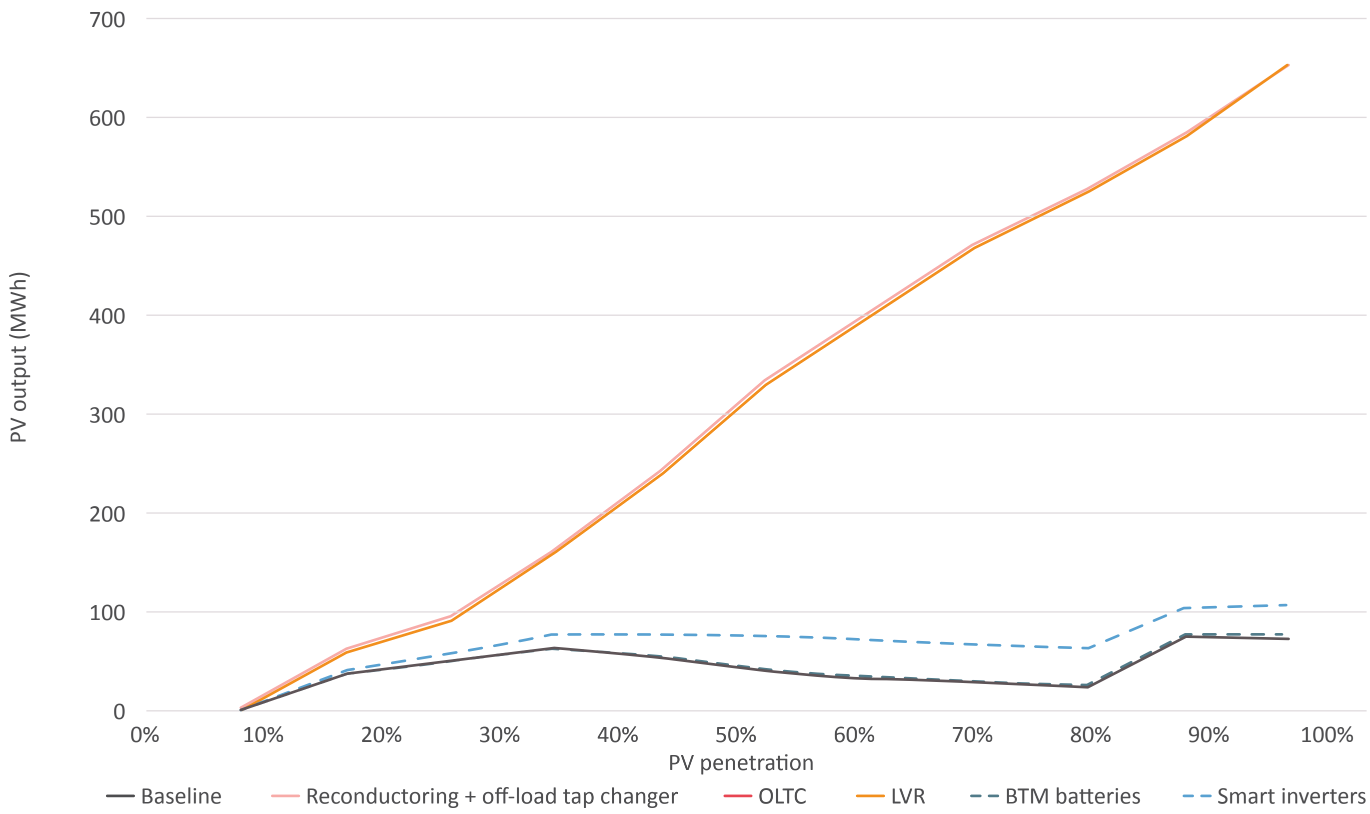
Urban C&I pole A - 315kVA - 150mm² LV ABC



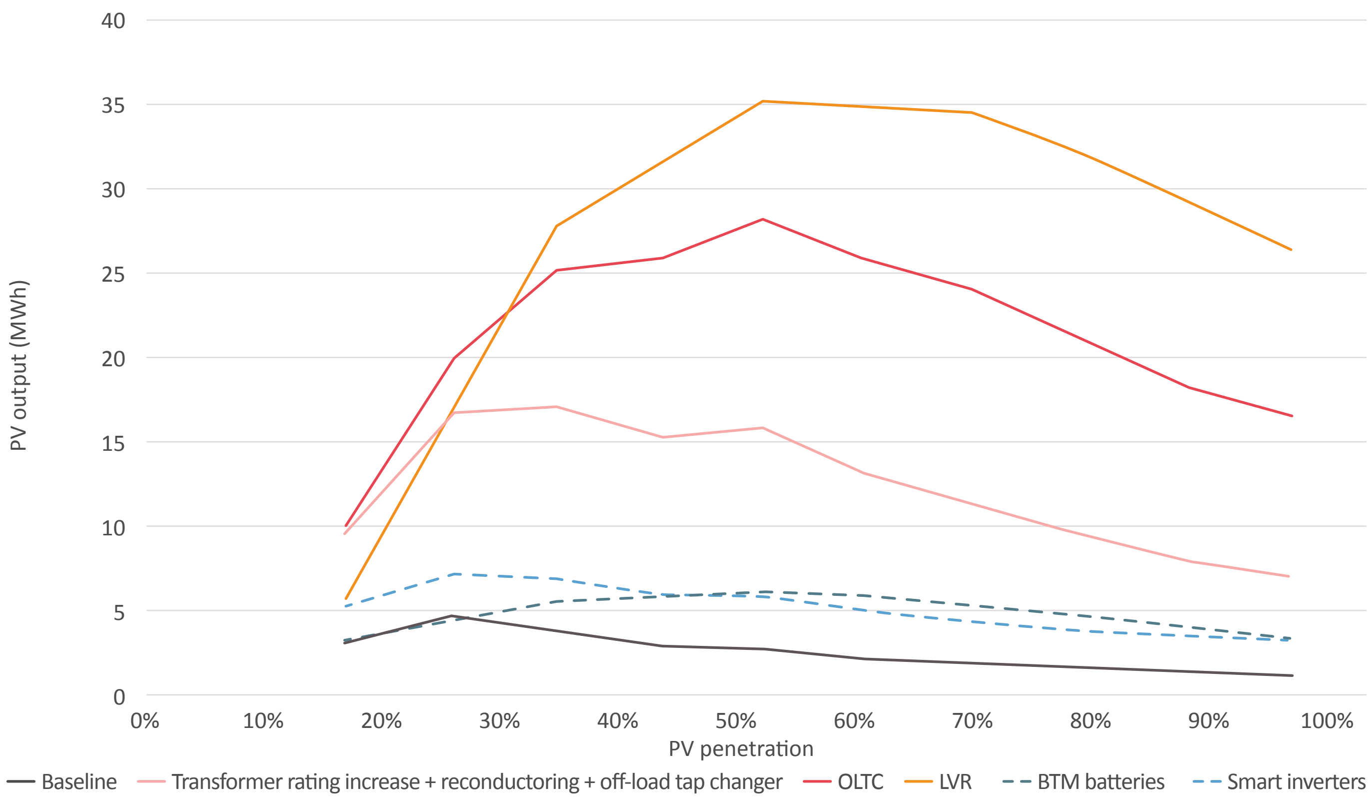
Remote rural SWER - 10kVA - 2-7/.064 Cu



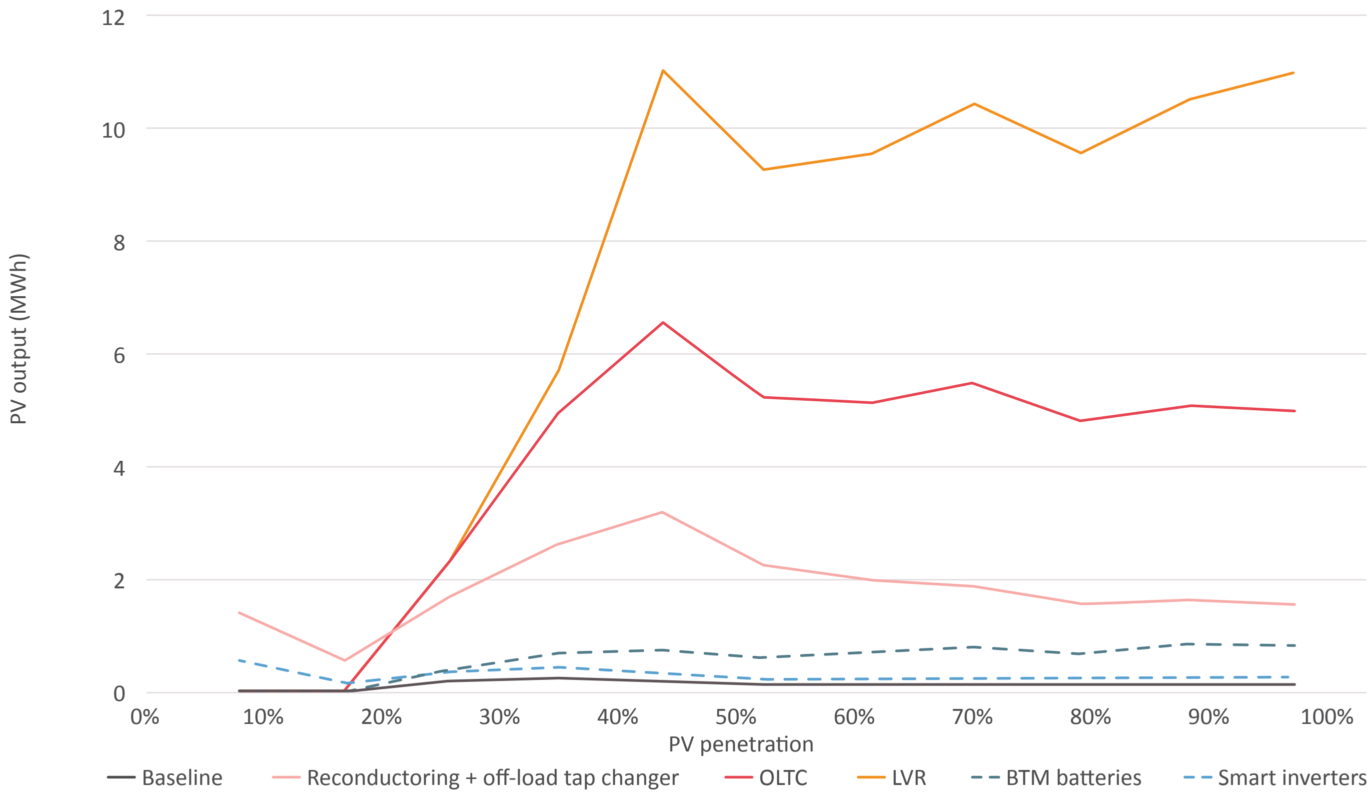
Urban C&I pole B - 315kVA - 4-6/.186,7/062 ACSR



Mid-density rural pole - 100kVA - 4-6/1/114 ACSR



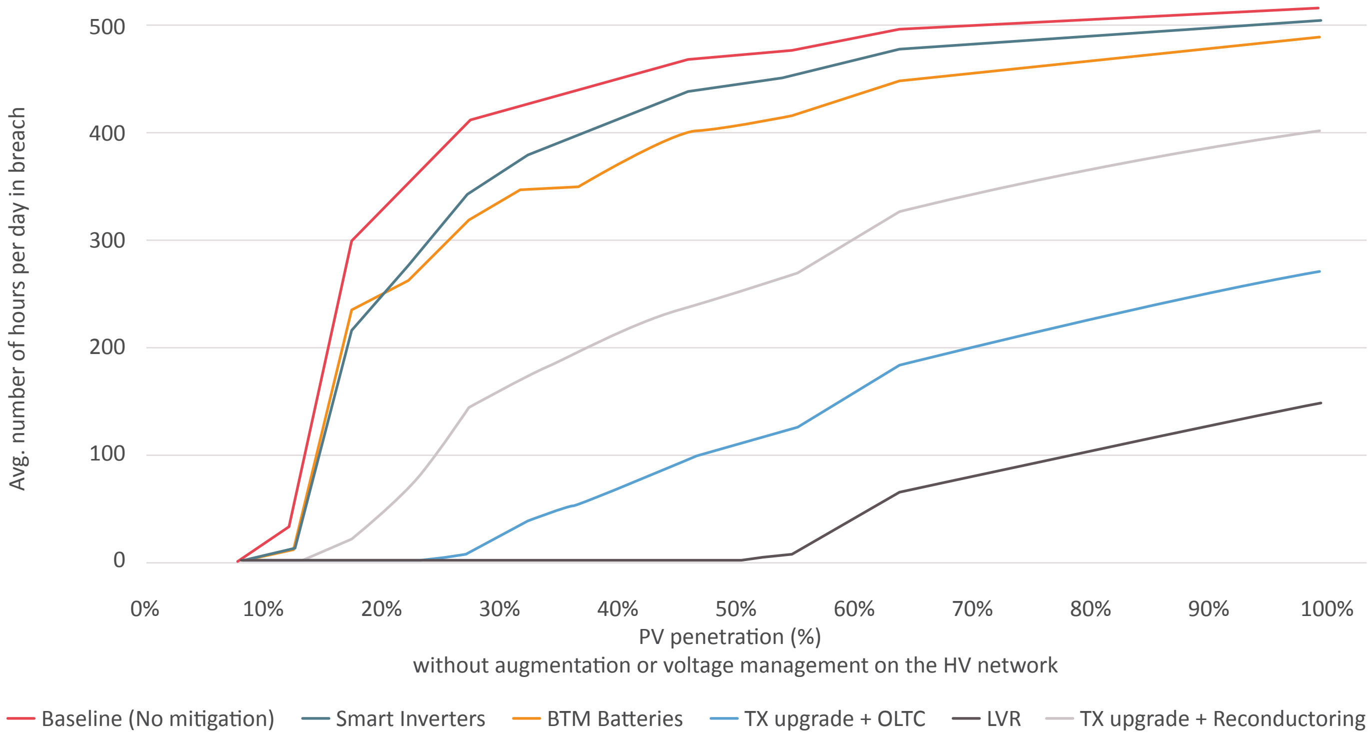
Low-density rural single-phase - 50kVA - 3-7/.064 Cu



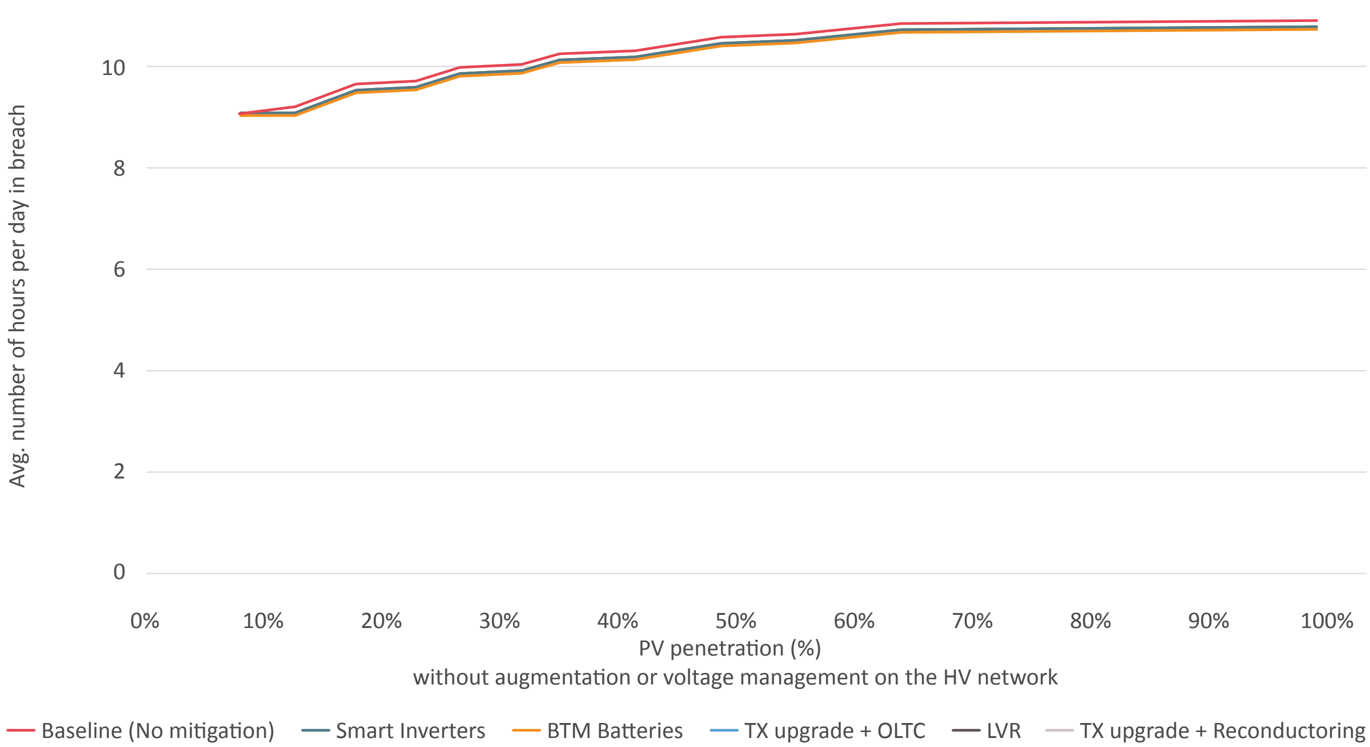
Average number of hours spent in breach

The following figures show the average number of hours per day spent in breach achieved by each mitigation measure compared to the baseline scenario for each LV network.

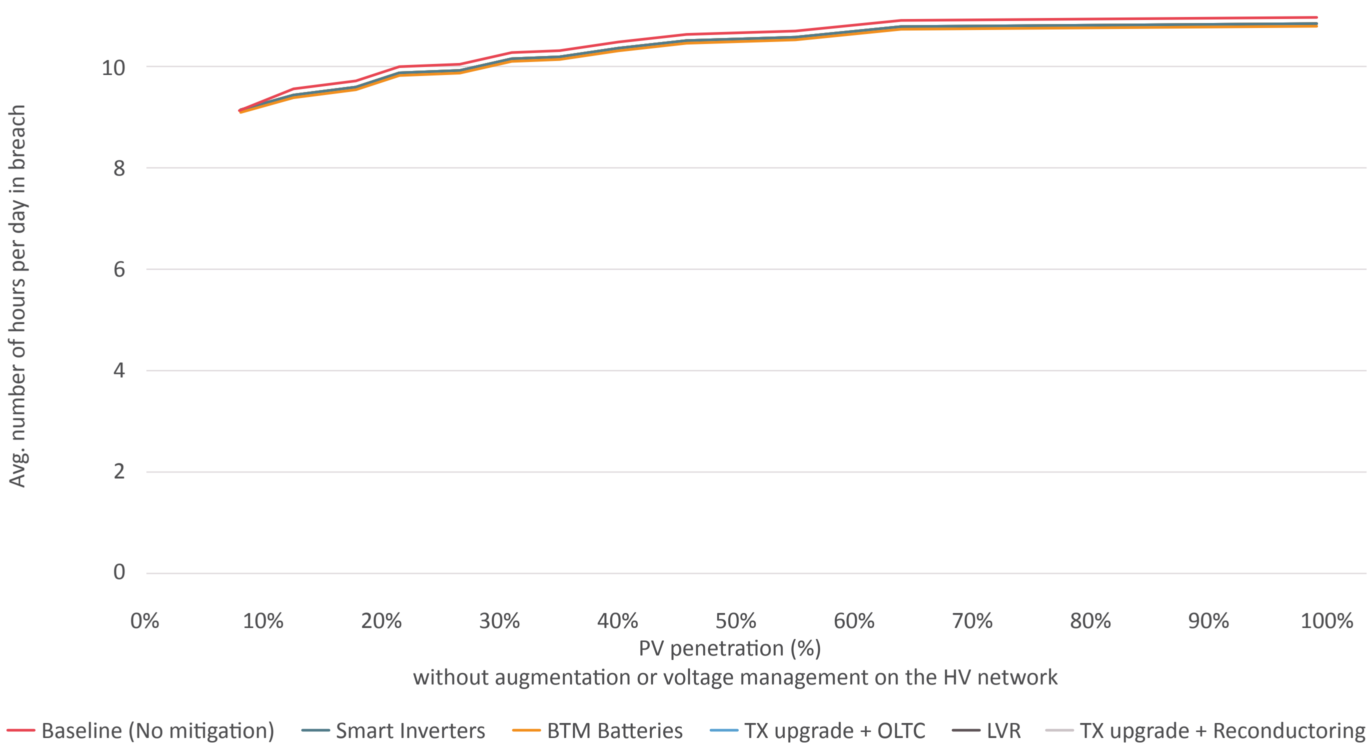
Urban pole - 315kVA - 150mm² LV ABC



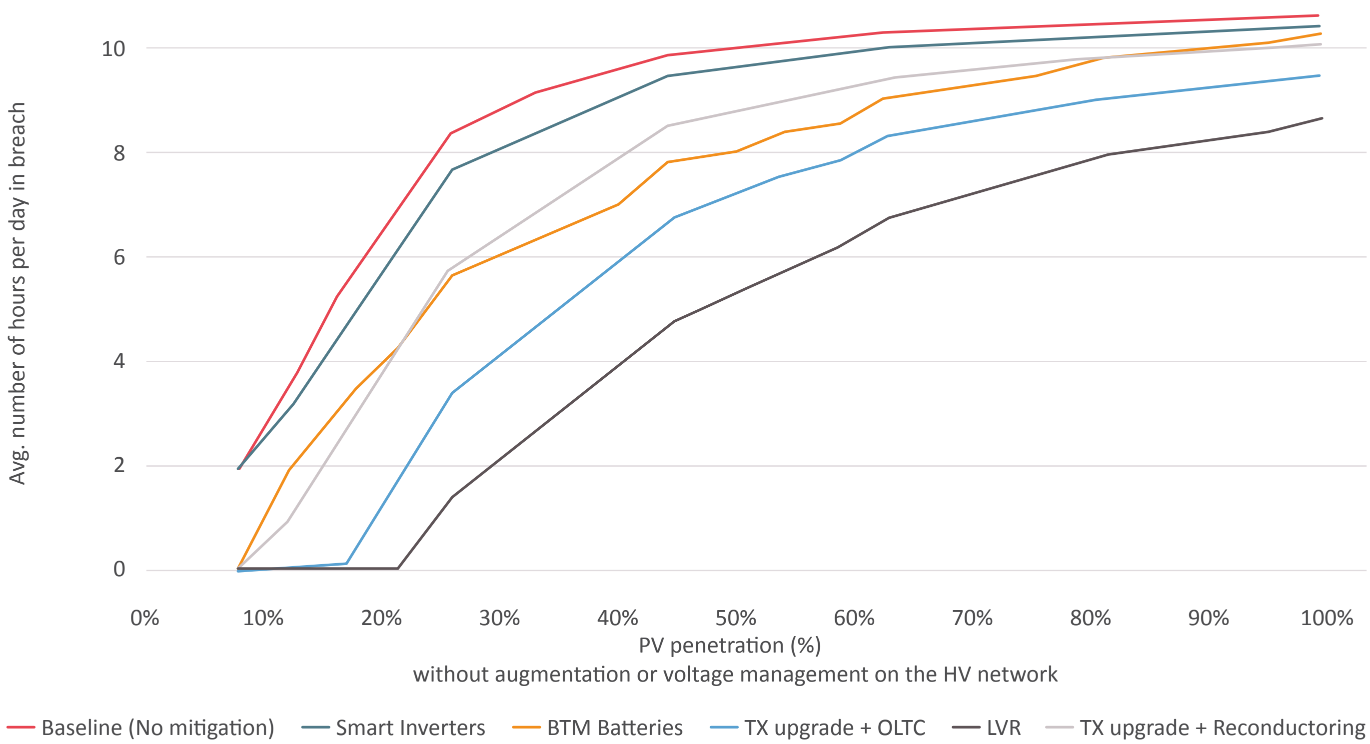
Urban pole - 315kVA - 150mm² LV ABC



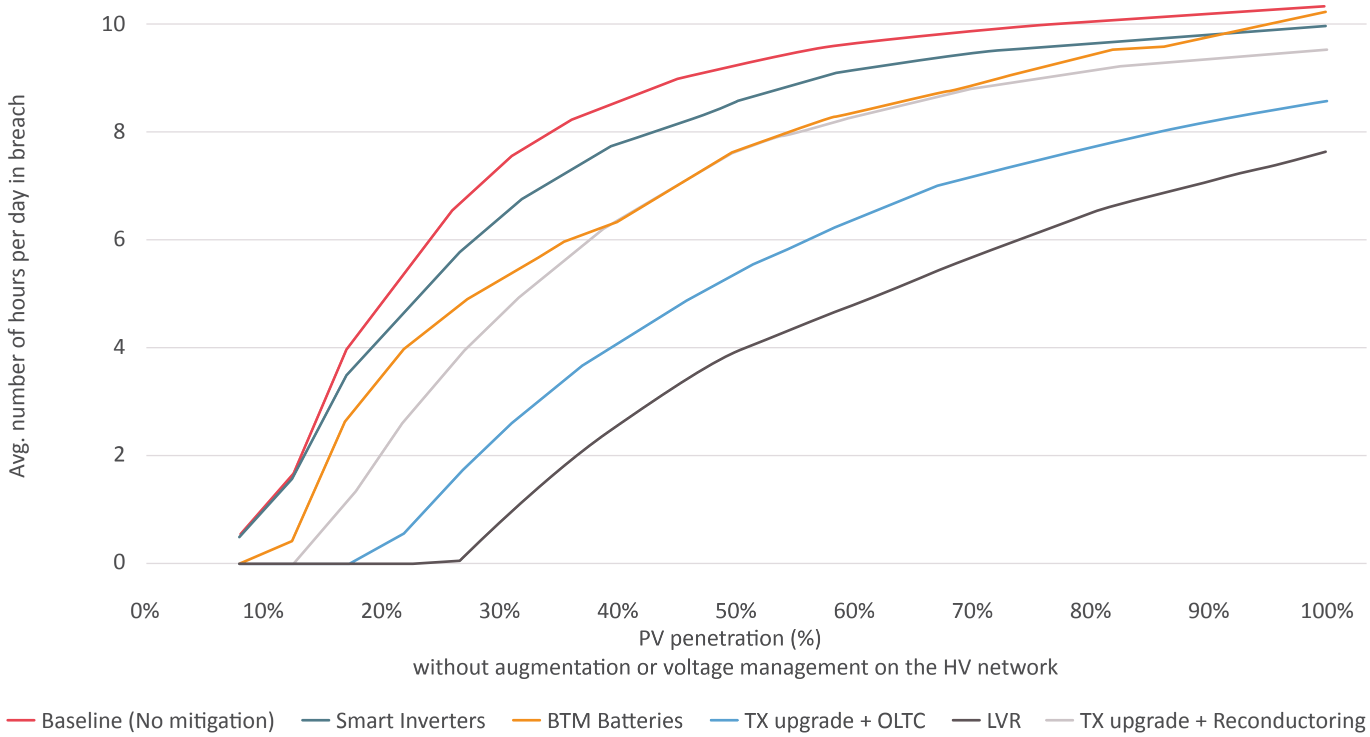
Urban C&I pole B - 315kVA - 4-6/.186,7/062 ACSR



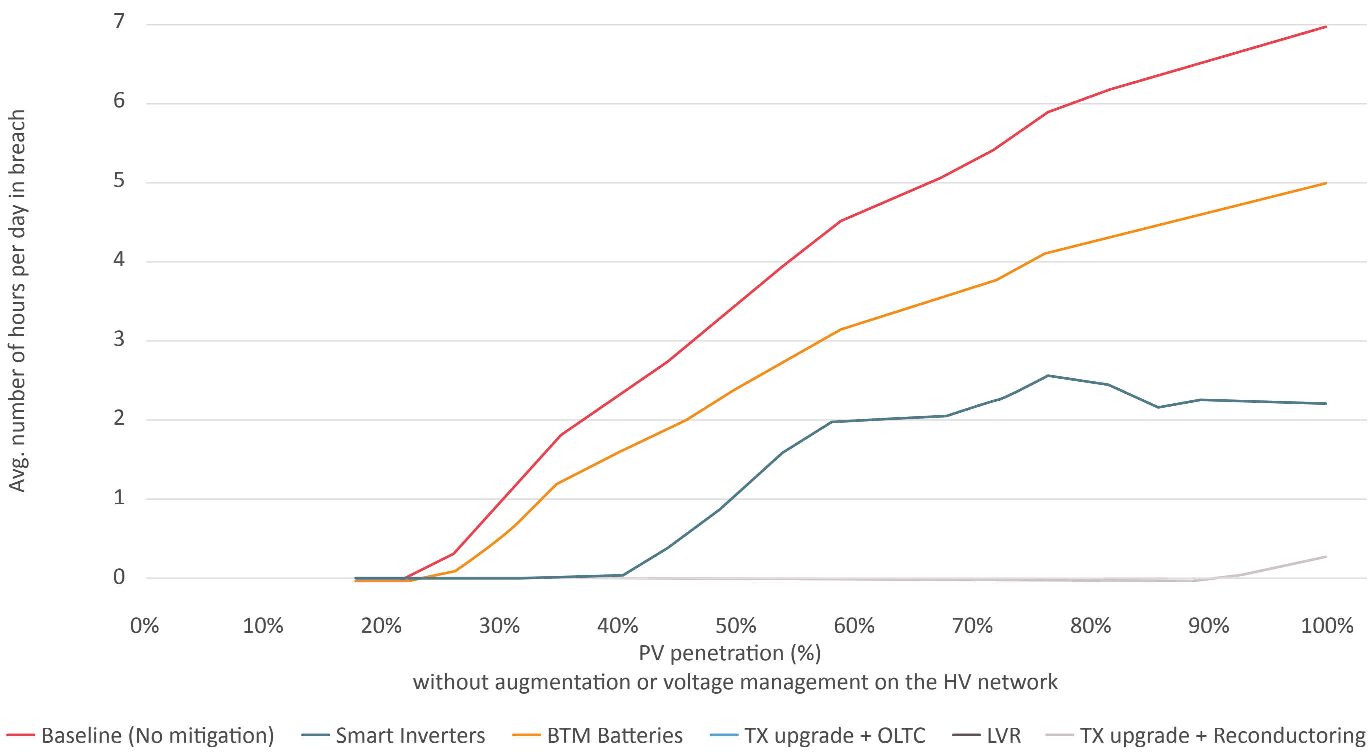
Low-density rural single-phase - 50kVA - 3-7/.064 Cu



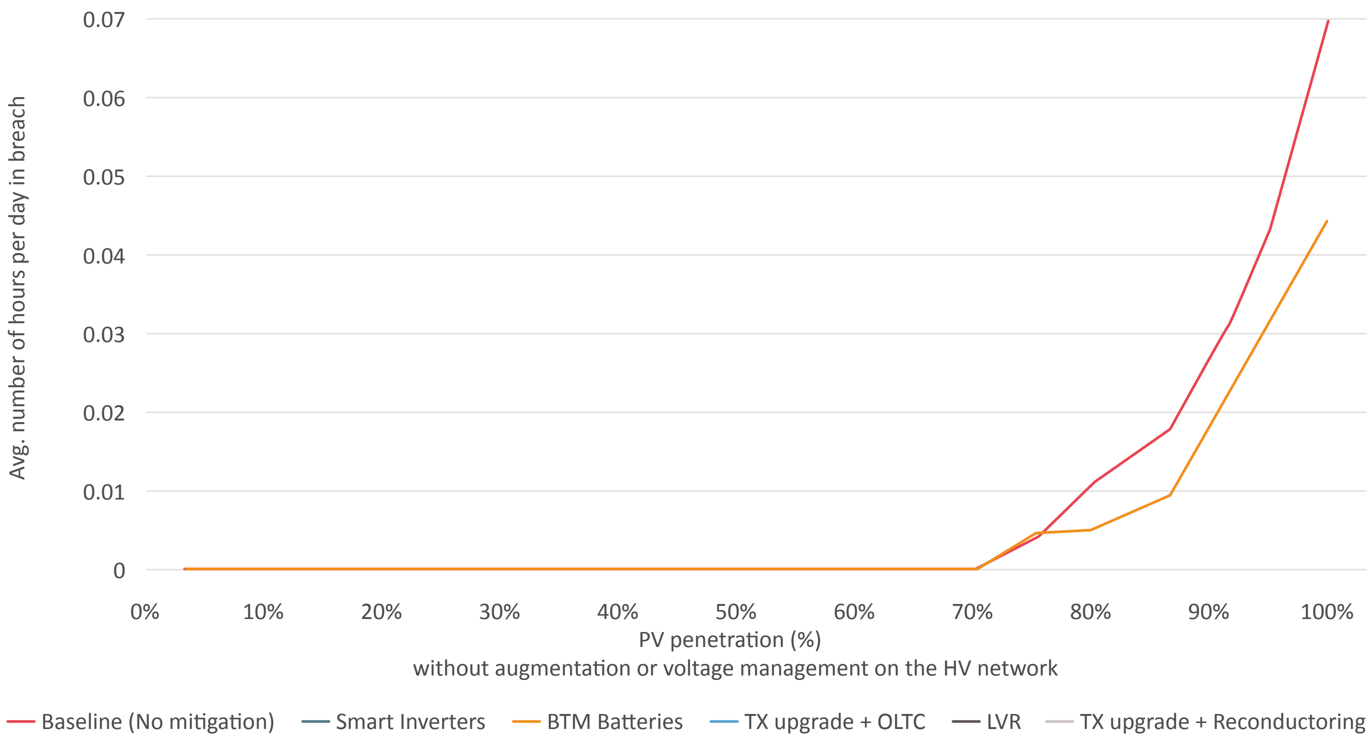
Mid-density rural pole - 100kVA - 4-6/1/114 ACSR



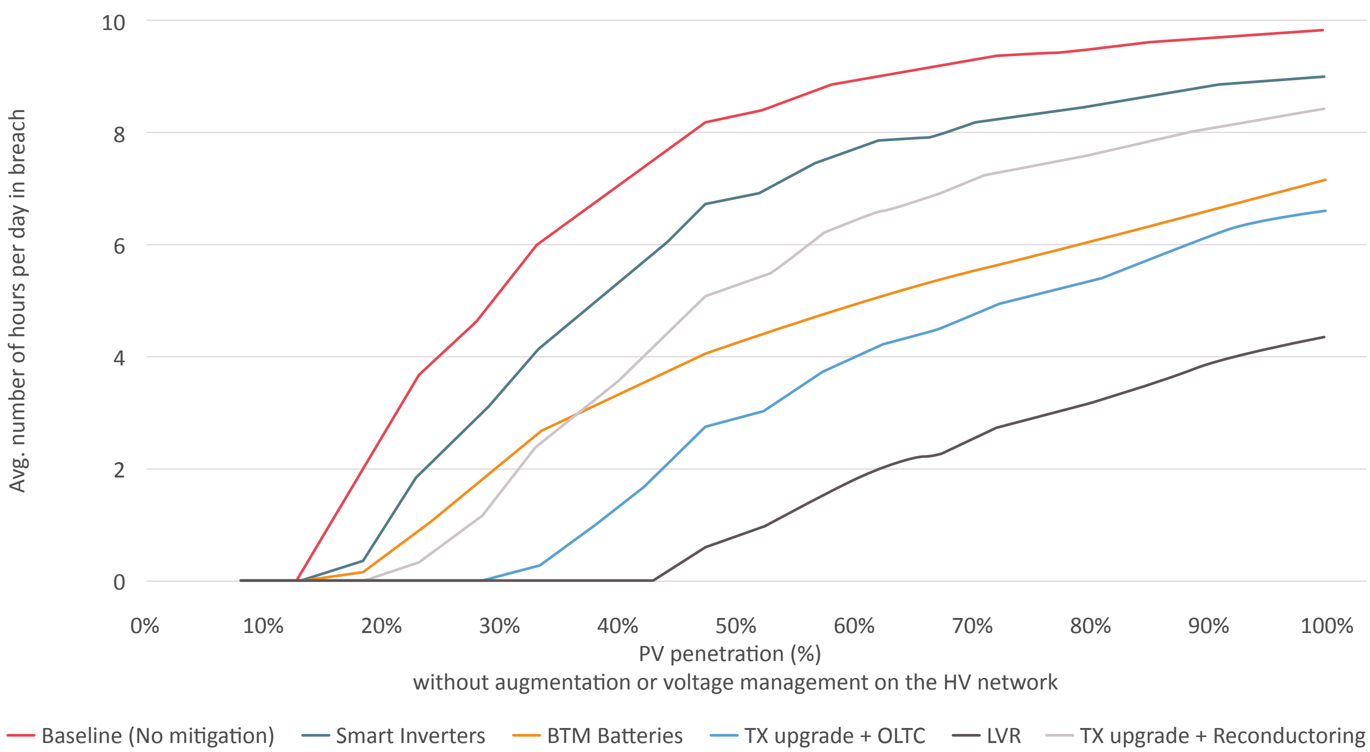
URD kiosk - 315kVA - 185mm² 4/c lv.sa.x



Mid-density pole - 500kVA - 4-19/3.25 AAC



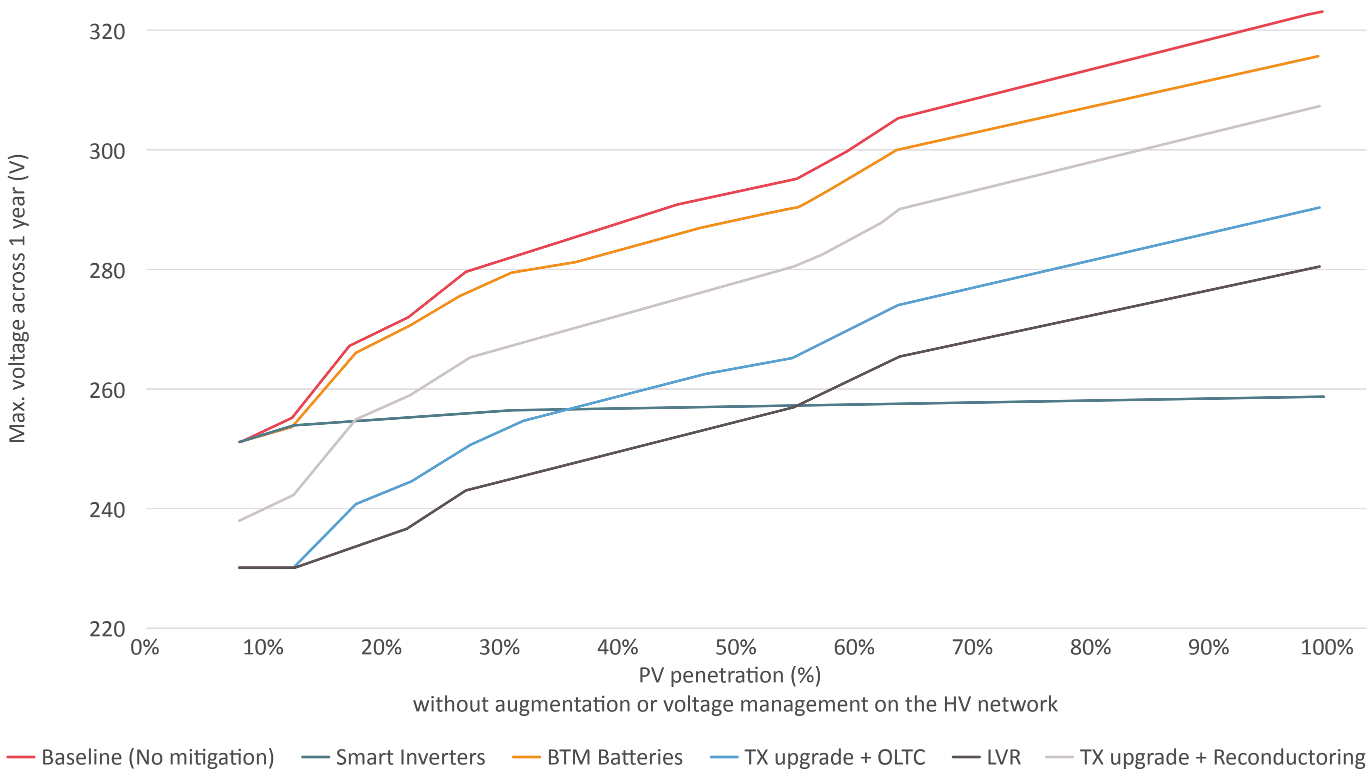
Remote rural SWER - 10kVA - 2-7/.064 Cu



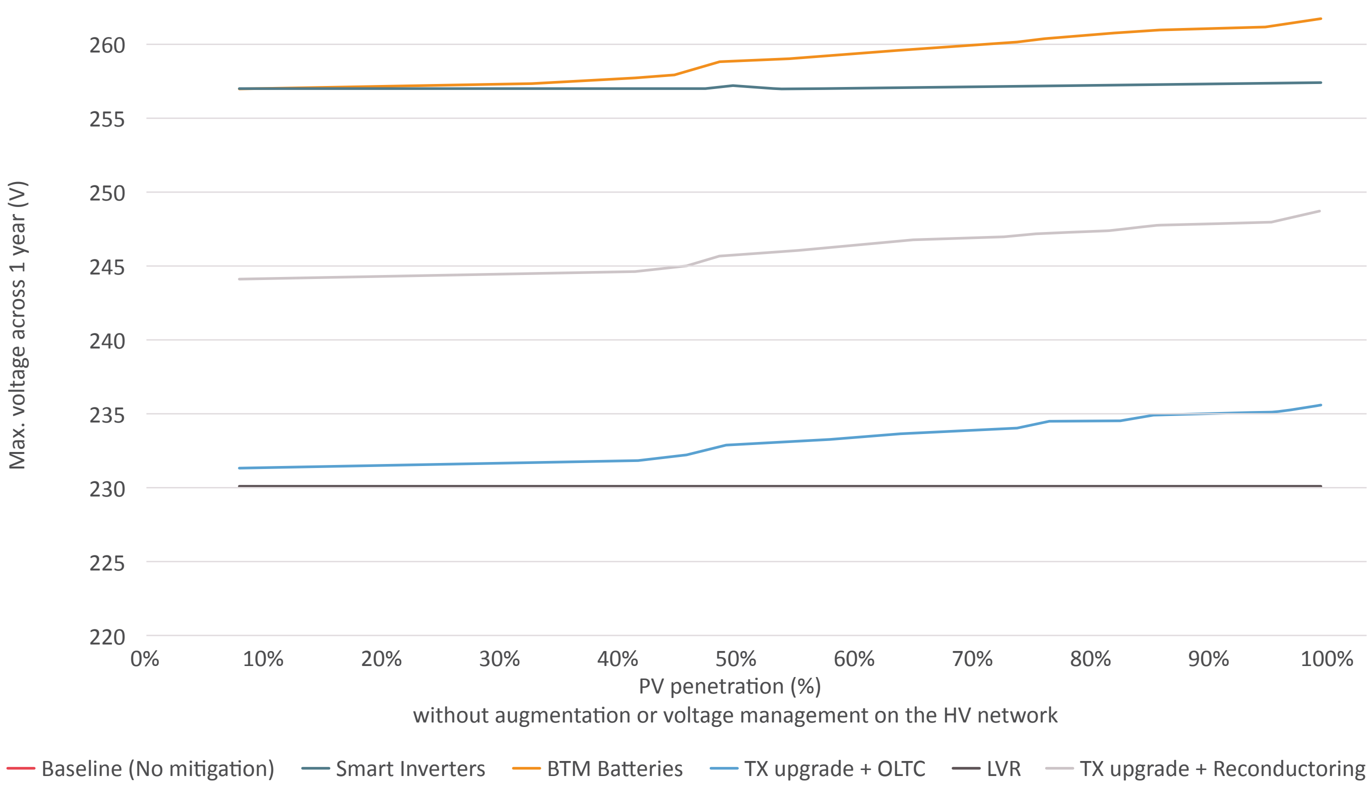
Maximum voltage rise as PV penetration increases

The following figures show the resultant voltage rise achieved by each mitigation measure for each LV network.

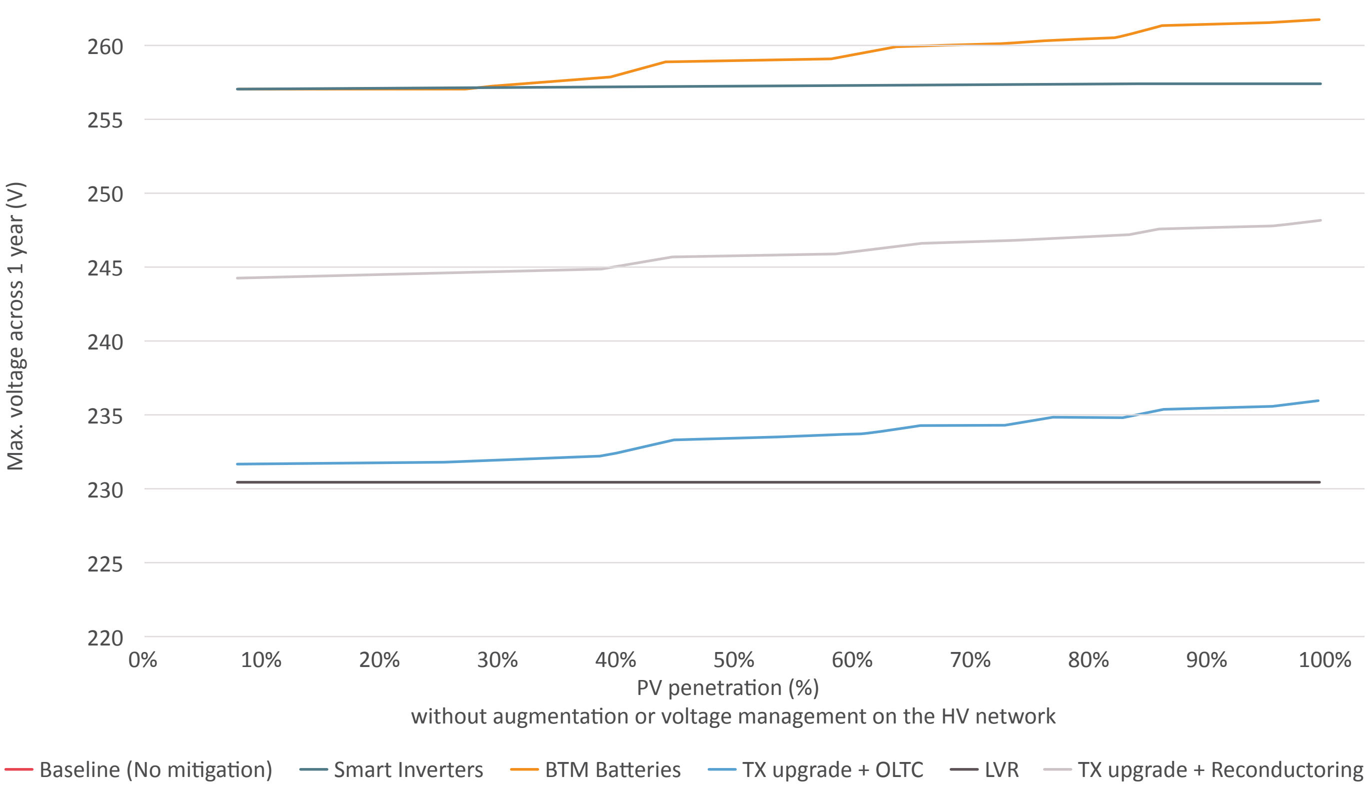
Urban pole - 315kVA - 150mm² LV ABC



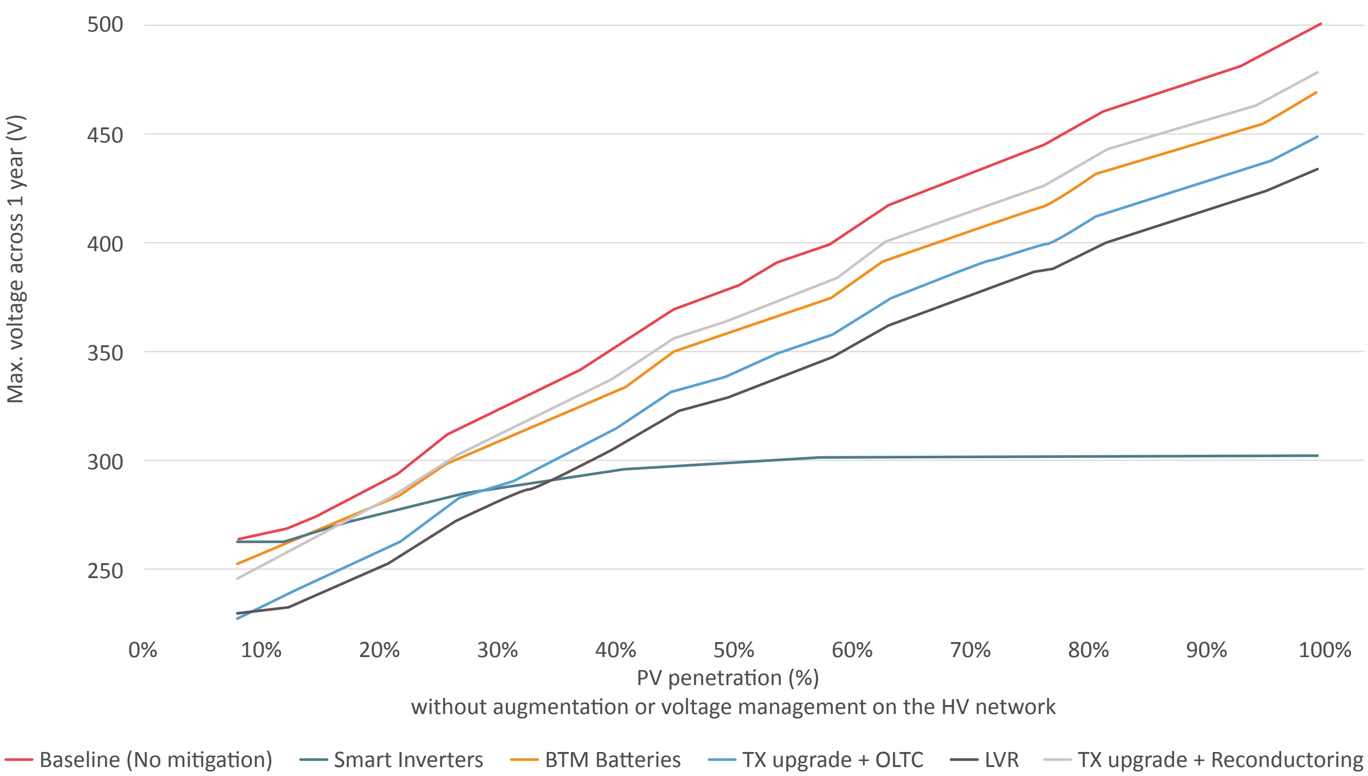
Urban C&I pole A - 315kVA - 150mm² LV ABC



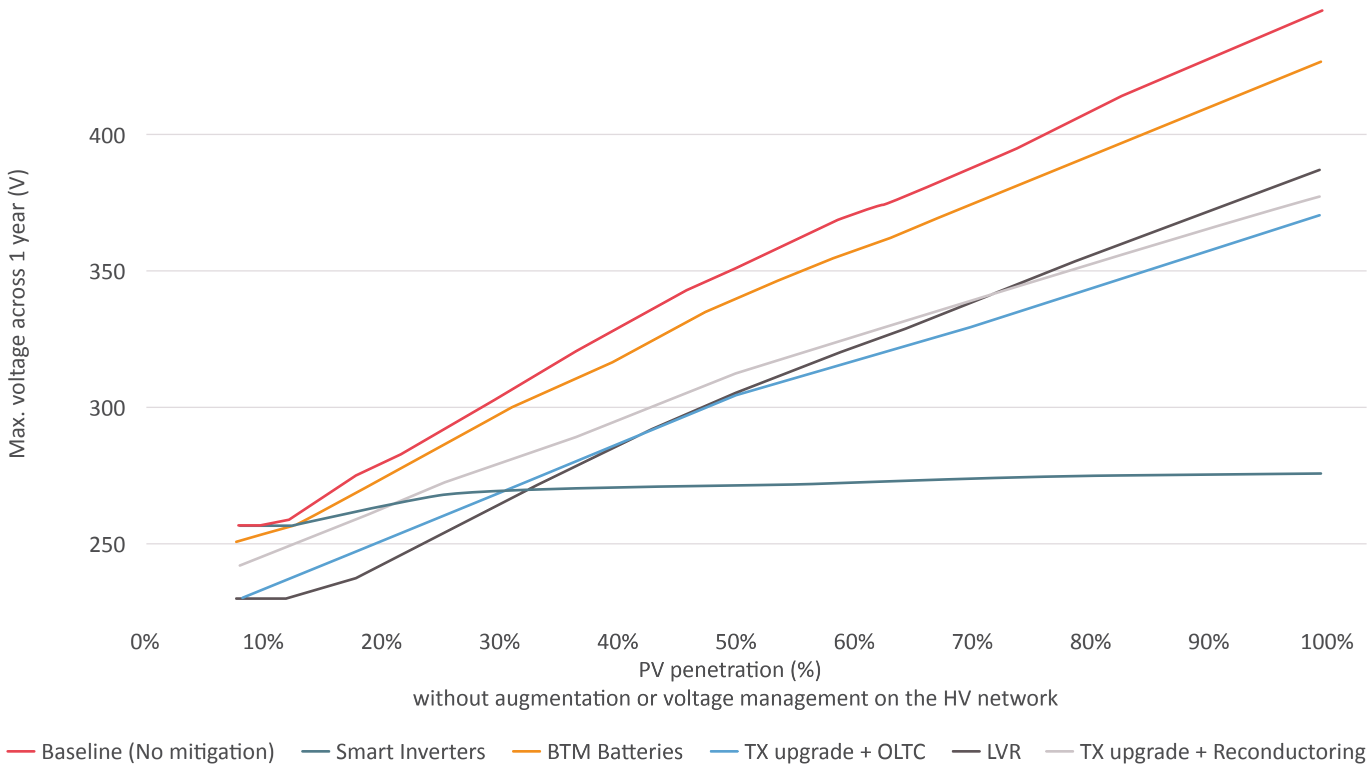
Urban C&I pole B - 315kVA - 4-6/.186,7/062 ACSR



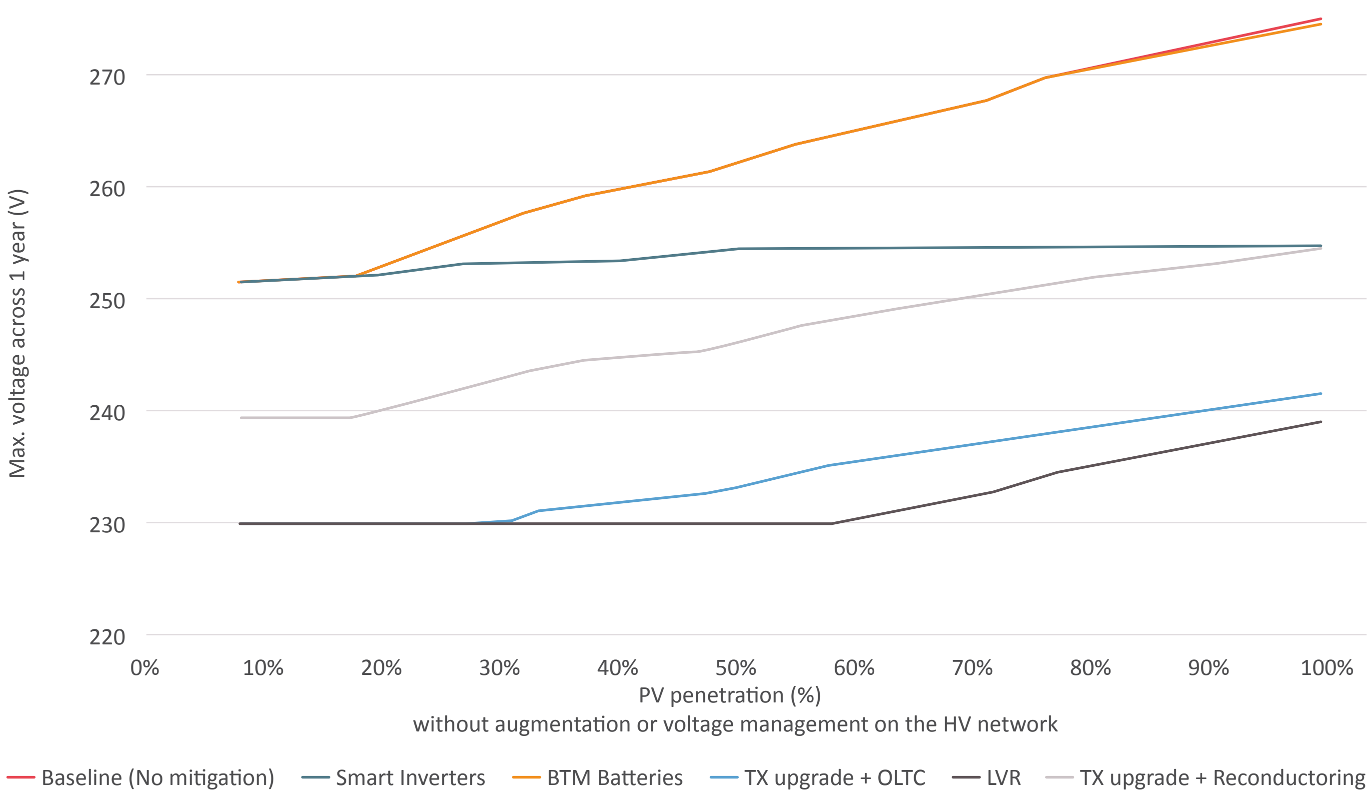
Low-density rural single-phase - 50kVA - 3-7/.064 Cu



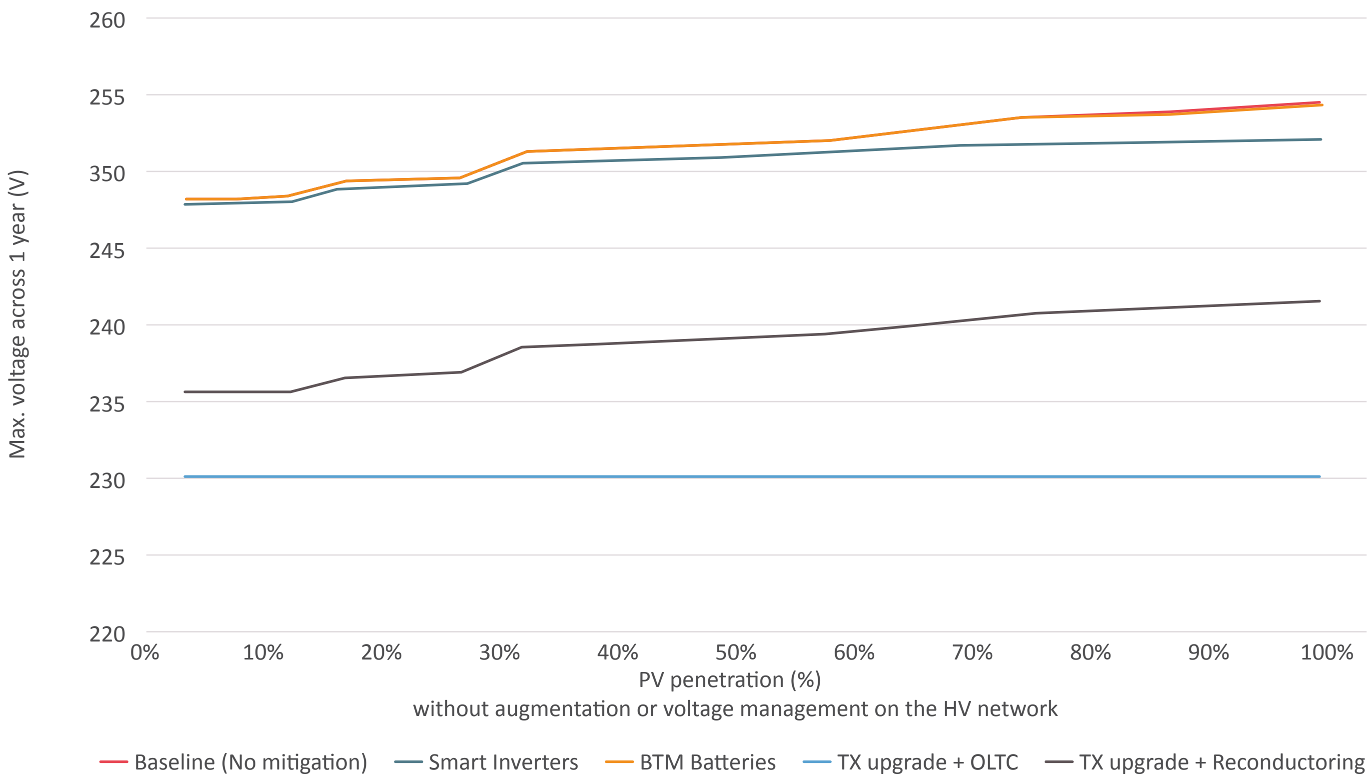
Mid-density rural pole - 100kVA - 4-6/1/114 ACSR



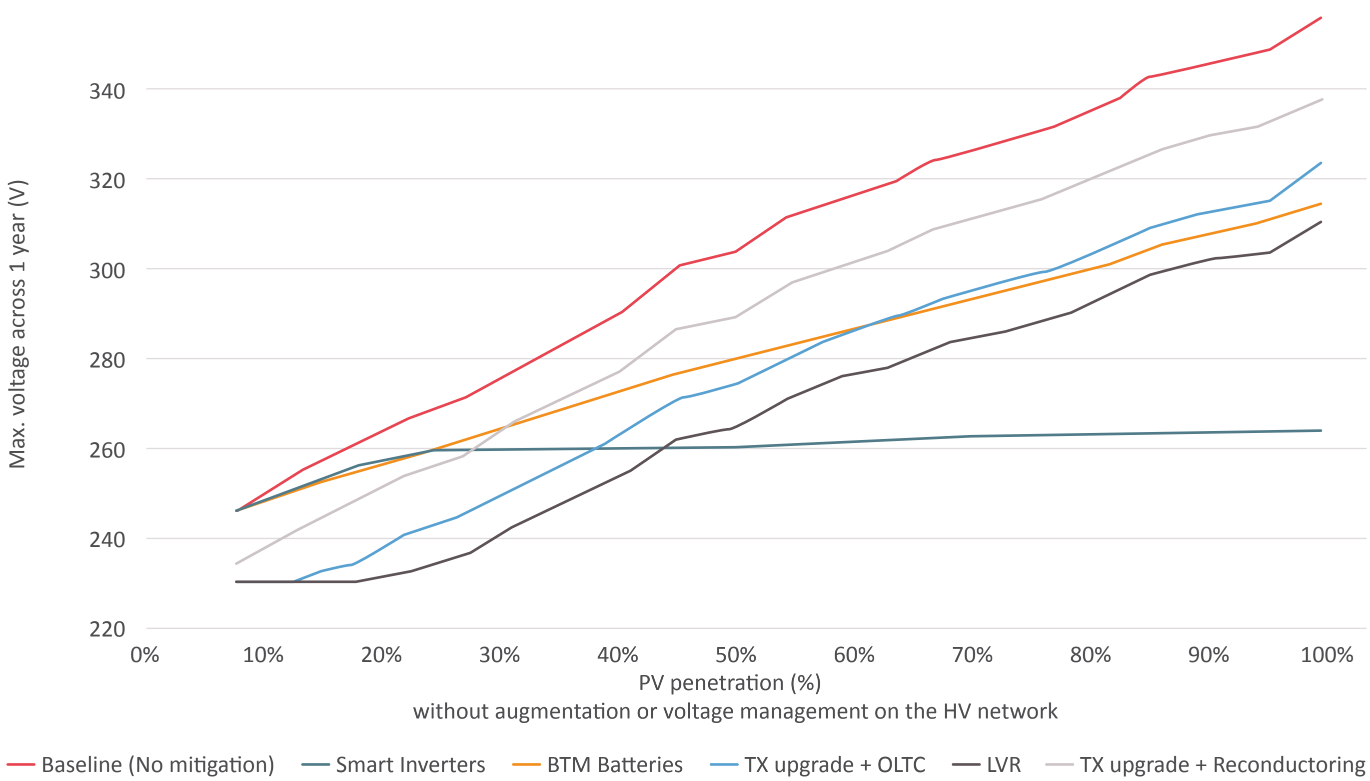
URD kiosk - 315kVA - 185mm² 4/c lv.sa.x



Mid-density pole - 500kVA - 4-19/3.25 AAC



Remote rural SWER - 10kVA - 2-7/.064 Cu



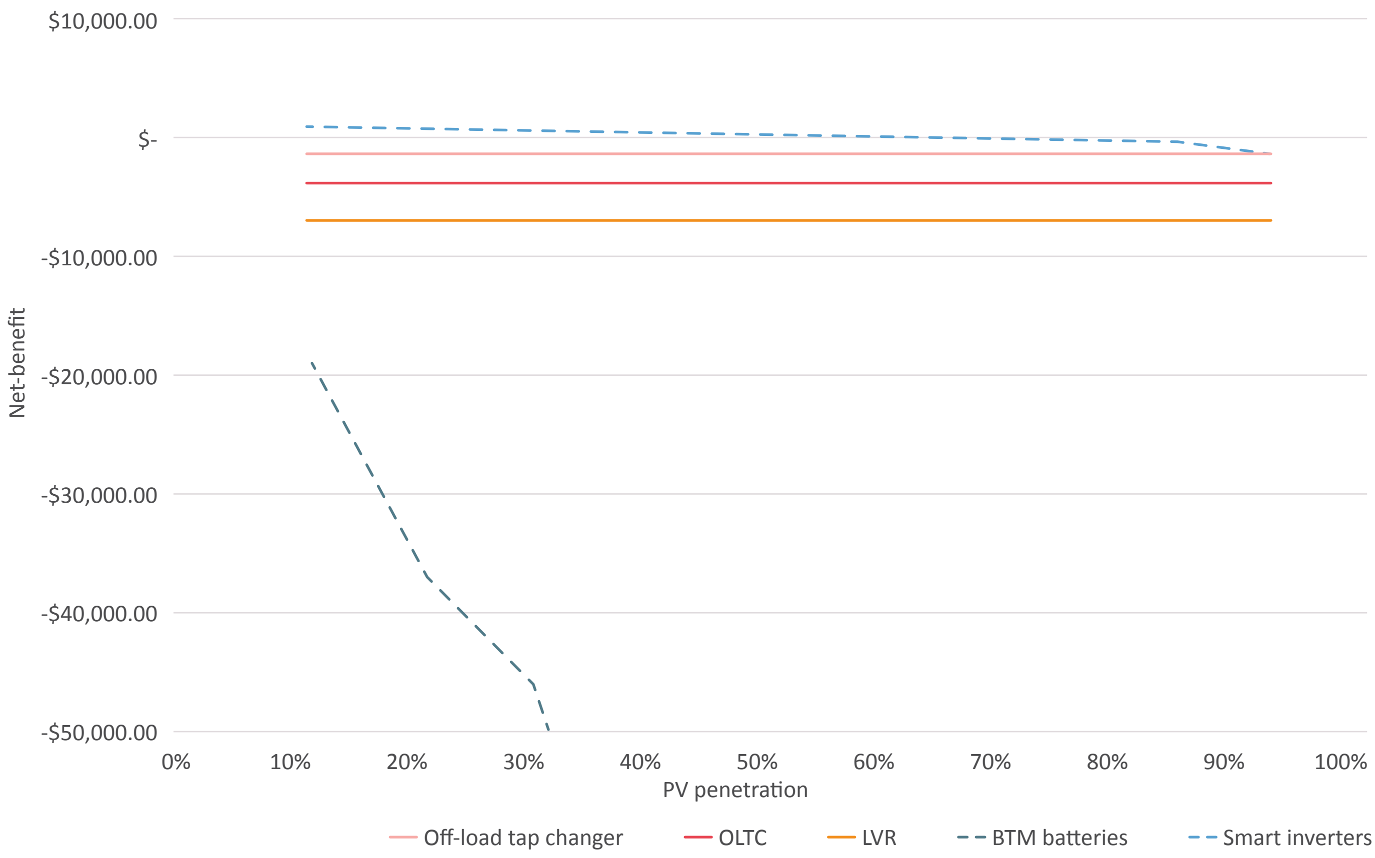
4 Cost-benefit analysis

Additional PV generation enabled by each mitigation measure was valued using the 2017–18 AEMO wholesale price for each timestamp. This was compared to the annualised marginal cost of each mitigation measure to give the net-benefit of each mitigation option under increasing PV penetration.

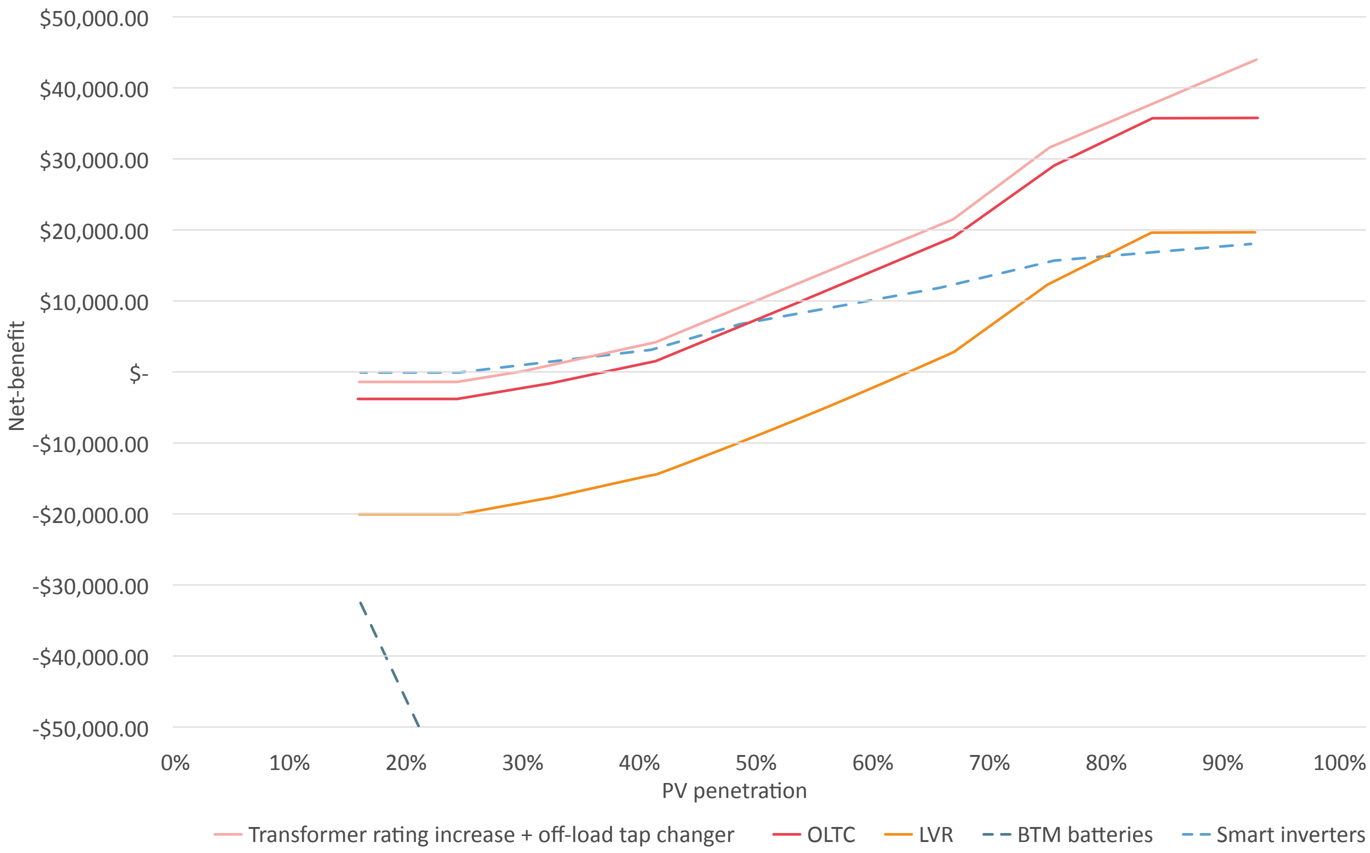
Net-benefit comparisons

The following charts illustrate the net-benefit of each mitigation measure under increasing PV penetration. When the benefits outweigh the costs, the net-benefit is positive.

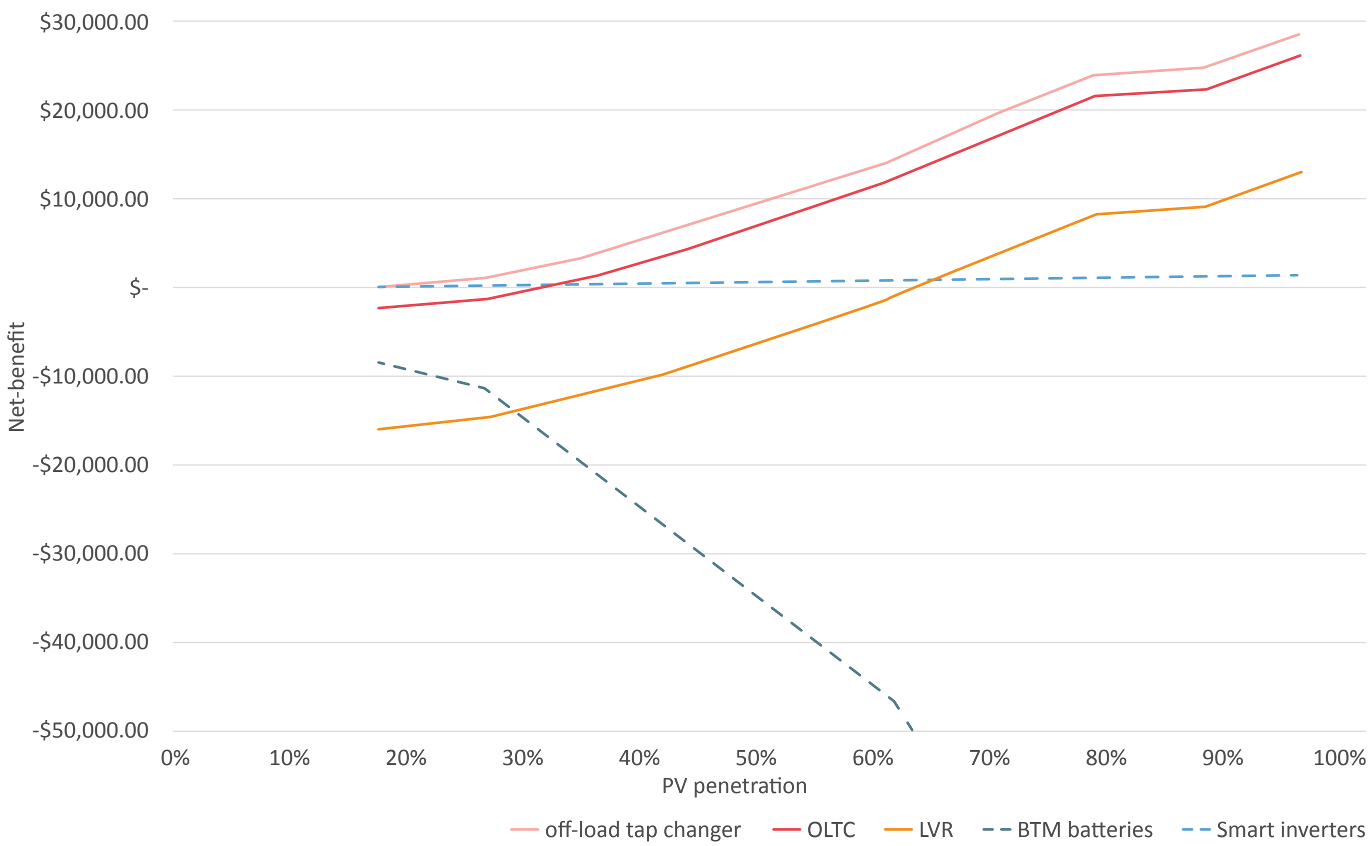
Mid-density pole - 500kVA - 4-19/3.25 AAC



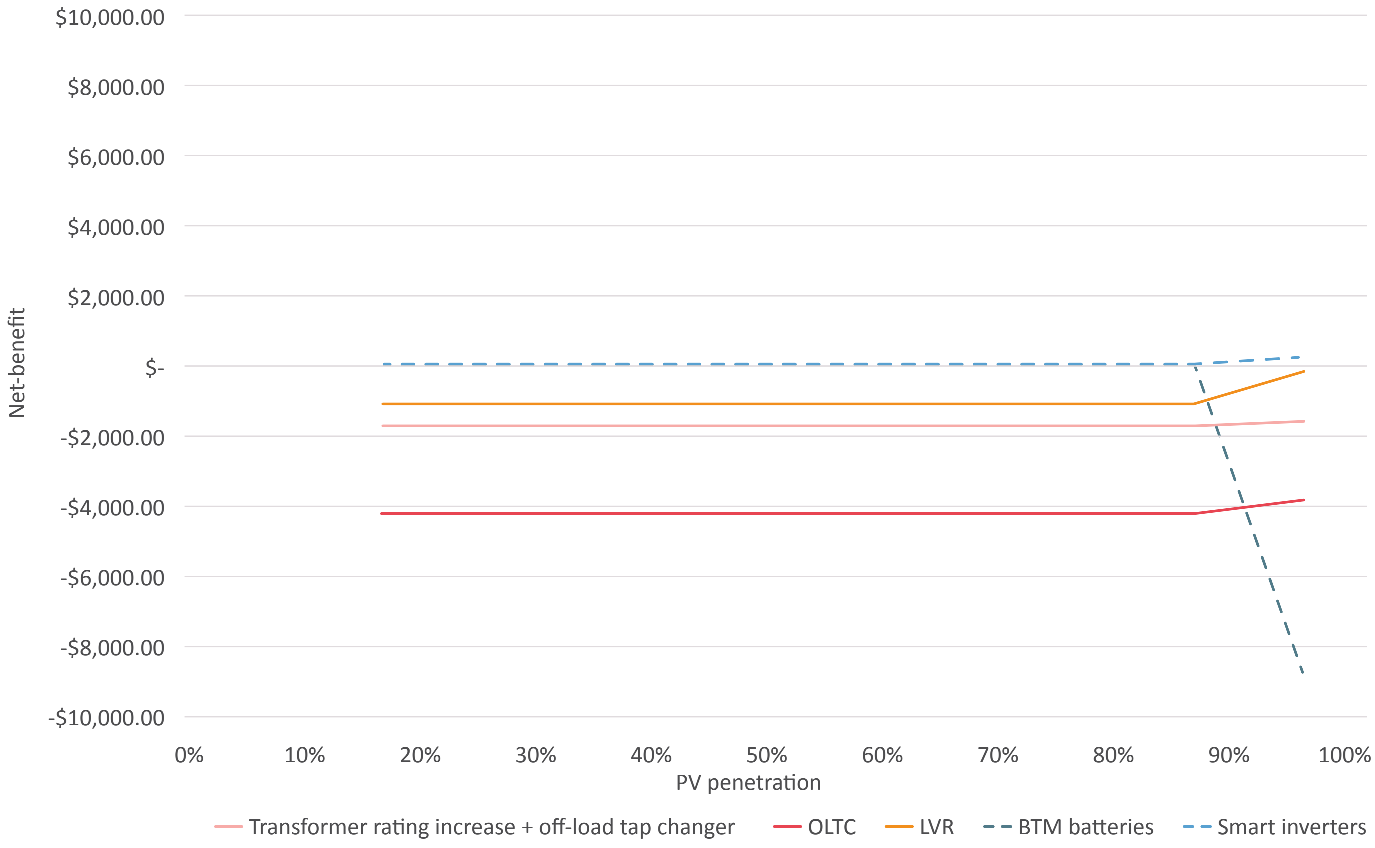
URD kiosk - 315kVA - 185mm² 4/c lv.sa.x



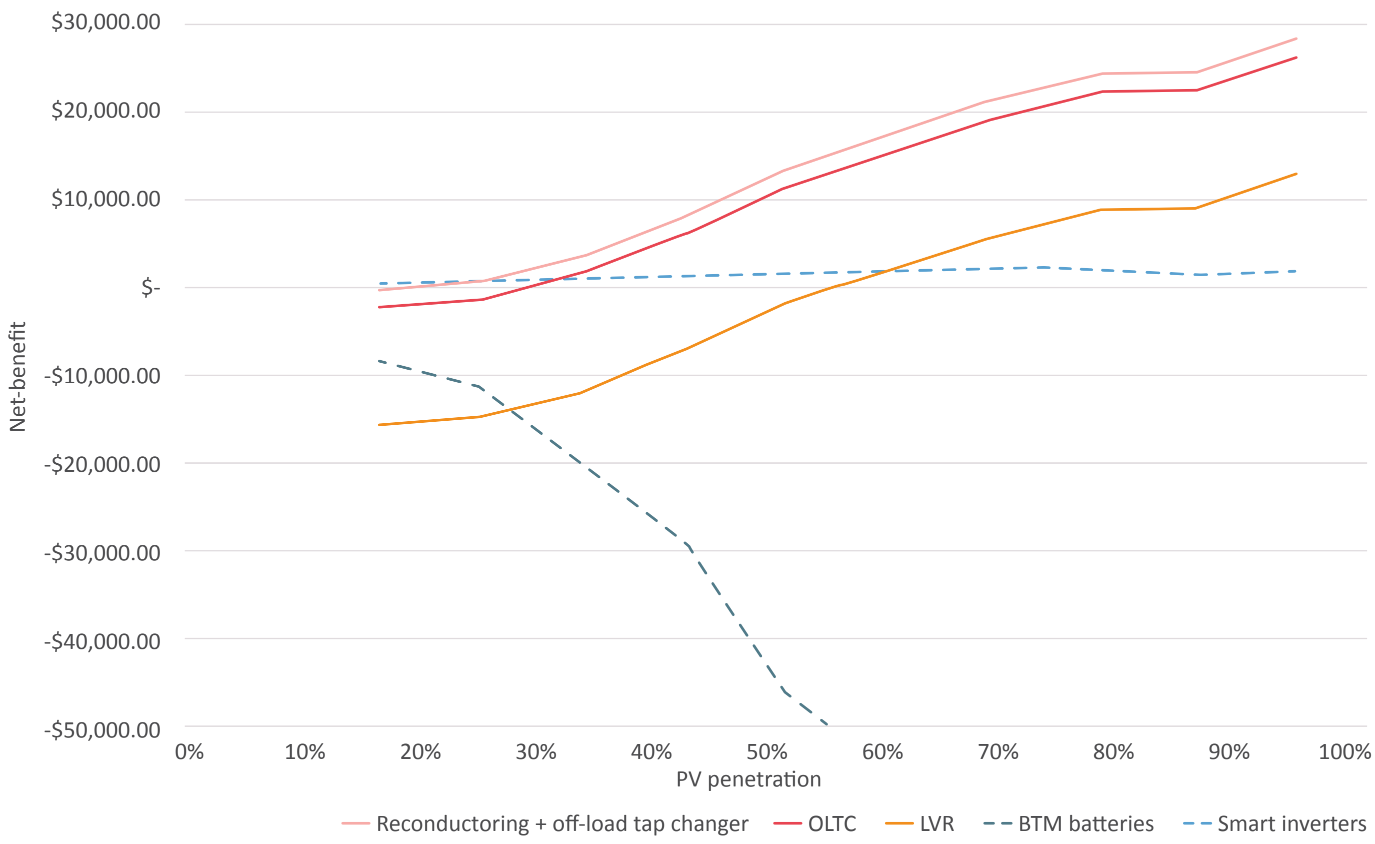
Urban C&I pole A - 315kVA - 150mm² LV ABC



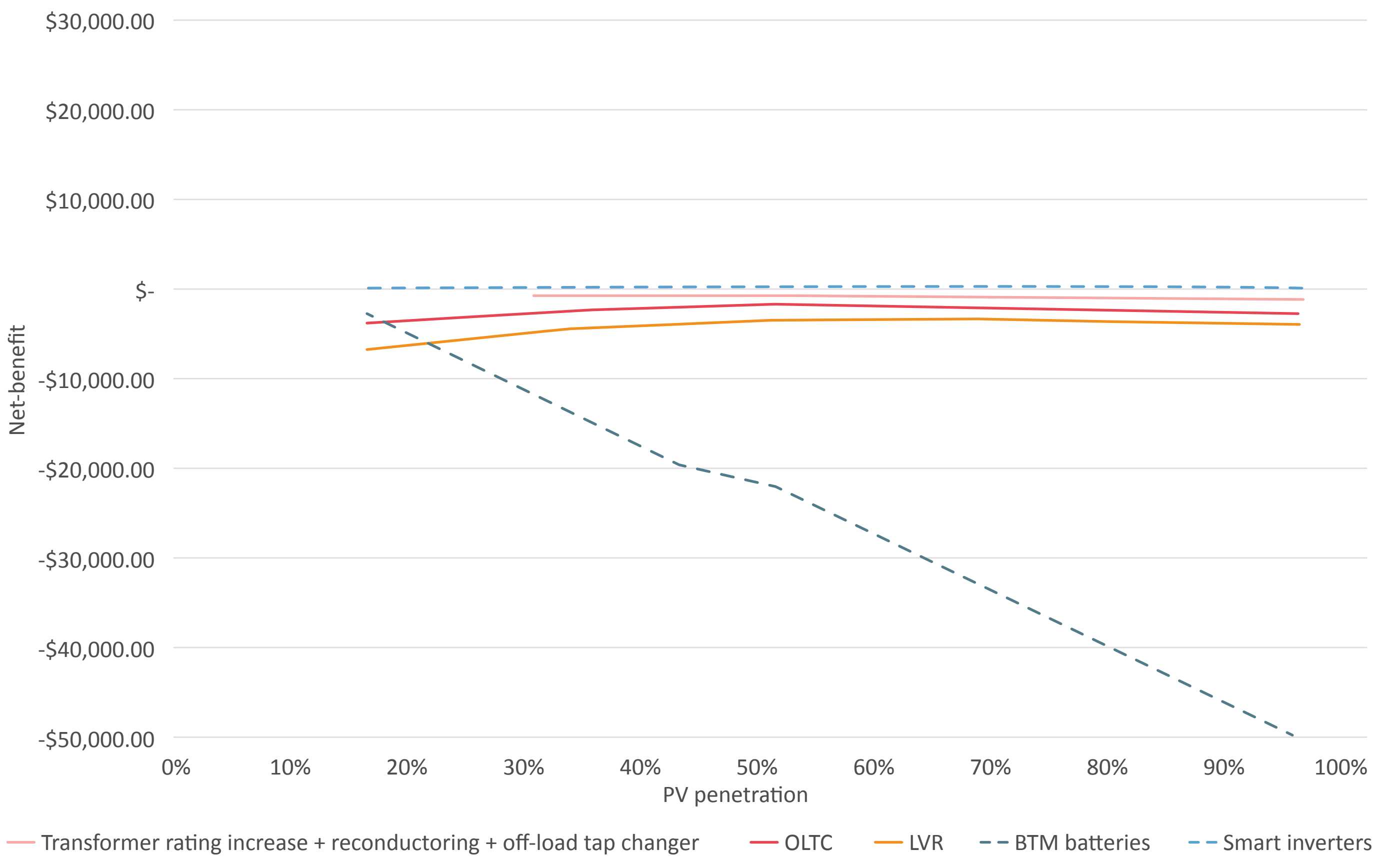
Remote rural SWER - 10kVA - 2-7/.064 Cu



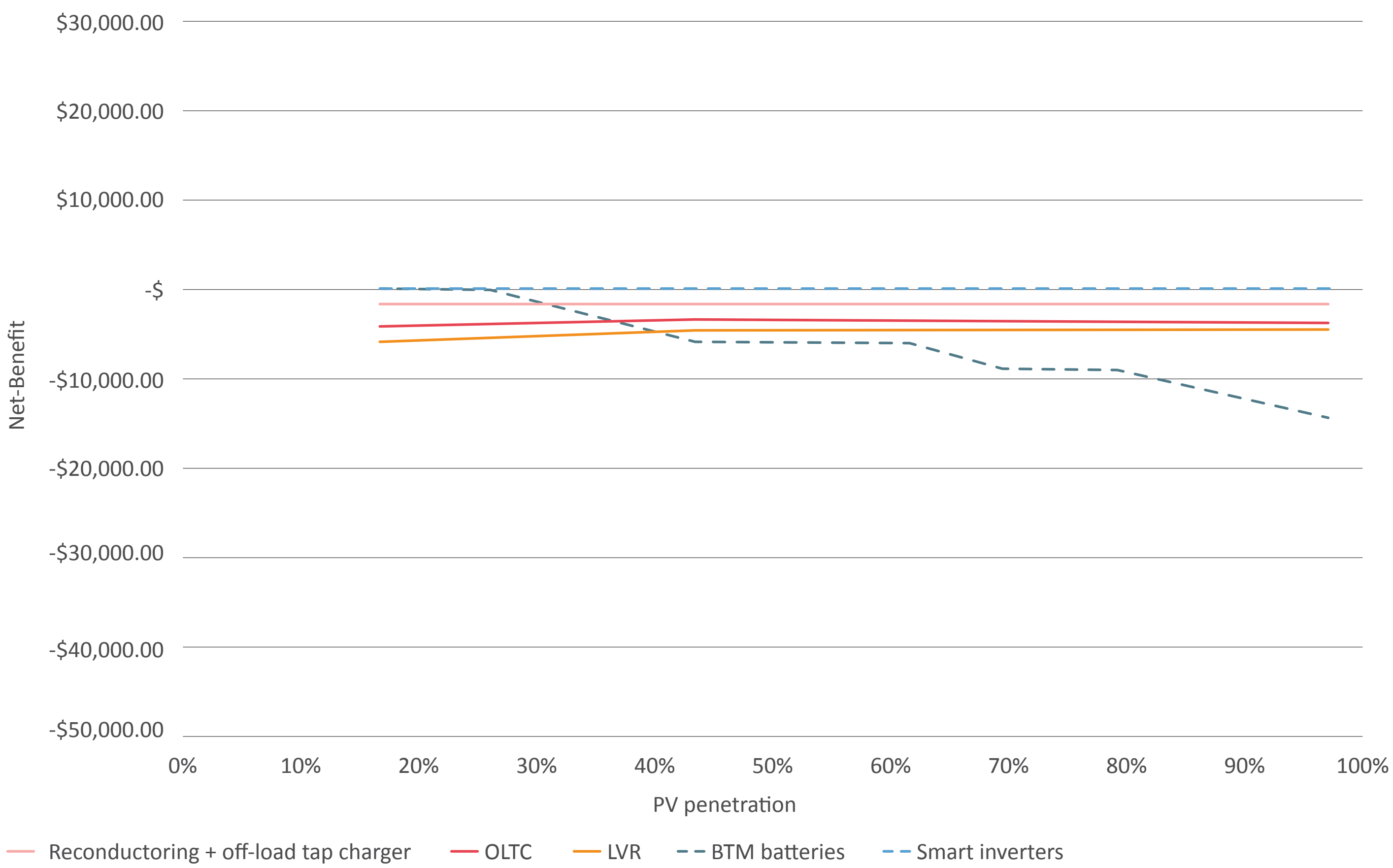
Urban C&I pole B - 315kVA - 4-6/.186,7/062 ACSR



Mid-density rural pole - 100kVA - 4-6/1/114 ACSR



Low-density rural single-phase - 50kVA - 3-7/.064 Cu



5 Mitigation measures

Below is a detailed explanation of low voltage regulators, on-load tap changers (dynamic voltage control), smart inverters and behind-the-meter batteries.

Low Voltage Regulators

Context

Bi-directional capability in a low voltage regulator (LVR) enables voltage regulation when power flow is reversed and the power flows from the low voltage (LV) network back to the distribution substation (DSS). DNSPs in Queensland and Victoria have demonstrated the use of LVRs to manage power quality issues:

1. Since 2008, Ergon Energy (now Energy Queensland) has installed over one thousand LVRs on SWER LV networks to improve voltage stability [1].
2. In 2014, United Energy performed a trial using four LVRs at specific locations that were experiencing high-voltage problems [2]. The aim of the six-month trial was to demonstrate the technical capability of the LVRs to regulate voltage and allow higher levels of solar photovoltaic (PV) on the circuit [3]. Trial results showed the LVRs were able to eliminate over/under voltages and voltage sags/swells compared to the same period in the prior year [2].

Working principle

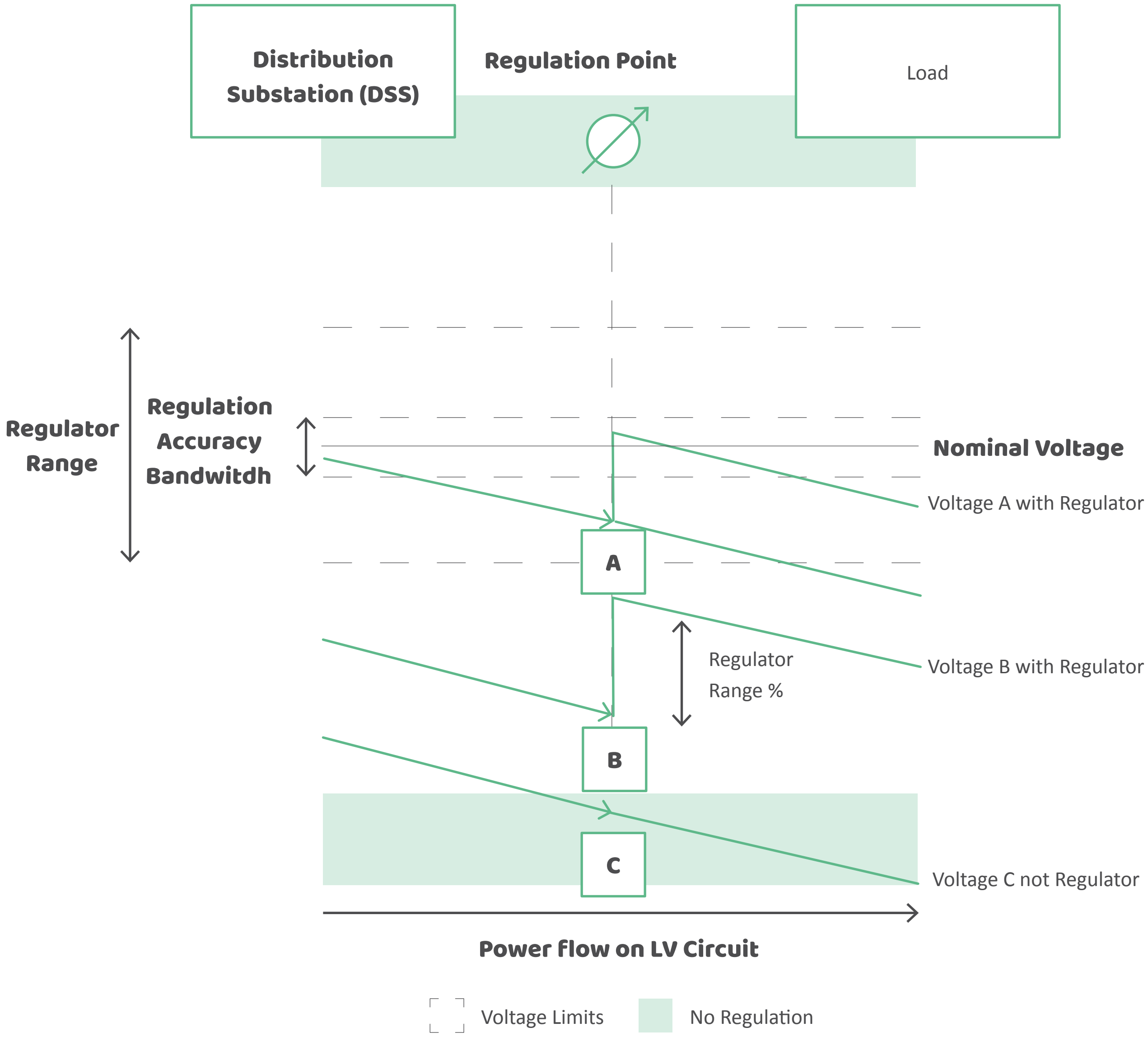
Operation

An LVR uses a controllable transformer to adjust the voltage on the LV network within a band set around a nominal voltage level [4]. Figure 1 shows the effect of the LVR on different input voltages on an LV network.

LVRs use a controller to adjust the turns on a transformer to increase (boost) or decrease (buck) the voltage on the LV network. At the point of voltage regulation, the operation of the LVR depends on the value of the input voltage. In Figure 1 below, the voltage is stepped up when power flows from the DSS to the load. When reverse power flows from the load to the DSS, the voltage is stepped down. The diagram shows three different voltage scenarios – A, B and C – which are discussed below.

3. Voltage A will fall outside the limit at the end of the LV network if it is not corrected. The LVR corrects the input voltage so that the output voltage value is in the regulation accuracy bandwidth. The regulation accuracy bandwidth is an output voltage value around the nominal voltage. For example, the Pacific Volt VR has a regulation accuracy bandwidth of +/-1V. At 230 V nominal voltage, the output voltage of the LVR-30 will be between 229V and 231V [5].
4. Voltage B is below the lower voltage limit. In this scenario, the maximum adjustment the LVR can make is the regulator range percentage. The regulator range is the size of the largest adjustment the LVR can make. For the Pacific Volt LVR-30, the range value is +/-13% [5] so the voltage at B will be increased by 13%. The voltage at the end of the circuit falls below the voltage limit, but at a value 13% above what it would be without LVR adjustment.
5. Voltage C is at a value that the LVR does not operate and no adjustment is made to the voltage.

Figure 1 • LVR operation on an LV network

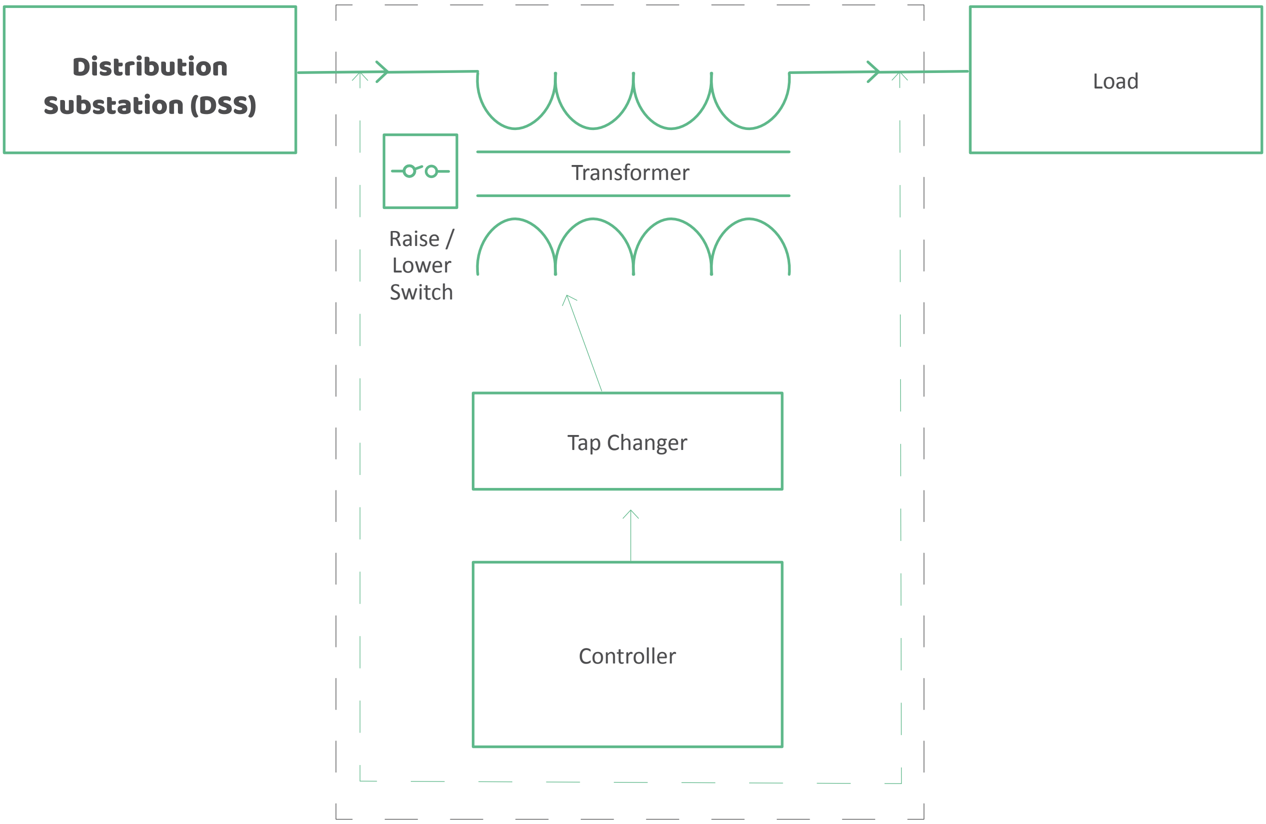


Functionality and characteristics

Figure 2 shows the component parts contained within an LVR and the connection to the LV network. The main components and their function within an LVR are: [6, 7]

1. Transformer: magnetically induces a higher or lower voltage in the LV network based on the tap size
2. Tap changer: mechanical or electronic switch that sets the size of the voltage adjustment
3. Raise/Lower switch: reversing polarity switch that sets the direction of the voltage change
4. Controller: microprocessor controller that measures the input and output voltages on the LV network to determine the adjustment and that instructs the tap changer. The controller is where the sensor detects reverse power flow to switch the regulation direction [4].

Figure 2 • Components of a voltage regulator



Manufacturers and costs

Some of the main manufacturers of LVRs worldwide include ABB, Eaton, General Electric, Siemens and Utility Systems Technologies (UST) [8]. Estimated costs for Pacific Volt single phase LVR are, on average, $9,000 for the equipment and $1,000 for installation [9]. An LVR available to residential customers, from Edge Electrons in Australia, and costs $1,485 for the unit [10].

Advantages and disadvantages of LVRs

Advantages	Disadvantages
Potential to install at different locations on the LV network line and substation [4]	Reduced regulation ability with increased thermal capacity on LV network [9]
LVR can continue regulating during periods of reverse power flow [5]	Expensive equipment for low density networks – the benefits for LV networks with low customer numbers do not match investment costs [9]
Electronic regulators do not require maintenance – they run until failure [9]	Voltage breaches greater than the tap range cannot be corrected
Pacific Volt LVR-30 offers the option of additional capabilities such as collection of data and remote monitoring [5]	
Voltage control on LV network reduces amount of operations of load tap changers at the substation [11]	
No disruption to power flow if voltage regulation stops [5]	

Dynamic Voltage Control (On-Load Tap Changer)

Context

Dynamic voltage control (DVC) involves installing a dynamically controlled tap changer on a transformer at the distribution substation (DSS), or at the zone substation (ZSS), to adjust the voltage on the LV network. Similar technologies have been used in Europe to manage voltage problems on LV networks:

1. German network company E.On collaborated with technology manufacturer Maschinenfabrik Reinhausen to develop a voltage regulated distribution transformer (RDT) [12, 13]. This technology was installed by E.On on their distribution network as a cost-effective alternative to grid expansion, to integrate renewable generation while maintaining grid stability [13, 14]
2. United Kingdom DNSP Electricity North West was part of a University of Manchester study that installed MR RDTs at two DSSs to adjust the voltage based on changes to load on the LV network. Results of the study showed the effectiveness of the technology in managing voltage issues in addition to increasing hosting capacity [15]
3. German DNSP EnBW trialled a Siemens RDT on an LV network to regulate the voltage. The results demonstrated the technology’s ability to control fluctuating voltages using adjustments based on the prevailing load flow [16].

Working principle

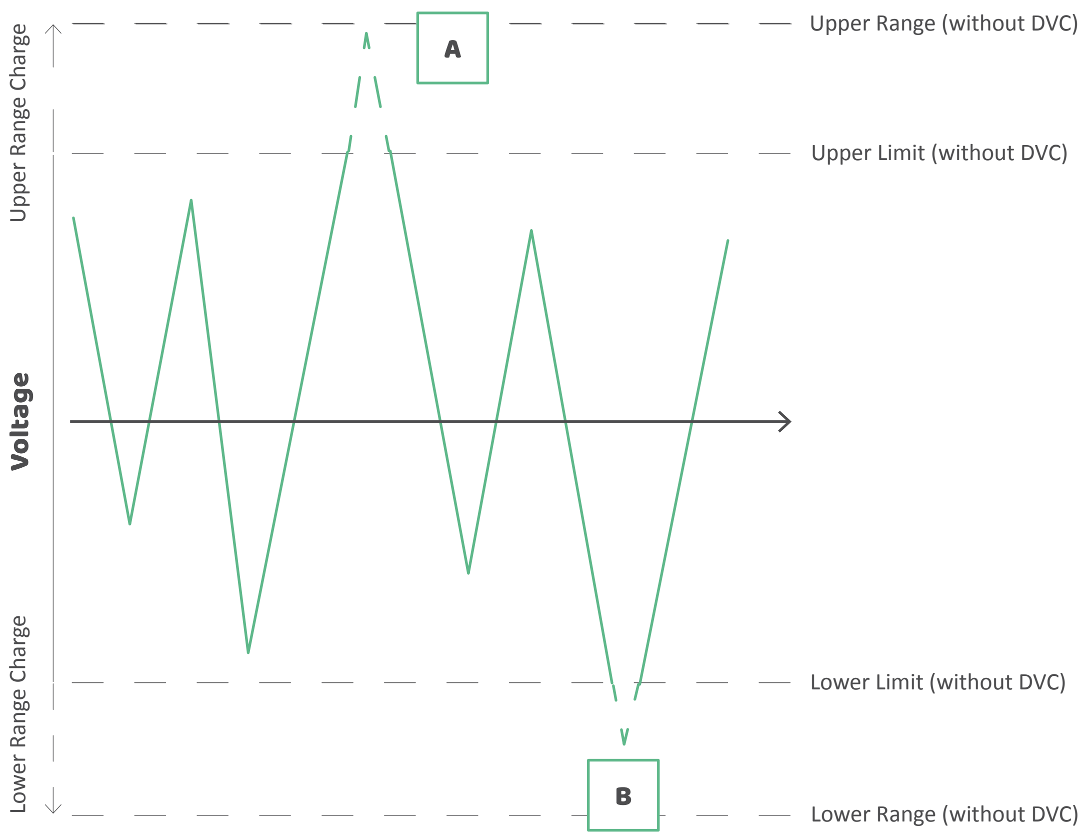
Operation

DVC adjusts the voltage at the DSS to ensure it remains within regulation limits on the LV network. Based on the load characteristics on the LV network, the voltage at the DSS is automatically adjusted by a tap changing transformer. The overall effect of DVC is to increase the range of controllable voltages on the LV network. This shown in the Figure 3, with time series voltage variations.

The voltage range enabled by DVC is shown on the green lines in Figure 3. DVC adjusts the voltage at the DSS based on load conditions on the LV network.

A and B show two scenarios of the operation of DVC. At these points the DVC adjusts the voltage at the DSS up or down to ensure that the voltage on the LV network remains below, or above, the voltage limits.

Figure 3 • DVC operation for voltage adjustment

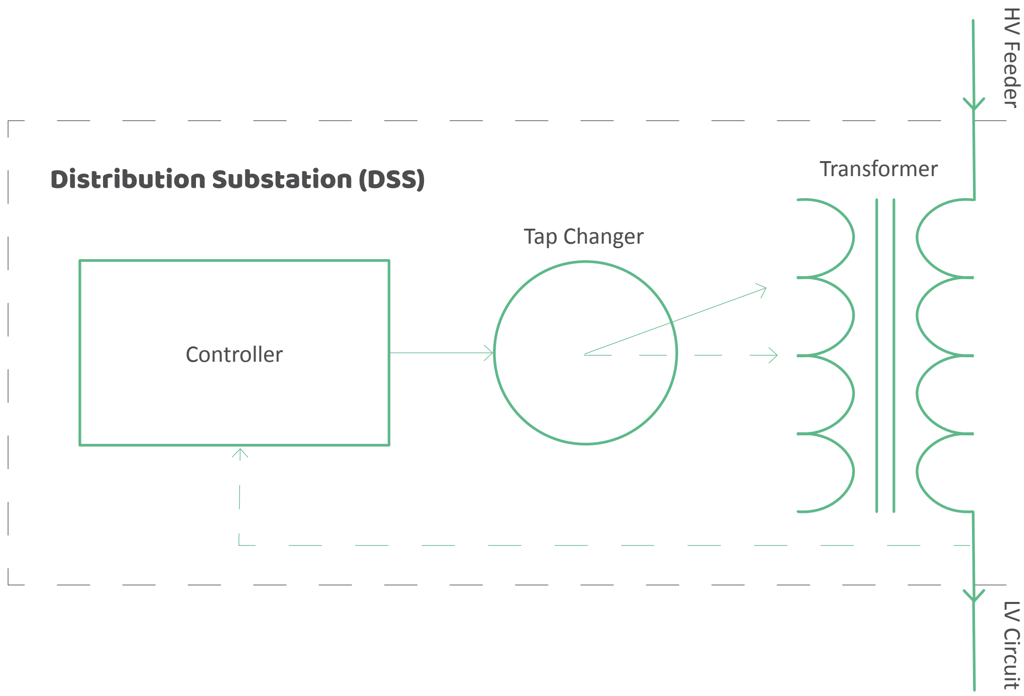


Functionality and characteristics

The components of DVC within the DSS are shown in Figure 4. The function of each component part within the system are:

1. **Controller:** uses the load levels on the LV network to determine the voltage adjustment required. Sends instructions to the tap changer to increase or decrease tap
2. **Tap changer:** receives instructions from the controller to adjust the tap on the DSS side transformer. Tap changes adjust the turns ratio on the DSS side transformer to increase, or decrease, the voltage
3. **Transformer:** depending on the turns ratio in the transformer, the incoming voltage is adjusted by magnetic induction of a voltage from the DSS side

Figure 4 • DVC components



Manufacturers and costs

Automatically adjusting transformers cost more than a traditional distribution transformer but are less expensive than network upgrades [12]. International manufacturers of distribution transformers include Maschinenfabrik Reinhausen (MR) and Siemens. In Australia, Wilson Transformers and ETEL manufacture the equipment.

Advantages and disadvantages of DVC

Advantages	Disadvantages
Cost-effective alternative to network upgrade for DNSP [17]. In Germany, an estimated saving of USD 1.9 billion on low voltage network upgrades over the next ten years [13]	May not be a feasible solution for all LV networks: individual investigation required for long circuits with high distributed generation levels [17]
DVC can reduce voltage issues for entire LV network once installed at the DSS [12]	Does not resolve thermal issues on LV network [12, 17]. Voltage breaches greater than the tap range cannot be corrected
Some new technologies estimate maintenance-free operation for the lifetime of the transformer [18]	

Smart inverters

Context

Inverters are a necessary part of every PV system, for using energy in appliances and potential grid export.

1. In Germany and Hawaii, smart inverters were used to resolve existing grid operational problems. In comparison, in Arizona and California, the analysis was for preventing future power quality issues [19]
2. In Australia, a trial by United Energy in south-east Victoria used advanced control methods with smart inverters to demonstrate how strategic control of smart inverters could resolve power quality issues [20]. This was part of a broader ARENA-funded project, Networks Renewed [30], seeking to use smart inverters to provide grid support.

Working principle

Operation

Direct current (DC) electricity produced by solar PV installations requires an inverter to convert to alternating current (AC) for use or to export to the grid. Smart inverters can assist with management of power quality on the grid by adjusting real and reactive power delivered to the grid. Figure 5 below shows the operation of a smart inverter in adjusting real (Volt-Watt) and reactive power (Volt-VAR) with changes in voltage on the grid [21, 22].

The smart inverter senses the grid voltage and reacts by adjusting real power and reactive power, depending on the grid voltage to nominal voltage ratio:

1. At a voltage level V1, the reactive power is set at 45% VAR. As voltage increases from V1 to V2, the reactive power decreases linearly from 45% VAR to 0% VAR
2. For nominal voltage levels between V2 and V3b the reactive power is set at 0% VAR, power factor of 1
3. When the grid voltage increases from V3 to V4, both reactive and real power adjustments are made:

- the reactive power import decreases linearly from 0% VAR, power factor 1, to -45% VAR
- once the maximum voltage limit (nominal +10%) is reached, the real power export reduces linearly from 100% (maximum real power) to 20%.

4. When voltage reaches a maximum limit, generation from the PV system is curtailed.

Functionality and characteristics

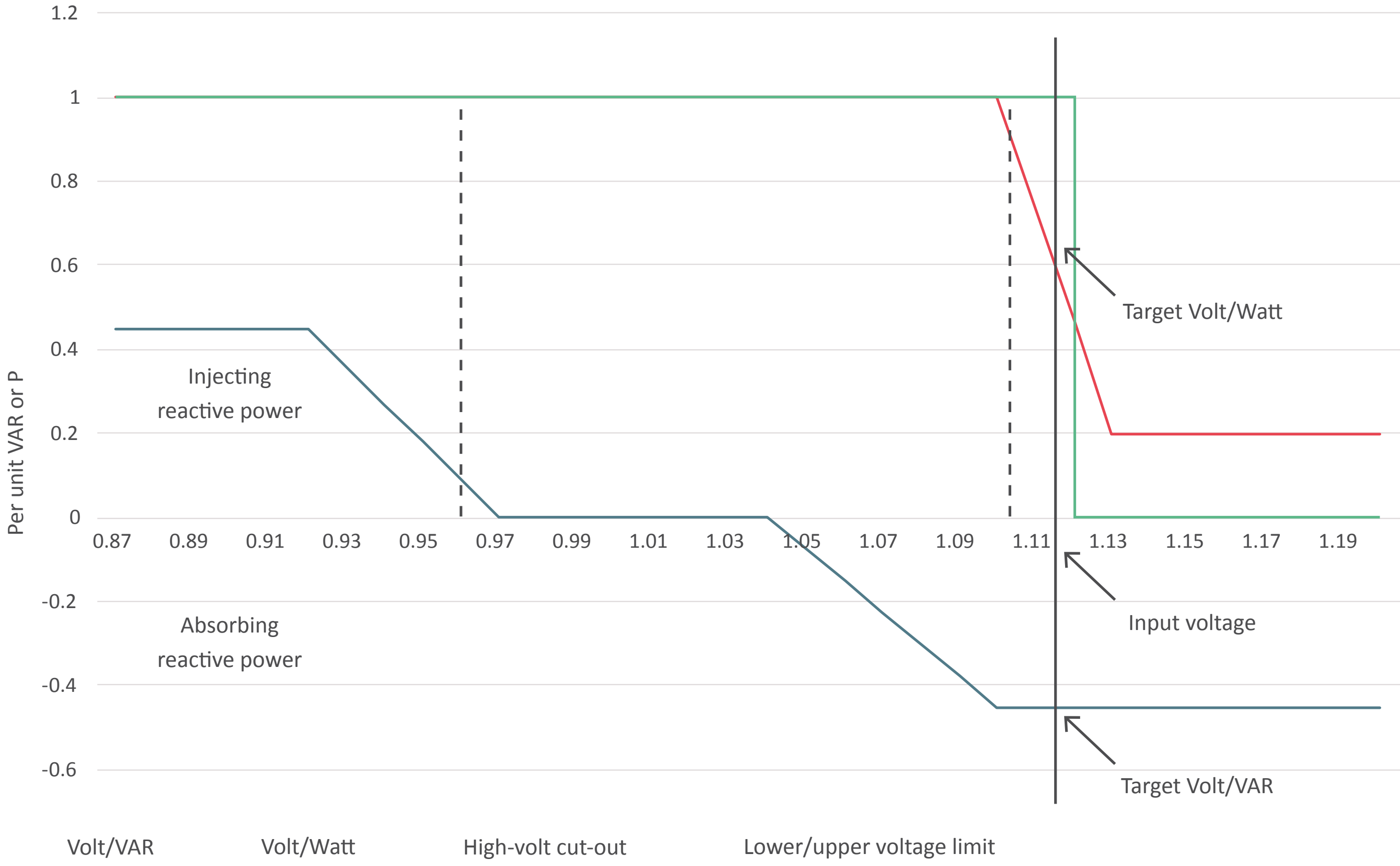
A smart inverter consists of the same hardware as a standard inverter, but includes increased functionality enabled by software changes [23]. Some of the smart functionalities of a smart inverter include [24, 25]:

1. Ride-through capabilities: a wider range for voltage and frequency disturbances can be set for the inverter, which prevents automatic disconnection during temporary grid disturbances
2. Reactive power control: dynamically controls reactive power injection (volt-VAR control) and power factor adjustment based on grid conditions
3. Power curtailment: dynamically controls the real power exported to the grid
4. Grid connection: reconnection to grid after outage can be staggered by system operator in a "soft start method".

Manufacturers and costs

Inverter prices in Australia vary based on brand, due to differences in build quality and reliability [26]. The most common residential inverter is the string inverter, which controls a string of PV panels [27]. A premium brand Fronius 1.5 kW string inverter costs $1,100 and a Fronius 5 kW string inverter costs $1,490 [26]. Hybrid inverters can manage both a battery and solar PV panels [28]. The extra capabilities make hybrid inverters more expensive than string inverters [29], with an estimated cost for a Fronius 5 kW hybrid inverter of $3,555 [29].

Figure 5 • Smart inverter Volt-Watt and Volt-VAR adjustments with change in nominal voltage



Advantages and disadvantages of smart inverters

Advantages	Disadvantages
Helps grid stability – control of ride through capabilities stops automatic inverter disconnection for short-term minor grid disturbances [25]	Smart capabilities increase the size of the surface area for potential cyber attacks [30]
Prevents further outages due to staggered reconnection of inverters on grid restart [25]	Challenge of policy and regulations to allow full use of technology capabilities [25]
Potential for DNSPs to defer capital investment, through reduction of transformers and regulation device usage [23]	Financial loss for PV owners with curtailment of exports to the grid [26]
Enhanced visibility of PV generation, not available with net metering, will assist DNSP forecasting and planning [23, 31]	Financial cost for DNSP if they have to pay inverter owners for grid stability services [25]
Helps power quality management through potential inverter control to reduce PV output variability [31]	Potential cost of upgrading communications infrastructure to enable [23]
Investment risk lowered with reduction and stabilisation in technology costs [32]	

Behind-the-meter batteries

Context

Both behind-the-meter batteries and network-scale batteries have been used in Australia to demonstrate their potential in resolving power quality issues and to enable integration of higher levels of renewable energy on the grid:

1. The ARENA-funded 'Networks Renewed' project demonstrated how solar PV and batteries combined with smart inverters can support network voltage as an alternative to network augmentation [20]
2. Ergon Energy, a distribution network service provider (DNSP) now part of Energy Queensland Limited, developed a 25 kW / 100 kWh Grid Utility Support System (GUSS) [33]. The technology, consisting of a battery and a control system, was used to resolve power quality issues on remote single wire earth return (SWER) lines in Atherton Tableland in Queensland [34]. After successful trial results, Ergon acquired 20 lithium-ion batteries from S&C Electric, a United States manufacturer [35], to deploy on SWER lines as an alternative to network upgrade, estimating a saving of $4.6 million [36]
3. United Energy (UE), a DNSP in Victoria, began a trial in 2017 to use solar photovoltaic (PV) systems with battery storage to meet peak demand and defer network augmentation [37]. The trial involved installation of solar photovoltaic (PV) and battery storage at locations connected to overloaded distribution substations. The interim report demonstrated how the DNSP controlled discharge of the batteries during peak periods to supply customer load. The value to the DNSP was demonstrated through deferral of grid upgrades by using the solar and storage systems to manage the overloading on the network. The results also demonstrated the longer-term potential of using control of batteries as a method for resolving power quality issues arising with increasing photovoltaic (PV) penetration [37].

Working principle

Operation

A September 2018 report by the Smart Energy Council indicates that 62% of all batteries available for purchase in Australia were lithium-ion [38]. Lithium-ion batteries have reduced in cost, due to use in portable electronics and policies generating use in the electricity sector and electric vehicle market [39]. Lithium-ion also has performance advantages over other batteries, such as longer cycle life and energy and power density [39].

Batteries have the capability to shift load by storing and releasing energy at different times of the day [34]. The stored energy can be used for demand management or to provide grid support services. The charging and discharging cycle of a battery over the course of a day is shown in the Figure 6.

Peak PV generation occurs during daylight hours. When load demand is low, the battery can charge to full capacity. In the evening time, when PV generation has reduced and load demand is increasing, the full capacity of the battery can discharge to supply power to the network. This peak demand provided by the battery can reduce the DNSP requirement to augment the network.

The battery is also able to provide other grid services:

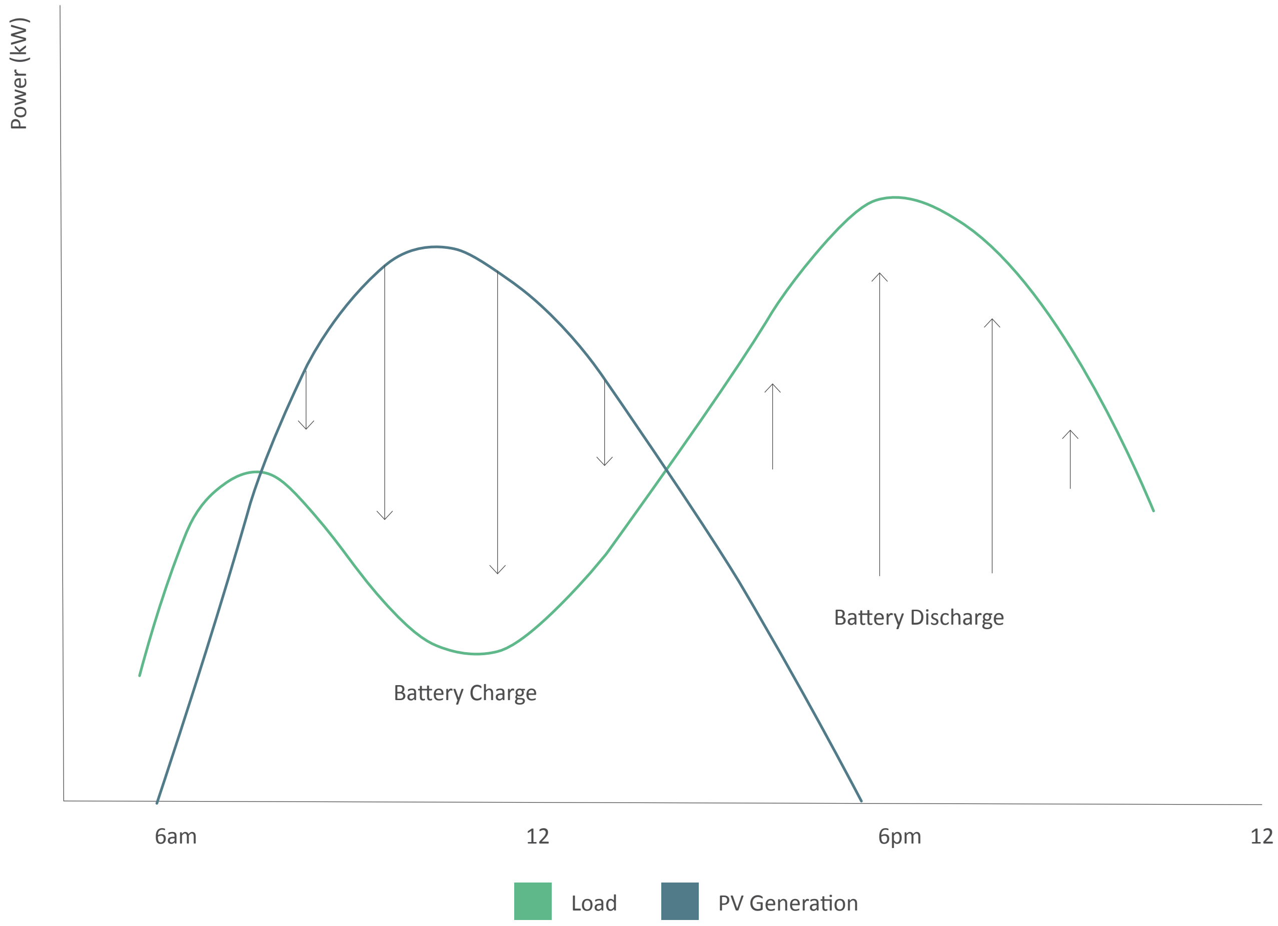
1. Rapid reaction capability of batteries, in charging and discharging, can correct PV output fluctuations faster than conventional generators. In some scenarios, clouds can reduce the PV output by 90% almost instantaneously [39]
2. Reactive power capabilities of the battery can assist with power quality, through power factor correction. This was demonstrated in the AusNet trial near Melbourne, where the power factor was maintained successfully at 0.95 using a battery [40].

Functionality and characteristics

The components of a battery consist of an energy system and an inverter with a thermal control within the battery container. These components are shown in Figure 7. The component parts of the battery are:

1. The battery management system monitors and protects the battery through management of the voltage, current, temperature as well as the battery charge level [41]
2. The energy system contains battery cells, where electro-chemical reactions convert electrical energy to chemical energy for storing. The opposite reaction occurs when the battery is discharging, with chemical energy converted to electrical energy [42]. Cells can be added in series with each other to combine the voltages into a higher value for scaling to increase the battery size [43]
3. The thermal control system manages the temperature of the battery to prevent ambient temperature affecting the battery [44]. This is an important consideration with lithium-ion batteries that can have problems with overheating [39]
4. An inverter is required to convert the direct current (DC) output of the battery to alternating current (AC) for usable power (inverting) and conversion of grid AC power to DC for storage (rectifying). The bi-directional inverter allows energy flow in both directions, to enable charging and discharging of the battery [43].

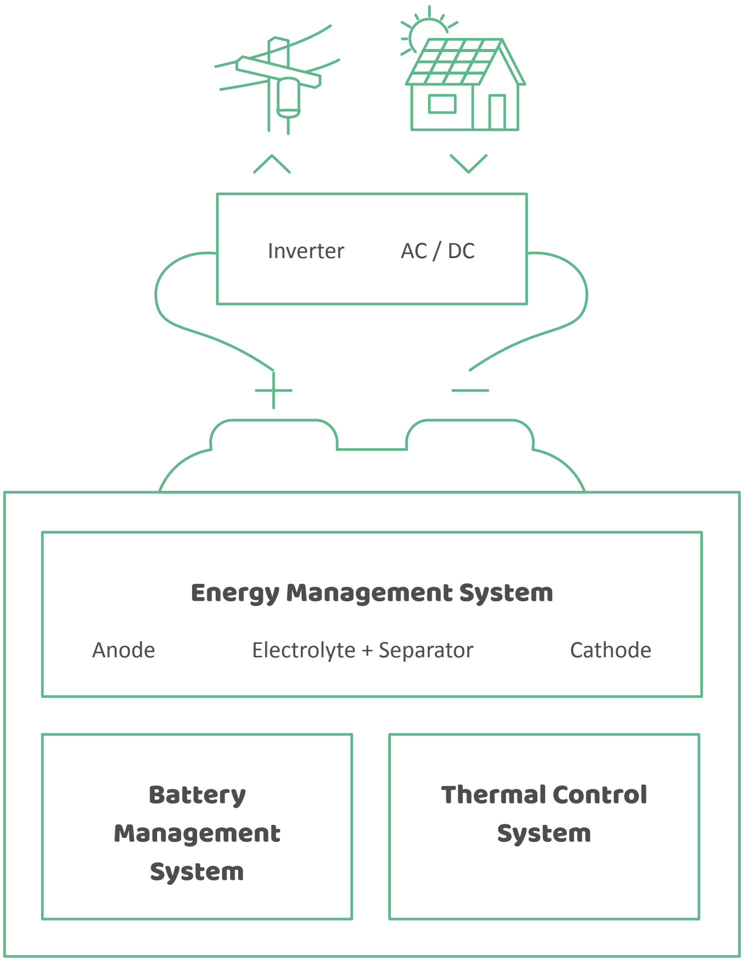
Figure 6 • Behind-the-meter battery operation



Manufacturers and costs

Bloomberg New Energy Finance (BNEF) indicates an average price of USD 176 / kWh for lithium-ion batteries [45] and a total price including shipping, installation and hardware of USD 422 / kWh [46]. The Tesla Powerwall 2 is estimated to cost AUD 11,700, including supporting hardware and installation costs [47]. Lithium-ion battery costs have decreased significantly in the past few years, with the International Renewable Energy Agency (IRENA) reporting that small-scale residential batteries in Germany have reduced in cost by 60% from 2014 to 2017 [48]. The benefit of their use in electric vehicles will lead to an IRENA estimated 54–61% decrease in the costs for stationary lithium-ion installations by 2030 [48].

Figure 7 • Network battery components



Advantages and disadvantages of behind-the-meter batteries

Advantages	Disadvantages
Potential revenue streams could include grid services and participation in the wholesale market [49, 50]	Safety concerns with certain batteries, such as lithium-ion, due to overheating and fire risk [51]
Potential to defer network investment for DNSPs [37]	Selection of battery characteristics is dependent on future network conditions, difficult to predict [52]
Ability to shift PV electricity generation capability to match demand [52]. Load shifting was a highlighted as a benefit of the Ergon GUSS trial in Queensland [34]	
Bloomberg estimate a 65% reduction in the weighted average battery price per kWh from 2018 to 2030 (lithium-ion) [45]	
Ability to provide power factor adjustment as demonstrated in AusNet trial in Victoria [40]	
Very fast response times, fractions of seconds compared to minutes from other generators [53]	

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