VICTORIA UNIVERSITY OF WELLINGTON TE HERENGA WAKA NEW ZEALAND
Archives of Sustainable Energy Systems
https://www.wgtn.ac.nz/sustainable-energy-systems

Technical evaluation of retrofitting solid-state transformers and battery energy storage systems for peak shaving within the footprint of ageing line-frequency distribution transformers in Aotearoa New Zealand

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Abstract
Aotearoa New Zealand's distribution network faces significant strain from a 250% increase in distributed solar photovoltaic installations between 2013 and 2022. These trends increase vulnerability to failure of line-frequency transformers (LFT). The objective of this paper is to investigate the technical feasibility of retrofitting existing LFT footprints with integrated solid-state transformers (SST) with battery energy storage systems (BESS). Using MATLAB/Simulink to simulate an 11 kV radial feeder, the study evaluated performance under strenuous dual-peak winter demand periods with transformers loaded to 110% of their rated capacity. The research demonstrates the potential recovery of up to 80% of the physical volume compared to LFTs allowing the footprint to be repurposed for decentralised BESS. The findings indicate that the medium density storage technologies (0.15-0.35 kWh/L) are the best option. The technology enables a load curtailment of 20% reducing the transformer loading from 110% down to the safe 90% threshold. However, the dual-peak demand profile for Aotearoa New Zealand's often depletes storage during morning cycles, while restricted charging windows limites utilisation of higher-density storage. Furthermore, while successful at the 0.4 kV busbar level, the aggregate impact of the main 11 kV feeder remaines minimal below 7.6%. It is recommended that future research focus on predictive control methods to optimise storage state of charge across successive peaks and the integration of downstream renewables to expand charging windows.

Keywords: Solid-state transformer (SST); Battery energy storage system (BESS); Peak shaving; Distribution networks; Aotearoa New Zealand.

1. Introduction

The distribution network is evolving and new terms like active distribution network and hybrid distribution networks are being used (Zheng et al., 2022a; Thokar et al., 2024; Lee, 2026). This originates from the integration of distributed energy resources (DERs), which transitions the network from a passive state to an active, bidirectional system (Ilyushine al., 2025). Aotearoa New Zealand undergoes a similar transition. Figure 1 illustrates the rapid 250% increase in distributed solar photovoltaic (PV) in less than 10 years (between 2013-2022) (Electricity Authority Te Mana Hiko, 2023).

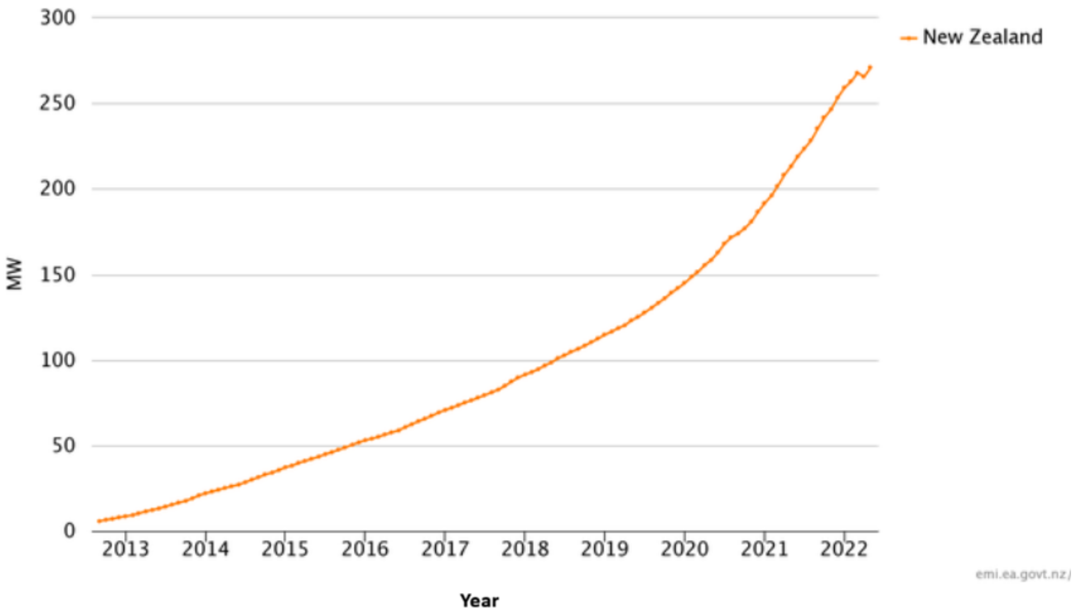

Figure 1. Growth in distributed solar PV installations in New Zealand (2013–2022) (Source: Electricity Authority Te Mana Hiko, 2023)

Transpower, the country's transmission grid operator and owner, notes the risk and challenges with current DERs increase and recommends that distribution networks make changes. The advice is for distribution operators to function as a transmission system, requiring physical capabilities in the network to manage bidirectional power flow (Transpower, 2025). Transpower propose a transition in the distribution network from the traditional passive to an active network. One of the bottlenecks or challenges in achieving this goal is the traditional transformer, which is limited in bidirectional power flow capabilities. Transformers from the 90s and prior are not designed for the bidirectional power flows caused by increased DERs, resulting in extreme temperature rise (higher than the permitted 140°C), causing rapid aging and failure (Ilyushin et al., 2025). Aotearoa New Zealand lines companies must replace approximately 3.8% of the nation's 196,130 distribution transformers and 9.4% of its 1,297 zone substation transformers within the next five years (PwC New Zealand, 2024). This necessitates the replacement of roughly 7500 distribution units averaging 1500 per year and 121 zone units averaging 24 per year. Distribution circuits in this case include transformers, cables, lines, switchgear and all equipment that allows power flow in distribution networks.

Beyond the aim of this paper, in terms of physical footprint benefits, SSTs can provide low voltage visibility challenges in local distribution network. SSTs result in multi functions that include power factor correction, voltage regulation and bidirectional power flow networks in Aotearoa New Zealand (Afonso et al., 2021; Cervero et al., 2023). A SST is designed with DC buses that can be used to integrate energy resources that include storage, solar photovoltaic (PV) systems or wind (Ju et al., 2025; Schwanninger et al., 2025; Wald et al., 2025).

Distribution companies in Aotearoa New Zealand published asset management plans mention visibility of low voltage circuits. This is said to be an obstacle to the expansion of distributed renewable energy resources. Quoting Unison, an electricity distribution network company based in Hastings: "*it is critical that we continue to grow our understanding of the low voltage network, including establishing additional autonomous monitoring and control*" (Unison Networks Limited, 2025). Autonomous monitoring and control, according to the distribution companies in the country, will help forecasting and networking planning. Additionally, planning for renewable energy, the challenges faced in Aotearoa New Zealand because of poor visibility of distribution include longer time locating faults and little information on utilisation of low voltage equipment (Reeve and Barton, 2020). This results in increased operational costs by the lines company that can be, for example, over or under sizing a low voltage networks (Reeve and Barton, 2020). This is due to more traditional methods of designing distribution networks, which may be obsolete for the evolving distribution grid. The challenge of predicting investment planning is reduced by the availability of data at low voltage circuits (Powerco, 2023). Distribution companies report on observing increased dips and peaks in the network causing swings and safety challenges due to bidirectional flow. The high penetration of renewable energy impact protection and network safety due to increase in fault level current requiring upgrades in circuit breakers and recalibration or replacement of protection equipment (Buller Electricity, 2025). Safety thermal loadings, phase loading imbalances, neutral currents, harmonics, and neutral voltage rise put the network at risk (Reeve and Barton, 2020).

This paper investigates one of the possible solutions to reducing the impact of high penetration of renewable energy resources in distribution networks. The specific challenge investigated in this paper is on reducing the peak and dips of the demand curves; in other words to flatten the curve. A combination of solutions will be required to modernise the distribution network and turn it into visible network for monitoring and control. The integration of SSTs and BESS technology is a promising solution, which is currently under research in Europe, USA and Asia (Cervero et al., 2023).

1.1. Objective of the paper

One of the important benefits mentioned in the literature on SSTs is improved volumetric power density resulting in a reduced footprint. The study uses a conventional transformer's size and power rating as a baseline. It evaluates how switching to a solid-state transformer frees up space for integrating energy storage within the same volume. The investigation aims to assess how gained storage can be used for peak shaving to lower the transformer loading to a percentage of full capacity.

Simulations to investigate the capabilities of storage gained are carried out in MATLAB/Simulink. The only SST property considered in the simulations is power density. This study utilises volumetric power and energy density data published in recent literature, alongside Aotearoa New Zealand demand curves from the Energy Efficiency and Conservation Authority (EECA) Regional Energy Transition Accelerator (RETA). A distribution network is assumed to consist of a 11 kV feeder with 10 transformers of different sizes ranging from 50 to 1500 kVA 11 kV to 415V mostly found across the Aotearoa New Zealand distribution network.

Maintaining the traditional transformer footprint enables the investigation into the potential increase in distributed storage in urban areas constrained footprint, as shown in Figure 2. To show that this is not an isolated case, Figure 3 provides supporting context by illustrating how similar transformer installations are distributed throughout the Wellington CBD, reinforcing the importance of space preserving retrofits. The improvement in volumetric energy density and volumetric power density can help use the distribution transformers in limited areas to be part of the active distribution network. Different energy densities for different storage technologies that are practical for these locations are simulated to investigate if the energy capacity can help peak shave and to what percentage of the capacity of the transformer. Additionally, the capability of the same storage in supplying power downstream in case of feeder fault up stream was also considered.

The objective of this paper is to evaluate the technical feasibility of integrating SSTs and BESS within existing transformer footprints to achieve peak shaving under dual-peak Aotearo New Zealand distribution network conditions.

Figure 2. 300 kVA distribution substation at 222 Willis Street, Wellington

Figure 3. Urban distribution transformer installation in the Wellington CBD

2. Literature review

The literature focuses primarily on SSTs and energy storage, evaluating the transition from passive LFT to active SST with storage. Areas covered include the volumetric power density and volumetric energy density improvements. Furthermore, literature covers the advantages and disadvantages of SSTs and BESS.

2.1. Solid-state transformers

Coelho et al. (2025) provide a typical structure of SST (see Figure 4). SSTs are designed using different topologies depending on function(Mollik et al., 2022; Karlis et al., 2025; Wald et al., 2025). The three parts include two DC buses bars that can be used to integrate energy resources. The two DC buses – the medium voltage DC bus and low voltage DC bus – make the solid-state transformer multifaction device in the grid. SSTs using power electronic converters and high-frequency magnetic links results in increased functionality over low frequency transformers, or LFTs (Khan et al., 2022). The use of high frequency transformers (HFTs) or medium frequency transformers (MFTs) helps achieved the reduced size (Sunny et al., 2025; Mojlish et al., 2025). However, literature critiques this structure noting that while modularity improve reliability through redundancy it potentially increases complexity in control and adding auxiliary power supplies.

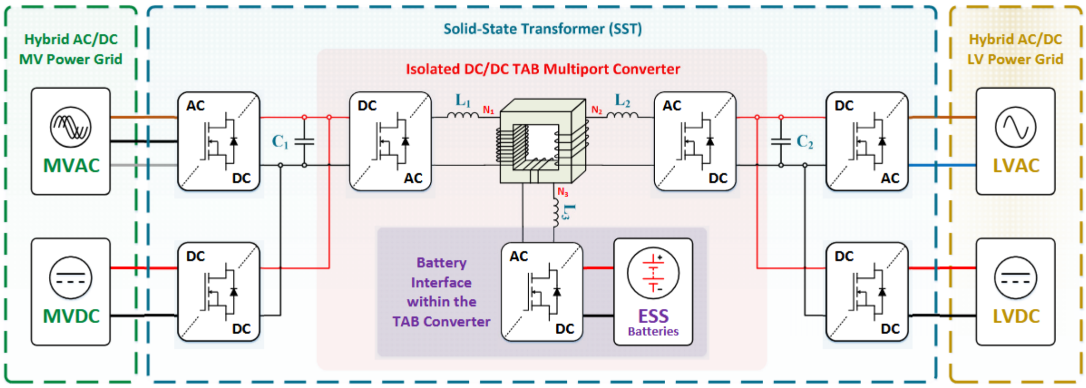

Figure 4. Multiport SST architecture for integrated BESS and DER interfacing (Source: Coelho et al., 2025)

A significant criticism in literature involves the gap between theoretical and system-level power density. While a HFT or MFT can theoretically offer 4500% (HFT reaches range of 10 kVA/L) reduction in size compared to the LFT (Ren et al., 2024). The first generation of SST could not offer this benefit; in 2014 the FREEDM volumetric power density is 0.5W/inch^3 that results in 0.03kW/L. The traditional transformer volumetric power density is within the range that is around 0.145 - 0.222 kVA/L for 500kVA to 1000kVA (Mishra et al., 2021). However, SST density improved over the years considering that in 2018 the FREEDM was 8.3W/inch^3 that is equal to 0.5075kW/L, UT Austin in 2022 was 25W/inch^3 equal to 1.5256kW/L, and the highest published from Delta achieved a volumetric power density of 6kVA/L (Xu et al., 2023a; Imperiali et al., 2025). Power electronics technology contributes to the improvements with the wide band gap devices in the equation (Ravindran and Massoud, 2025). The current limitation mentioned in literature is the voltage magnitude handled by the power electronics devices, limiting voltage level for use of SSTs to distribution networks. The highest voltage level of switching power electronics devices reported in literature to be commercially available is 10 kV influencing range of use of SSTs.

Additionally, SSTs can include multi ports as shown in Figure 4, allowing for hybrid setup of BESS and generation resources (Hossain et al., 2025). The literature regards the transformer as the backbone of the electricity grid making the transformer an important research area to improve the penetration of DERs and EVs.

The solid-state transformer, because of this architecture, can precisely control voltage, reactive power, sags, swells, and fluctuations (Avdeev et al., 2020; Tsareva et al., 2022; Kala, Rawat and Uniyal, 2025) . This results in improved power quality in distribution networks and the potential to increase more distributed renewable energy resources (Valedsaravi et al., 2022; Mandal et al., 2025). SSTs inherently include active filters capable of removing harmonics resulting from nonlinear loads, reducing THD and improving power quality (Carreno et al., 2024; Mandal et al., 2025; Mojlish et al., 2025).

On safety the power electronics circuits are designed to limit fault current levels, isolate faults from either the HV or LV side of the transformer and internally build protection relay for each module or stage (Shadfar et al., 2021b; Rashed Hassan Bipu et al., 2025) . And SST topologies can still offer galvanic isolation because of the high frequency transformer akin to low frequency transformer, a crucial safety feature (Shadfar et al., 2021b; Valedsaravi et al., 2022). Finally, SSTs are capable of grid forming operations allowing for island mode for a feeder or section of the distribution network (Elshenawy et al., 2023). In addition, the modularisation architecture of SSTs improve reliability (Acharya et al., 2021; Choi et al., 2025; Han et al., 2025).

The major or current setback to adoption is cost, and the tried and tested traditional transformer is superior in efficiency (Huang et al., 2024; Joshi et al., 2025; Predescu and Ros, 2025a; 2025b). The motivation in literature to pursue the technology is that cost and efficiency should not be limited to initial cost and static efficiency, but rather the overall cost of operation and dynamic efficiency (Afonso et al., 2021; Granata et al., 2022; Cervero et al., 2023; Joshi et al., 2025; Predescu and Ros, 2025b; Stathatos et al., 2025). Literature argues that all the benefits highlighted above should be quantified to determine if SSTs are indeed more expensive considering things like power quality that can reduce losses in power flow. Additionally, sources highlight the issue of improved capacity and the reduction in need for flexible AC transmission systems to impact on cost reduction for network operates by use of SSTs.

Current advancements aim for improvements in efficiency, topologies, control, power electronics devices and protection of SSTs (Wald et al., 2025). SST prototypes are now in field tests, for instance in Europe, to address the issue of no real-world demonstration (Cervero et al., 2025). SSTs are used in hybrid grid systems that combine AC and DC. This interest in a hybrid network is driven by the need to increase fast charging systems for the transition of the transport system (Etaveni and Nukala, 2026). The railway industry is included in the research and development of SSTs for use in high-speed railway vehicles (Kim et al., 2025). They are also used in interconnected microgrids for their grid forming and following properties (Sérgio Coelho et al., 2025; Sergio Coelho et al., 2025; Zhou et al., 2026).

2.2. Storage technology

Several storage technologies are available but for distribution networks electrochemical, flywheel energy, super capacitor, and superconducting magnetic energy storage are technically feasible (Elalfy et al., 2024). The most popular being electrochemical lithium-ion batteries. Upcoming new chemistry includes sodium-ion batteries, zinc-based batteries, and flow batteries with the advantage of using more available resources (Anik et al., 2025). The range of volumetric energy density for the storage technologies mentioned previously are shown in Figure 5. Volumetric energy density due to applications that include residential places, cars and portable devices drives the need to keep improving it (Reber et al., 2023; Njema et al., 2024; Pathak et al., 2024). New improvements rein storage technologies include for instance fly wheels using carbon fibre and graphene reinforced composites material to improve efficiency (Jayabal, 2025). The electrochemical storage technology is also experiencing improvements. The solid-state battery achieve a higher of volumetric energy density and life span (Schmaltz et al., 2023; Joshi et al., 2025). Research to enhance efficiency and durability in electrochemical batteries, aiming to extend their lifespan, is ongoing. Effective battery management is also crucial; if properly designed, it can significantly boost performance and longevity (Elalfy et al., 2024).

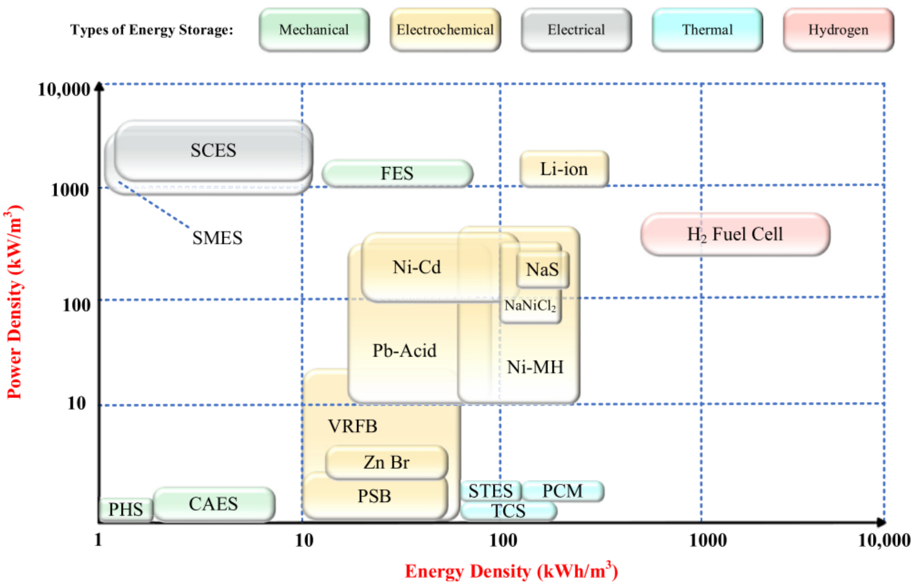

Figure 5. Volumetric energy and power density comparison across BESS technologies.
(Source: Fang et al., 2025)

Storage for distribution networks shows electrochemical to be the technology with better volumetric energy density and slower self-discharge rate. Table 1 provides an overview (Mo et al., 2025). Each technology excels in a specific area and from the table the ones with low self-discharge and higher volumetric energy density are limited in life span cycles. The ones with longer life spans show poor self-discharge rates. The flow battery is a potential solution, but still requires improvements in volumetric energy density considering the life cycle is high.

Storage in distribution networks offer benefits that include peak shaving, stability and reliability (Simic et al., 2022; Alguhi et al., 2023). The potential is in reducing the duck phenomena (Roy and Oo, 2024). BESS helps to mitigate the fluctuating power demands of EV charging stations, particularly fast and extreme fast charging which draws high current (Delta Electronics (Americas), 2022). Additionally resulting in mitigating thermal stress on upstream feeder cables, transformers due to sudden surges in power/current and defer costly infrastructure upgrades and minimizing electricity costs (Joglekar et al., 2022; Diahovchenko, 2024; Mojlish et al., 2025). Storage provides capability to the grid to inject or absorb reactive power resulting in improved voltage and power quality (Reeve et al., 2024; Rezaei and Esmaeili, 2024; Kala et al., 2025). In Aotearoa New Zealand, besides the ancillary services, storage is potentially used for arbitrage (Reeve et al., 2024).

Table 1. Key performance parameters of energy storage technologies

Type	Volumetric power density (kW/m^3)	Volumetric energy density (kWh/m^3)	Lifetime cycles (times)	Round-trip efficiency (%)	Self-discharge per day (%)
Lithium-ion batteries	1300 – 10000	140–630	1000–10000	90–97	0.1–0.3
Lead-acid batteries	10 – 400	50–80	500–2000	70–80	0.1–0.4
Liquid current batteries	140 – 180	150–250	2 500–4 500	Below 90	0.1–0.3
Flywheel energy storage	1000 – 5000	20–80	Greater than 20000	75–95	55–100
Supercapacitors energy storage	40000 – 120000	10–20	Greater than 50000	60–97	20–40
Flow batteries		20-75	13000-20000	65–85	
Sodium batteries		150-350	2500- 40000	75-90	
Sources	(Volterion GmbH & Co., 2024b; Domínguez et al., 2025; Jayabal, 2025; Liu et al., 2025; Mo et al., 2025; Sharmoukh, 2025; Voß et al., 2025)				

The technologies in Table 1 from literature provide different functions in line with the storage capabilities in mentioned in previous paragraph. Fly wheel and super capacitors mostly for grid short term requirements that include frequency and voltage whilst the other technologies for long term requirements that is mainly storage (Mugyema et al., 2023; Elalfy et al., 2024; Wangmo et al., 2024; Domínguez et al., 2025). Flywheel is mentioned to provide short term peak shaving capabilities on top of the inertia, which is the primary function (Olabi et al., 2024; Jayabal, 2025). Figure 6 summarises ongoing research on hybrid storage pairing logic, showing that combining complementary technologies can address the trade-off between fast response and high energy capacity (Elalfy et al., 2024; Olabi et al., 2024). The other challenge facing storage is cost, which is reported to be improving over the years (Reeve et al., 2024; Takagi et al., 2024; Rana et al., 2026).

The new chemistries for stationary applications include sodium and flow batteries (Renewable Energy Agency, 2025) . Sodium competes with the lower end of the lithium technology and will potentially become less expensive soon due to the abundance of resources compared to lithium (Csikor et al., 2025; Voß et al., 2025). The specific energy/energy density reported shows that for lithium is 214 Wh/kg and 507 Wh/ L, and for sodium the range is 147–206 Wh/kg and 333–419 Wh/L (Voß et al., 2025). The Renewable Energy Agency (2025) reports a comparison range of lithium of 150-300 Wh/kg and 200-700Wh/L, and for sodium 150-240 Wh/kg and 150-350Wh/L.

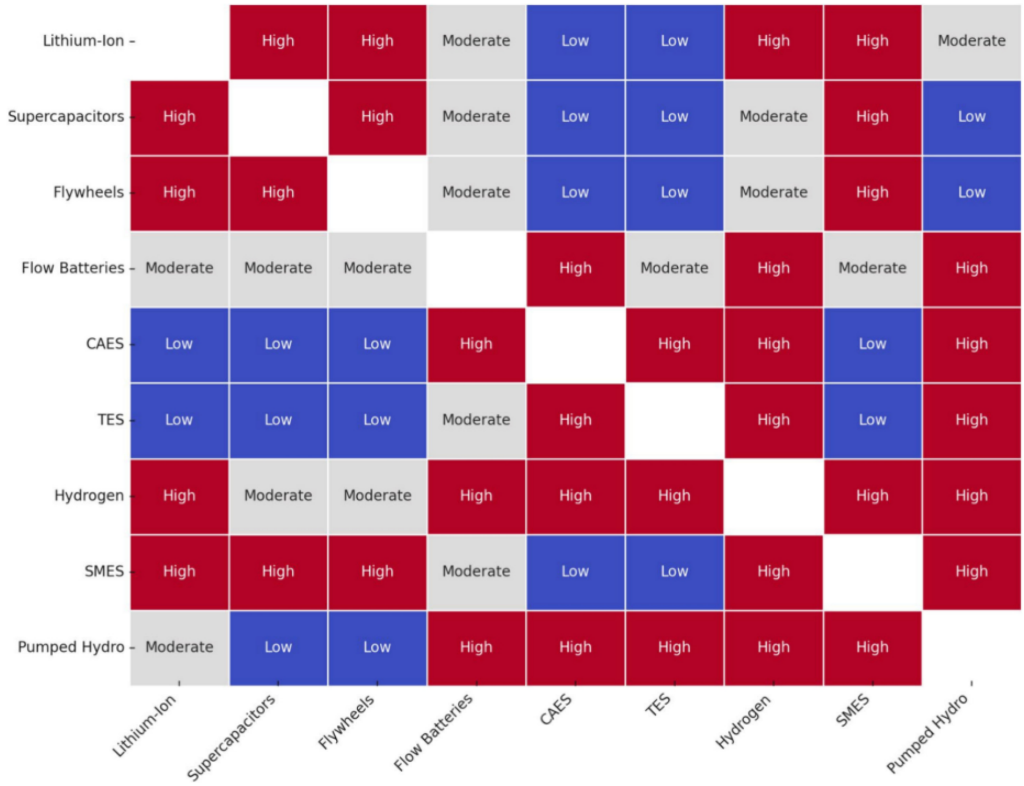

Figure 6. Performance matrix of hybrid energy storage system combinations
(Source: Fang et al., 2025)

Finally, the flow battery technology is on the rise with several significant projects now in operation. A Brazilian energy company installed the technology in the substation for service that include long term storage and ancillary services to meet regulations requirements (Cellcube, no date). The system size is 250kW/1000kWh, which demonstrates the high-power output of flow batteries. Flow batteries are gaining traction because of safety (no risk of thermal runaway), 100% depth of discharge, long life cycles – two times more than lithium, scalability up or downsizing, efficiency of 80%, and potential for low levelized cost of storage (Leba Akman et al., 2025) . The advantages are resulting in increased interest, but the technology still faces major hurdles like lower volumetric energy density compared to lithium and initial cost of setup (Leba Akman et al., 2025). The German company Volterion is manufacturing sizes that stacked for residential and commercial use (Flow Batteries Europe, no date; Volterion GmbH & Co., 2024a, 2024b). As of March 2023, 1000MWh of flow batteries are reported to be installed globally (Det Norske Veritas group, 2024). Redox-flow batteries are good for storing a large amounts of energy ranging from 1 kWh to 10MWh and, with over 10 000 cycles, makes it useful for most stationary applications (Anik et al., 2025).

2.3. Integration of storage with solid state transformers

The previous two sections show that combining the two technologies can potentially improve the transition from passive to active distribution network. The integration means a reduction in the required equipment to connect storage to the grid with SST providing the interface and control (Roger et al., 2021; Chen et al., 2024; Sunny et al., 2025; Gabriel et al., 2025). Several papers carried out research that showed the feasibility. The the main challenge remains cost. The reason is that SSTs currently in development still cost more compared to traditional transformers and the operational costs are not fully know with current research investigating that part (Stathatos et al., 2025). Long-term improved efficiency, loss in reduction, and the ability to perform energy arbitrage are being considered as factors that could contribute to lower overall operational costs for the distribution network (Zheng et al., 2022b; Kala, Rawat and Uniyal, 2025). A study found that the possibility of arbitrage reducing operational cost by over 21% compared to LFT cases plus the already mentioned deferred upgrade cost (Simic et al., 2022). Overall, the major benefit is to the environment by integrating more renewable energy resources, which is the aim of such technologies being developed (Rahman et al., 2021; Adeyinka et al., 2024).

3. Research methods

The study employed a methodology comprising of data collection, modelling, and simulation. The sources of data included Aotearoa New Zealand regulatory institutions' websites, and transmission and distribution companies. The software used for modelling and simulation was MATLAB. This study acknowledges modification of a model developed by MathWorks (2026) to meet the requirements.The assumptions made include:

1. Network and load profile:
   - A network is assumed covering the typical sizes of transformers found in Aotearoa New Zealand distribution networks. Figure 7 shows the key ten-transformer radial feeder setup used to evaluate peak shaving at both local busbar and aggregate feeder levels.
   - The demand curves are estimated from the Energy Efficiency and Conservation Authority (EECA) RETA project sourced on the website.
2. BESS technology parameters:
   - The volumetric energy and power density for BESS technologies and transformer technologies respectively are assumed from numbers published in journal papers (see Table 1).
   - The low-density technology values assumed using numbers for flywheel as lower benchmark despite the main use of flywheel being frequency control.
   - To ensure comparison of the storage technologies discharge C-rate is fixed at 1C.
3. Peak shaving and control logic:
   - In this study, peak shaving is defined as capping the load at a specific percentage of the transformer's rated capacity (kW). For example, or a 1500 kVA transformer, "95% peak shaving" means that whenever demand exceeds 95% of 1425 kW (95% of capacity), the BESS discharges to cap transformer loading at 1353.75 kW threshold. Assuming a power factor of 0.95.
   - Recharging the BESS is strictly limited to off-peak periods and is controlled so that the total load (demand plus charging) never exceeds the aimed peak shaving threshold
4. Economic exclusion:
   - The research focuses on technical feasibility of the strategy. Price of charging, discharging, technology cost and any other associated cost are not part of the research objectives.

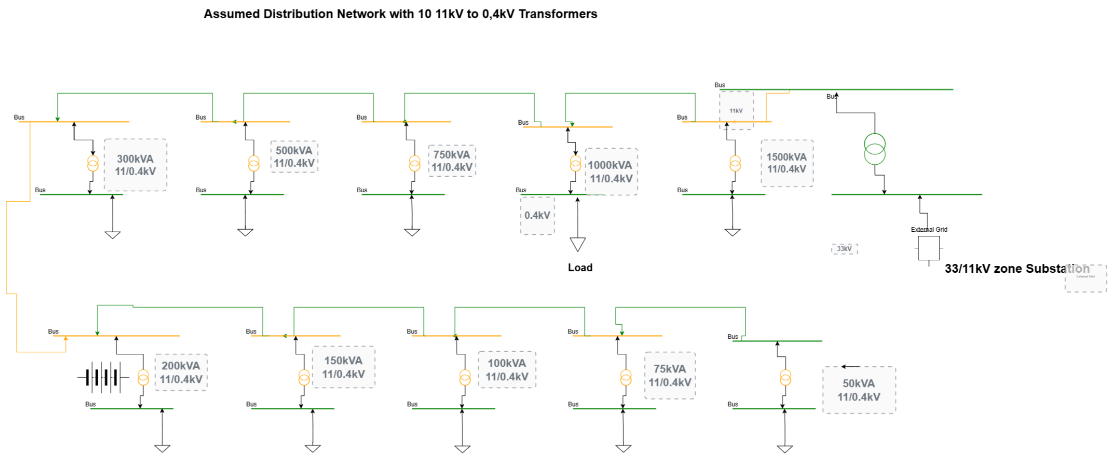

Figure 7. Schematic of the 11 kV radial feeder and 10-transformer simulation

3.1. Data collection

The study's data sources were derived from an extensive survey of validated technical reports and scholarly journal articles. The reports are from the lines company, Transpower, the Energy Efficiency and Conservation Authority (EECA), the Electricity Authority (EA), and transformer manufacturing companies in Aotearoa New Zealand. The data from these sources included finding out how the network operates loading of transformers, demand curves, transformer size in distribution networks, growth and challenges involved in the integration of renewable energy.

EECA (2025) carried out a project titled regional energy transition accelerator. The project published reports that included demand curves across the country's zone substations. The data is mentioned to be from SCADA. Figures 8 and 9 show snippets from some of the zone substations in the reports. The data collection first involved going through the sections that showed the demand curves to make observations of the characteristics of Aotearoa New Zealand demand profiles. The curves are over 100 in number from the over 100 zone substations across the country. Figures 8 and 9 provide supporting evidence from the RETA dataset that the demand commonly exhibits a dual-peak structure across a day.

The asset management plans from the lines companies provided data on the sizes of the transformers typically found in the networks; see Table 2 (Alpine Energy, 2022; Firstlight Network, 2023; Powerco, 2023; WEL Networks, 2023; Wellington Electricity, 2025). The networks show that the majority of the transformers are in the range 50 to 1500 kVA. Furthermore, the reports also show that some of the feeders and some radial justifying the use of a radial network in the simulation.

The journal papers were the primary source of data on volumetric power density and volumetric energy density of the feasible storage and solid-state transformer respectively. Table 3 presents the input parameters used in the simulation of scenarios.

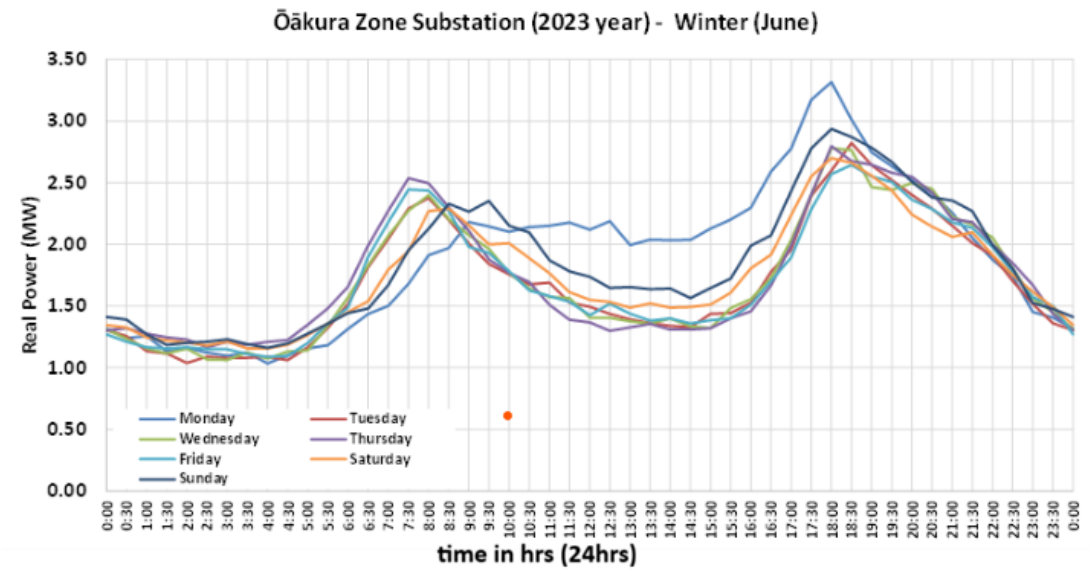

Figure 8. Regional dual-peak demand profile snippet from RETA reports (case 1).
(Source: EECA, 2025)

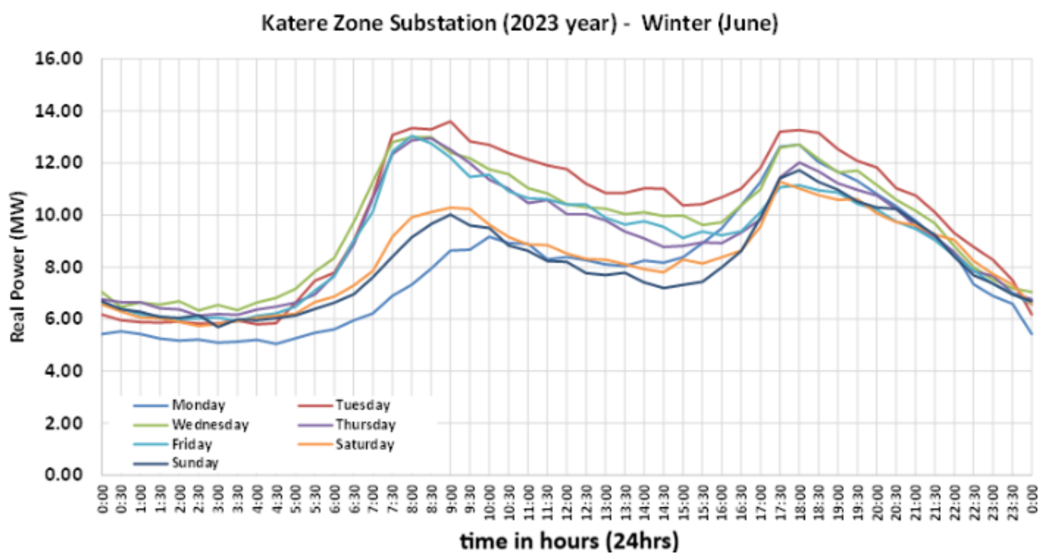

Figure 9. Regional dual-peak demand profile snippet from RETA reports (case 2).
(Source: EECA, 2025)

Table 2. Reported transformer loading conditions from asset management plans

Lines Company	Loading level (% of Capacity)	Duration of overloading mostly wintertime
Counties Energy	150% (for "peaky" residential loads) 100% (for spread loads)	1 to 2 hours (for peaky loads) winter or summer
Electra	>100% of nameplate rating	More than 120 hours (240 half-hours) per year
WEL Networks	Exceeding overload rating	
Network Tasman	110% (10% over nameplate rating)	
Buller Electricity	>80% of nameplate rating	
Wellington Electricity	Cyclic capacity and emergency overload	2 hours (short duration emergency)
First light Network	>100% of thermal rating	More than 5 hours (10 consecutive half-hours)
Nelson Electricity	100% (Not to exceed full load)	Snapshot during peak times

Table 3. Simulation input parameters for SST and BESS technologies.

Technology	Volumetric power density kVA/L	Volumetric energy density kWh/L	Source
Traditional transformer	0.145 - 0.222		Mishra et al., 2021
SST	2.6		Wei et al., 2023
	1.524		Xu et al., 2023b
	0.45 - 0.625		Mishra et al., 2021
	6.9		Imperiali et al., 2025
Flow battery	80	0.025 - 0.035	Reber et al., 2023
Fly wheel	75- 95	0.02 -0.08	Mo et al., 2025
Lithium-ion	80-97	0.2 – 0.68	Mo et al., 2025
Lead acid	70-80	0.05-0.08	Mo et al., 2025
Lithium solid state	80-97	Approx. 1	Pathak et al., 2024
Sodium battery	75-90	0.15-0.3	Renewable Energy Agency, 2025

3.2. Modelling and simulation

A dynamic network model was developed in Simulink, in the form of radial 11 kV feeder with 10 transformers (1500 kVA, 1000 kVA, 750 kVA, 500 kVA, 300 kVA, 200 kVA, 150 kVA, 100 kVA, 75 kVA and 50 kVA). The transformer sizes represent common Aotearoa New Zealand distribution standards. Pre simulation involved calculating energy capacity based on the space recovered by replacing LFTs with SSTs. Equation 1 determines the

SST volume using its power rating and density. Equation 2 calculates the kWh capacity by multiplying recovered volume by energy density of the selected technology for a scenario. Figures 10 and 11 show that the increase in energy density significantly improves the capacity of energy storage within the same footprint.

$$Volume\ of\ SST = \frac{Power\ rating\ of\ traditional\ transformer\ (kVA)}{Power\ density\ (\frac{kVA}{L})} \quad (1)$$

$$Energy\ in\ kWh = (Volume\ of\ LFT - Volume\ of\ SST) * Energy\ density\ (\frac{kWh}{L}) \quad (2)$$

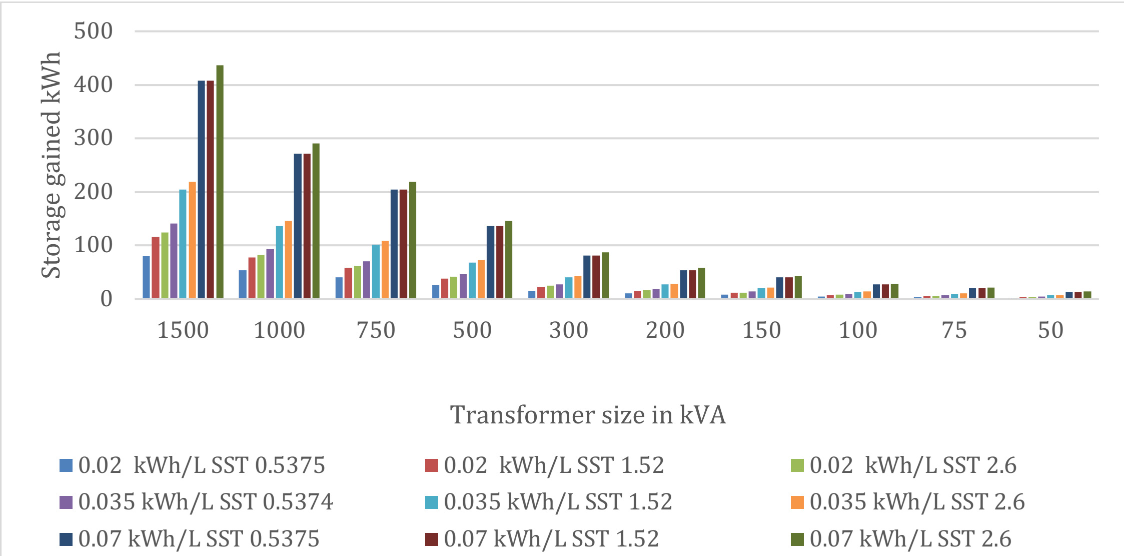

Figure 10. Footprint-recovered BESS capacity for low-density storage technologies (flywheel, flow battery, lead-acid)

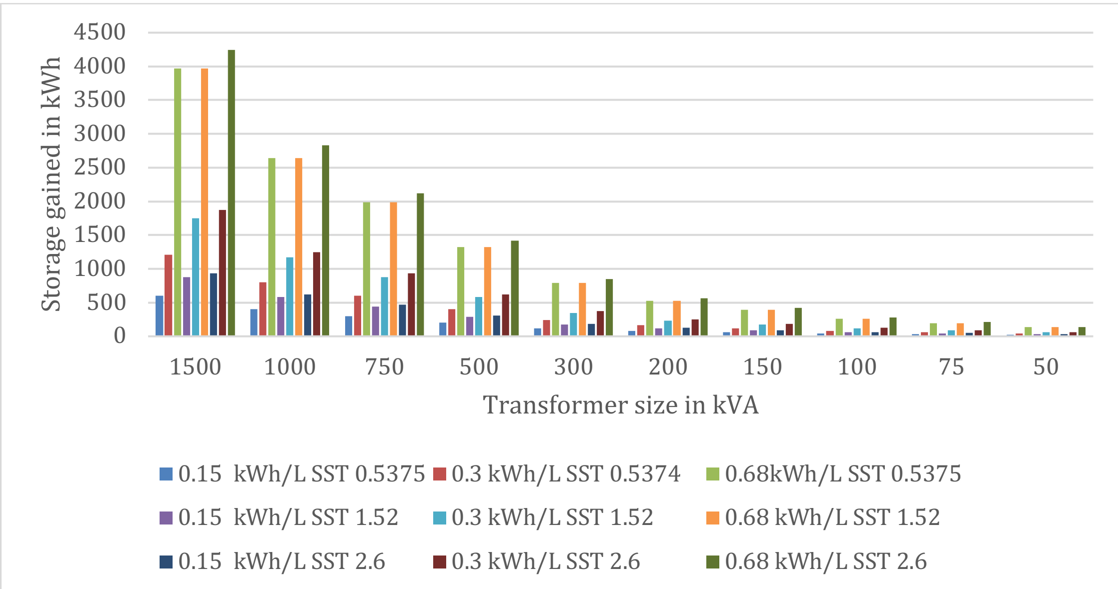

Figure 11. Footprint-recovered BESS capacity for medium- and high-density technologies (sodium-ion and lithium-based)

The simulation was designed as a sensitivity test to evaluate the SST and BESS in relation to varying demand scenarios. Demand curves were swapped and scaled while storage was adjusted efficiency was adjusted based on technology between 70% to 97%. Peak shaving logic was applied iteratively based on transformer capacity rating beginning with a 95% load cap. If the technology maintained this threshold, the target was increased. If the technology failed to cap variables, such as energy density or SST power density, the technologies were adjusted upwards systematically to isolate impacts (see Figure 12). During the 30-day winter simulation the parameters recorded included power (demand, from grid, battery charge/discharge) converted to percentage of transformer and state of charge as a percentage. The model recorded the energy from storage used per week and per month for analysis of utilisation of storage.

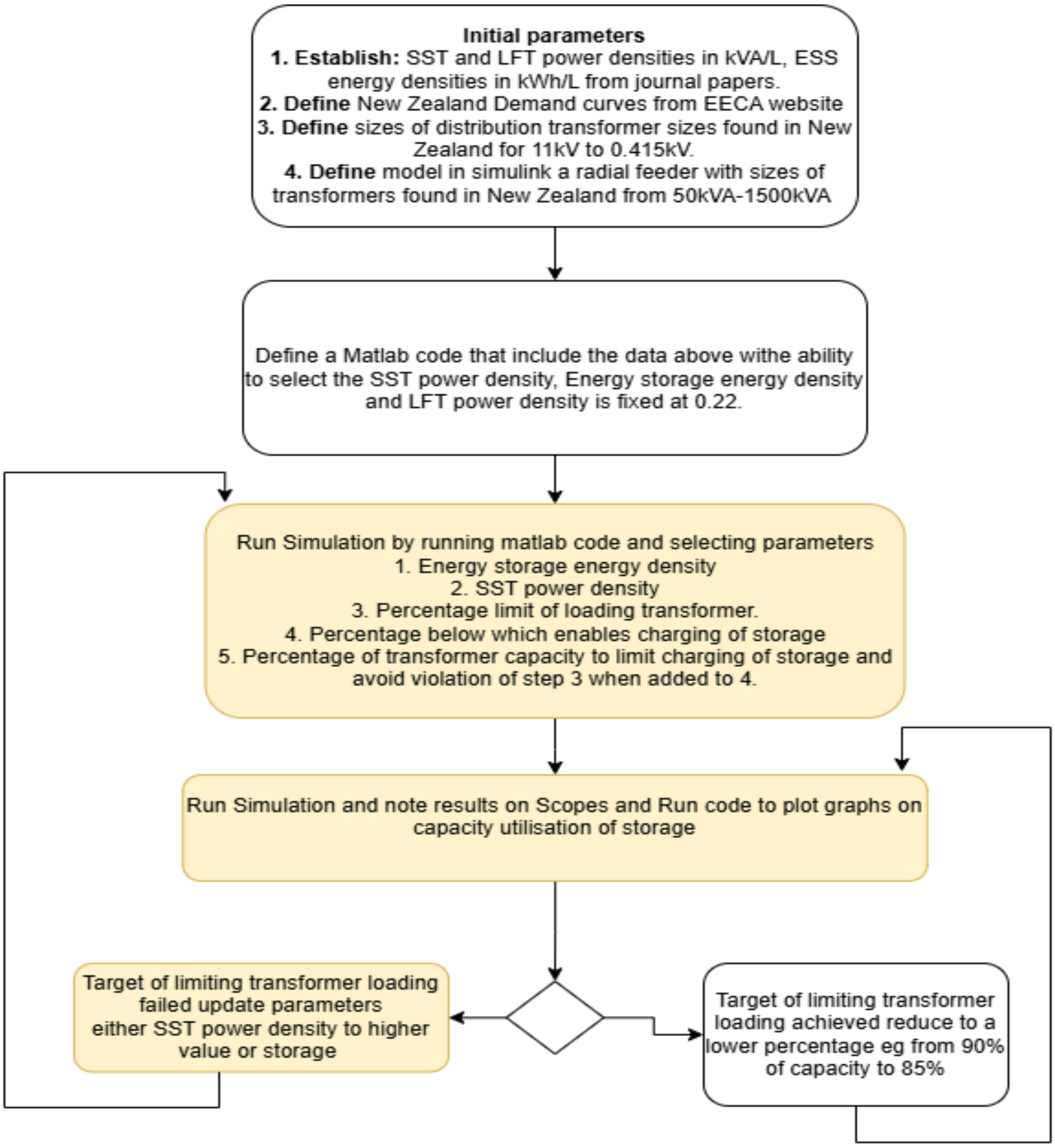

Figure 12. Flow diagram of the iterative simulation methodology

- Aggregate Feeder Impact (11 kV Level): The total power drawn from the main 11 kV feeder was plotted on the same axis as the cumulative demand of all ten distribution substations. This comparison identifies the net reduction in grid supply and determined if the integration significantly reduced zone substation stress or merely shifted the peak timing.

- Localized Transformer Performance (0.4 kV Level): Localised active power was compared directly against its specific substation demand. This metric assessed system's ability to successfully cap the load at the targeted 90% or 95% threshold of transformer capacity. Additionally, it showed which transformer sizes create capacity to effectively maintain sustained curtailment.
- BESS Operational Dynamics: BESS performance was monitored using the State of Charge (SoC) and active power flow (charge/discharge). These observations were critical for identifying long-term trends, such as storage depletion over successive dual-peak. Furthermore, revealing underutilisation of battery capacity when charging is restricted by transformer headroom.
- Operational constraints: Constraints remained constant to ensure a fair comparison. A 1C discharge rate standardised performance across all technologies. BESS charging was strictly controlled to ensure the combined load do not breach the capping. Charging was limited to a fixed maximum of 10% or 15% of the transformer's rated capacity. To maintain a 95% total load threshold, charging was only enabled when the demand fell below 85% or 80% respectively. This ensured that the sum of the fixed charging rate and the instantaneous demand remained within the safety limit.

4. Results and discussion

The research evaluated technical performance of retrofitting existing distribution transformer footprints with integrated SST and BESS. The study tested this system across ten simulation scenarios using a representative 11 kV radial feeder under strenuous winter demands. In these scenarios, peak shaving was defined as capping the load at specific percentage of the transformer capacity in kW. Table 4 summarises the classification of the SST and BESS technologies used in the study using power density and volumetric density respectively.

Table 4. Classification of SST compactness and BESS energy density benchmarks

Category	SST kVA/L Compact level	Battery energy density kWh/L	Explanation
Low	0.45-0.625 **low compact (LC)**	0.02 - 0.08 **low density (LD)**	Range for flow batteries, lead acid and flywheels
Medium	1.56 **Medium compact (MC)**	0.15 – 0.35 **Medium density (MD)**	Range for sodium and lithium lower end
High	2-2.6 **High compact (HC)**	0.40 – 0.70 **High density (HD)**	Range for advanced lithium
Very high	6.9 **Very high compact (VHC)**	Greater than 1 **Very high density (VHD)**	Range for solid state batteries lithium
	PM=evening peak	**AM**=morning peak	**SOC**=state of charge
	Tx=transformer	**ESS**=Energy storage System	

4.1. Scenario 1 results

This scenario utilised the lowest density benchmarks for storage, representative of flywheels or basic flow batteries. The results demonstrated a widespread failure to maintain the 95% of capacity. For larger units transformers 1500kVA- 750kVA (Buses 2-4), the storage depleted mid-peak, causing the grid supply to revert to full demand after approximately 30 minutes. In smaller transformers (Buses 6-11), the restricted physical footprint limited storage to negligible amounts, which were exhausted within fewer minutes. Successful shaving only occurred on Bus 9 transformer size 100kVA, where the demand excursion above the limit was minimal in duration. Table 5 summarises the results of the scenario. Scenario 1 main setback is energy density of BESS technology that is redox flow batteries and partly the constraint of charging between peaks.

Table 5. Peak-shaving performance for Scenario 1 (95% Load Cap).

Bus	TX Size (kVA)	ESS (kWh)	Capped Target kW	Max demand (kW)	Result	SOC Settling Range %	Peak Duration Handled/covered
2	1500	80.55	1425	~1550	Fail	10 - 90	~ <45 mins PM peak
3	1000	53.70	950	~1050	Fail	10 - 90	~ <30 mins AM peak only
4	750	40.27	712.50	~780	Fail	10 - 90	~ <30 mins PM peak
5	500	26.85	475	~514	partial	10 – 90	~ <30 mins AM peak ~ <20 mins PM peak
6	300	16.11	285	~310	Fail	10 - 90	~ <30 mins AM peak ~ <30 mins PM peak
7	200	10.74	190	~206	Fail	10 - 90	~ <30 mins PM peak
8	150	8.06	142.50	~155	Fail	10 - 90	~ <30 mins AM peak ~ <30 mins PM peak
9	100	5.37	95	~104	Success	75 – 90	~ <30 mins PM peak
10	75	4.03	71.25	~78	Fail	10 - 90	~ <30 mins PM peak
11	50	2.69	47.50	~52	Fail	10 - 90	~ <30 mins PM peak

4.2. Scenario 2 results

Increasing SST compactness to Medium Compact, the total recovered volume resulted in 361 kWh total storage for all 10 transformers. This additional capacity enabled bus 5 (500 kVA) to successfully cap the demand. However, large units (> 500 kVA) still failed to maintain the threshold during sustained evening peaks. Grid supply profiles indicated that while the dip in grid supply was deeper than scenario 1 the BESS still settled at the 10% state of charge floor before the demand curve returned below the target. Table 6 summarises the results. Larger transformers gained more storage but failed under extended peaks while smaller units were due to insufficient recovered volume. The potential capacity remained unutilised because of restricted charging windows and the dual peak demand pattern in Aotearoa New Zealand.

Table 6. Peak-shaving performance for Scenario 2 (95% Load Cap)

Bus	TX Size (kVA)	ESS (kWh)	Capped Target kW	Max demand (kW)	Result	SOC Settling Range %	Peak Duration Handled/covered
2	1500	117.13	1425	~1550	Fail	10 - 90	~ <60 mins PM peak
3	1000	78.09	950	~1050	Fail	10 - 90	~ <60 mins AM peak only
4	750	58.57	712.50	~780	Fail	10 - 90	~ <30 mins PM peak
5	500	39.04	475	~514	partial	10 – 90	~ <30 mins AM peak ~ <30 mins PM peak
6	300	23.43	285	~310	Fail	10 - 90	~ <30 mins AM peak ~ <30 mins PM peak
7	200	15.62	190	~206	Fail	10 - 90	~ <50 mins PM peak
8	150	11.71	142.50	~155	Fail	10 - 90	~ <40 mins AM peak ~ <40 mins PM peak
9	100	7.81	95	~104	Success	75 – 90	~ <30 mins PM peak
10	75	5.86	71.25	~78	Fail	10 - 90	~ <30 mins PM peak
11	50	3.9	47.50	~52	Fail	10 - 90	~ <30 mins PM peak

4.3. Scenario 3 results

In scenario 3, the system utilised the upper boundary values for low density (LD) storage, which resulted in total storage capacity of 1444 kWh. The BESS successfully capped transformer loading at 95% for nine out of the ten simulated buses. Comparison graphs between demand and grid supply showed a consistent shaved top at the 95% threshold, with the 1000 kVA transformer being the only exception. Crucially, the state of charge levels settled well above the 10% depletion allowed typically remaining between 30% to 50% for the six out of the ten. This performance showed that the upper boundary of low-density storage provides sufficient capacity to cap at 95% mark. Table 7 provides a detailed summary of the results for scenario 3.

Table 7. Peak-shaving performance for Scenario 3 (95% Load Cap)

Bus	TX Size (kVA)	ESS (kWh)	Capped Target kW	Max demand (kW)	Result	SOC Settling Range %	Peak Duration Handled/covered
2	1500	469	1425	~1550	success	40 - 90	~ <120 mins PM peak
3	1000	312	950	~1050	Fail	10 - 90	~ <60 mins AM peak only ~ <60 mins PM peak
4	750	234	712.50	~780	success	30 - 90	~ <60 mins PM peak
5	500	156	475	~514	success	10 – 90	~ <30 mins AM peak ~ <120 mins PM peak
6	300	93	285	~310	success	10 - 90	~ <60 mins AM peak ~ <120 mins PM peak
7	200	62	190	~206	success	40 - 90	~ <120 mins PM peak
8	150	47	142.50	~155	success	30 - 90	~ <120 mins AM peak ~ <120 mins PM peak
9	100	31	95	~104	success	75 – 90	~ <30 mins PM peak
10	75	23	71.25	~78	success	15 - 90	~ <120 mins PM peak
11	50	16	47.50	~52	success	55 - 90	~ <120 mins PM peak

4.4. Scenario 4 results

Transitioning to Medium Density lower boundary (0.15 kWh/L) storage achieved a technically flawless performance for the 95% curtailment of the transformers loading. Total capacity reached 2,708 kWh. However, the results indicated significant underutilisation of resources, as the SOC rarely dropped below 50% for most of the transformers. Figure 13 illustrates the potential accumulated energy over the 30-day period and reveals significant resource underutilisation; the State of Charge (SoC) rarely dropped below 50% for most units. This substantial SoC headroom indicated that the system could manage a significantly more aggressive shaving target, which was evaluated in later scenarios.

4.5. Scenario 5 results

In this scenario, the capping of transformer loading was increased to 90% of its capacity. The parameters for the SST set at the Medium compact and the storage at lower boundary of medium density. The system successfully maintained the lower ceiling across all 10 buses (see Table 8). At this stage most scenarios start to include a longer morning peak and for some morning peak start emerge or get more pronounced.

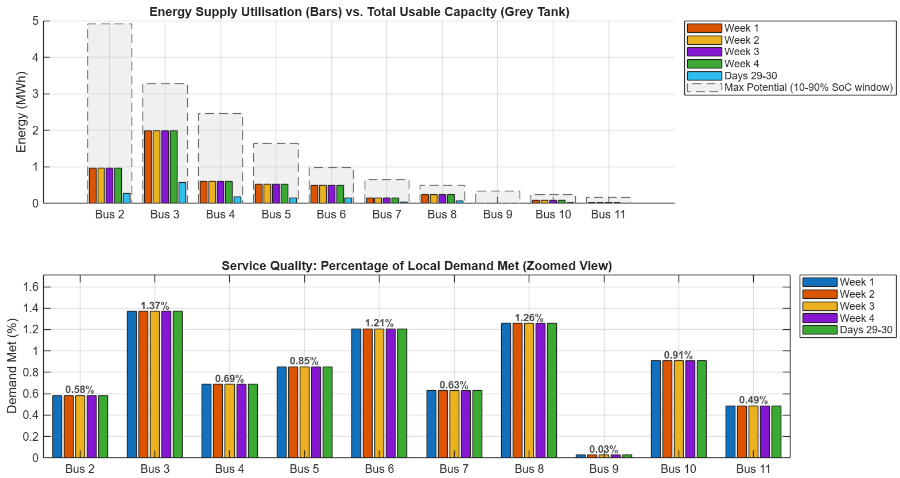

Figure 13. BESS performance variance across distribution transformer sizes (Scenario 2)

Table 8. Peak-shaving performance for Scenario 5 (90% Load Cap)

Bus	TX Size (kVA)	ESS (kWh)	Capping Target kW	Max demand (kW)	Result	SOC Settling Range %	Peak Duration Handled/covered
2	1500	2050	1350	~1550	success	50 - 90	~ <120 mins PM peak
3	1000	1367	900	~1050	partial	10 - 50	~ <120 mins AM peak only ~ <0 mins PM peak
4	750	1025	675	~780	success	60 - 90	~ <150 mins PM peak
5	500	683	450	~514	success	50 – 90	~ <60 mins AM peak ~ <120 mins PM peak
6	300	410	270	~310	partial	10 - 40	~ <60 mins AM peak ~ <60 mins PM peak
7	200	273	180	~206	success	60 - 90	~ <150 mins PM peak
8	150	205	135	~155	partial	10 - 50	~ <120 mins AM peak ~ <60 mins PM peak
9	100	137	90	~104	success	80 – 90	~ <120 mins PM peak
10	75	102	67.5	~78	success	45 - 90	~ <30 mins AM peak ~ <120 mins PM peak
11	50	68	45	~52	success	65 - 90	~ <30 mins AM peak ~ <120 mins PM peak

4.6. Scenario 6 results

Utilising the SST set at HC average value and storage at MD upper boundary provides a significant total storage capacity of 6,654 kWh. The change is minimal for buses (load centres) that are only partially satisfied in scenario five. Figure 14 shows the behaviour of Bus 8 during the first days when storage begins near a full state of charge and over the days dropping. This demonstrates that increased storage does not guarantee improved shaving when charging headroom is constrained. It must be noted that the aim is to reduce transformer load and thus constrained headroom.

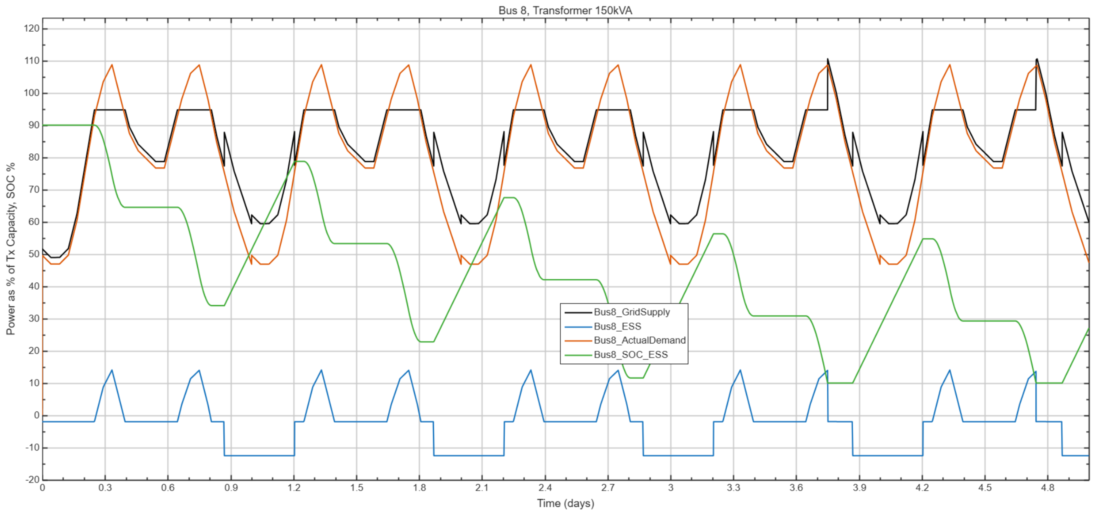

Figure 14. Bus 8 BESS discharge trends during the final seven simulation days (Scenario 6)

4.7. Scenarios 7 and 8 results

These scenarios integrate the highest density storage with a high-compact SST. The total capacity is 13,308 kWh, double of the previous scenarios. The same challenges observed in scenario 6 of failure to recharge storage resulting in partial curtailment. Scenario 8 involves reducing the SST parameters MC and storage to HD, capping the loading to 85% of transformer capacity and increasing the charging by 5% from 10% of the transformer capacity whilst maintaining the cap with no significant difference compared to scenario 7. The storage capacity is significantly underutilised due to limited charging capacity with weekly performance for 5 of the 10 bus/transformer points dropping in the weeks 2 to 4.

4.8. Scenarios 9 and 10 results

To evaluate the technical robustness of the integrated framework, sensitivity tests were performed by swapping per-unit demand profile shapes between transformer sizes (the 'Reverse' swap mode). This involved exchanging the profile originally used for the 1,500 kVA unit with that of the 50 kVA unit. A direct comparison between Scenario 5 (original profiles) and Scenario 10 (swapped profiles) maintaining constant technology parameters SST Medium Compact and storage Medium-Density Lower boundary. Curtailment at 90% revealed that this was the only scenario where a significant difference was observed.

4.9. Scenarios 1 to 10 results – main feeder 11 kV

The above focus on the individual transformers/buses and in this part, the focus is on the graphs of the main feeder for all the scenarios. Table 9 provides a summary of the observations. Figure 15 illustrates a representative feeder level result, showing that local shaving at downstream transformers produces only modest reductions at the 11 kV feeder peak.

Table 9. Summary of aggregate feeder-level peak demand reduction

Scenario	Storage Gained (kWh)	Feeder Peak Demand (kW)	Feeder Peak Reduction And new Peak (kW)	Downstream curtailment target for TXs
1	248.36	~4,600	0	95%
2	361.16	~4,600	Slight shift in time PM peak 0	95%
3	1,444.64	~4,600	PM peak 4400	95%
4	2,708.70	~4,600	PM peak 4400	95%
5	6,320.29	~4,600	PM peak 4250	90%
6	6,654.15	~4,600	PM peak 4250	90%
7	13,308.30	~4,600	PM peak 4250	90%
8	9,931.89	~4,600	PM peak 4350	85%
9	7,223.19	~4,150	Reduced duration PM peak By half	90%
10	2,708.70	~4,150	Reduced duration PM peak By half	90%

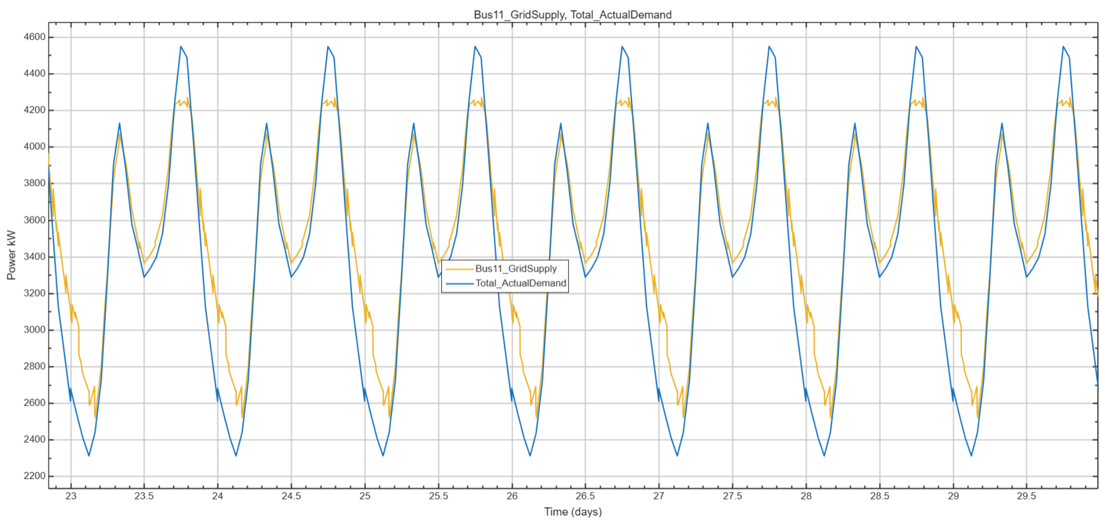

Figure 15. Aggregate demand reduction on the main 11 kV feeder (Scenario 5)

4.10. Discussion

The technical analysis confirms the footprint benefits of SST in freeing space useful for BESS installation. The results indicate that high-density BESS failed to achieve optimal performance despite superior energy capacity. This failure was primary attributed to the dual-peak depletion. The winter patterns were characterised by distinct morning and evening peaks. The sustained morning peaks frequently depleted the BESS state of charge. The charging constraint logic further hindered the performance of the BESS. To prevent creating new artificial peaks on the grid, BESS recharging was strictly limited to the available transformer headroom during off-peak periods. The restricted window prevented the high density BESS technology from reaching full charge before the evening surge. This failure to charge between peaks to full capacity rendered the increase in storage capacity useless.

The medium density energy BESS technology performed better because of its utilising capacity. This was because of the dip period between peaks provided enough time to fully recharge. The study also compared the localised benefit at the 0.4 kV busbars against the aggregate impact on the 11 kV feeder. While the system successfully achieved up to 20% load curtailment locally, reducing the transformer loading from 110% to 90%, the grid-wide impact was minimal. The data showed that feeder peak demand dropped from 4600 kW to 4250 kW, representing a reduction of 7.6%. Crucially, even when storage capacity was doubled in scenario 7, the reduction for the 11 kV feeder remained at 7.6%.

This demonstrates that after the medium density adding more storage capacity provided diminishing returns without changes in the control logic. Finally, volume recovery that SST technology enabled reached up to 80% physical footprint gained from replacing ageing LFTs.

5. Conclusion and recommendations

The research shows that retrofitting SSTs with integrated BESS is technically feasible for local peak shaving. The storage can be significant with an increase in energy density, but will require multiple strategies to fully realise this benefit. Using medium density BESS technology reduced transformer loading by 20%. This translates to 20 years delay in upgrading transformer size based on the reporting of some the asset management plans; of 1% annual increase in demand. The following strategic recommendations will guide the future development of this field.

- Predictive control development: Future research needs to focus on creating algorithms to optimise state of charge across successive peaks rather than relying on fixed threshold only to effectively manage energy flow and storage. Figure 16 provides evidence of the potentially gained energy.
- Downstream renewable energy integration: The integration of customer-side solar PV to assist in charging the BESS will increase the availability charging window.
- Value stacking research: Detailed economic modelling needs to be conducted of ancillary services, such as voltage regulation, increased hosting capacity, virtual power plants and additional revenue streams that offset upfront cost of SSTs and BESS.
- Standardisation: Potential regulatory guidelines are needed to improve safety, protection and best practise in installations.

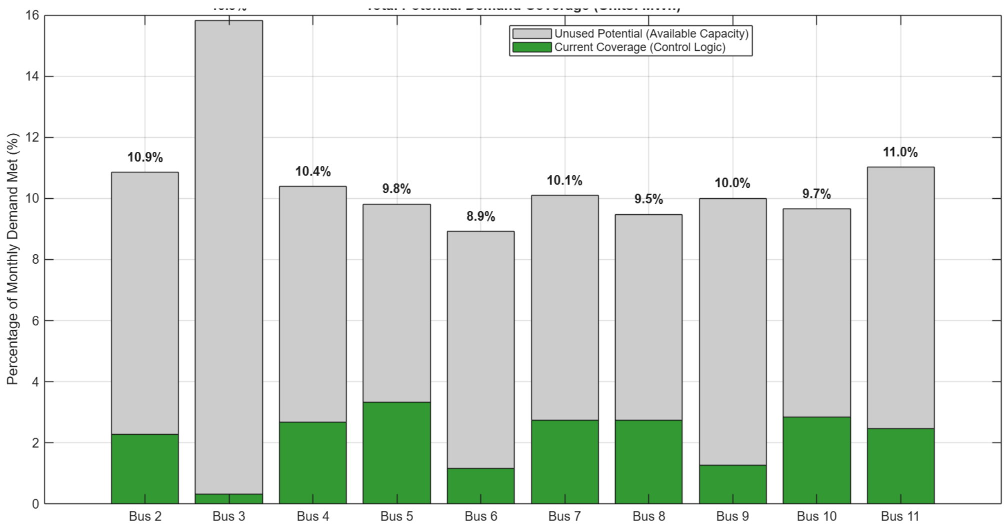

Figure 16. Scenario 8 shows how much of the storage can cover a percentage of demand and the potential it could cover

References

Acharya S, Anurag A, Chattopadhyay R, Rengarajan S, Prabowo Y, Bhattacharya S, 2021. A 10-kV SiC-MOSFET (Gen-3) half-bridge module-based isolated bidirectional DC-DC converter block for medium-voltage high-power applications. IEEJ Transactions on Electrical and Electronic Engineering, 16 (1), 127-138, doi:10.1002/tee.23275.

Adeyinka AM, Esan OC, Ijaola AO, Farayibi PK, 2024. Advancements in hybrid energy storage systems for enhancing renewable energy-to-grid integration. Sustainable Energy Research, 11 (1), 26, doi:10.1186/s40807-024-00120-4.

Afonso JL, Tanta M, Pinto JGO, Monteiro LFC, Machado L, Sousa TJC, Monteiro V, 2021. A review on power electronics technologies for power quality improvement. Energies, 14 (24), 8585, doi:10.3390/en14248585.

Alguhi AA, Alotaibi MA, Al-Ammar EA, Al Katheri AA, 2023. Battery energy storage planning in distribution network with renewable resources. IEEE Jordan International Joint Conference on Electrical Engineering and Information Technology (JEEIT), 306-311, doi:10.1109/JEEIT58638.2023.10185830.

Alpine Energy Limited, 2022. Empowering our community asset management plan. Accessed 26 August 2026 from: https://www.alpineenergy.co.nz/__data/assets/pdf_file/0025/18097/Final-AMP-5Apr-2022.pdf.

Anik MAHC, Bin Belal TMAI, Islam MM, Sharif A, 2025. A comprehensive review of next-generation grid-scale energy storage technologies and their role in a sustainable energy future. Journal of Control Science and Engineering, 2025 (1), doi:10.1155/jcse/5577507.

Avdeev B, Vyngra A, Chernyi S, 2020. Improving the electricity quality by means of a single-phase solid-state transformer. Designs, 4 (3), 35, doi:10.3390/designs4030035.

Buller Electricity Ltd, 2025. Buller Electricity asset management plan. Accessed 26 August 2026 from: https://bullerelectricity.co.nz/wp-content/uploads/AMP-2025-2035.pdf.

Carreno A, Malinowski M, Perez MA, Ding J, 2024. Effects of grid voltage and load unbalances on the efficiency of a hybrid distribution transformer. IEEE Open Journal of the Industrial Electronics Society, 5, 1206-1220, doi:10.1109/OJIES.2024.3486353.

Cellcube, n.d. Grid company congestion management, Brazil - Cellcube. Accessed 26 August 2026 from: https://www.cellcube.com/case-studies/grid-company-congestion-mgmt-brazil/.

Cervero D, Fotopoulou M, Muñoz-Cruzado J, Rakopoulos D, Stergiopoulos F, Nikolopoulos N, Voutetakis S, Sanz JF, 2023. Solid state transformers: A critical review of projects with relevant prototypes and demonstrators. Electronics (Switzerland), 12 (4), doi:10.3390/electronics12040931.

Cervero D, Garcia-Martinez E, Abad JI, Pinilla-Torremocha J, Sanz-Osorio JF, Melero JJ, 2025. A modular solid-state transformer for 3 kV DC grids: Design, topology, and performance evaluation. IEEE Access, 13, 148047-148059, doi:10.1109/ACCESS.2025.3601207.

Chen L, Qiao X, Yang M, Zhu J, Zheng S, Tang J, Chen H, 2024. Investigation of SMES-battery hybrid energy storage system for robustness enhancement of solid-state transformer. IEEE Transactions on Applied Superconductivity, 34 (8), doi:10.1109/TASC.2024.3463258.

Choi D, Park JH, Lee JS, 2025. Individual module power control of solid-state transformer for multiport configuration in railway traction systems. IEEE Transactions on Transportation Electrification, 11 (1), 3102-3113, doi:10.1109/TTE.2024.3434712.

Coelho S, Amin S, Monteiro V, Afonso JL, 2025a. A battery-oriented multiport DC-DC converter for enhanced power management in SST. 2025 IEEE 19th International Conference on Compatibility, Power Electronics and Power Engineering (CPE-POWERENG), doi:10.1109/CPE-POWERENG63314.2025.11027285.

Coelho S, Dionizio A, Cunha J, Monteiro V, Afonso JL, 2025b. Solid-state transformer: The catalyst for resilient and sustainable smart grids. Energy, 327, 136321, doi:10.1016/j.energy.2025.136321.

Csikor D, Eisinger Balassa B, Gulyas P, 2025. Beyond lithium: Evaluating sodium-ion batteries for the next generation of electric vehicles. Engineering Proceedings, 113 (1), 41, doi:10.3390/engproc2025113041.

Delta Electronics Americas, 2022. News center - Delta demonstrates 400kW solid state transformer-based extreme fast EV charger to partners GM, DTE Energy, NextEnergy, American Center for Mobility and U.S. DOE - Delta. Accessed 26 August 2026 from: https://www.deltaww.com/en-us/news/35766.

Det Norske Veritas group, 2024. Bringing flow to the battery world (II). Accessed 26 August 2026 from: https://www.dnv.com/article/bringing-flow-to-the-battery-world-2/.

Diahovchenko I, 2024. Analyzing the influence of electric vehicle charging scheduling on distribution transformer lifespan. Heliyon, 10 (21), doi:10.1016/j.heliyon.2024.e39904.

Domínguez M, Fernández-Cardador A, Fernández-Rodríguez A, Cucala AP, Pecharromán RR, Urosa Sánchez P, Vadillo Cortázar I, 2025. Review on the use of energy storage systems in railway applications. Renewable and Sustainable Energy Reviews, 207, doi:10.1016/j.rser.2024.114904.

Elalfy DA, Gouda E, Kotb MF, Bureš V, Sedhom BE, 2024. Comprehensive review of energy storage systems technologies, objectives, challenges, and future trends. Energy Strategy Reviews, 54, 101482, doi:10.1016/j.esr.2024.101482.

Electricity Authority Te Mana Hiko, 2023. Solar generation now and in the future. Accessed 26 August 2026 from: https://www.ea.govt.nz/news/eye-on-electricity/solar-generation-now-and-in-the-future/.

Elshenawy MA, Radwan A, Mohamed YARI, 2023. Coordinated grid-forming controller for solid-state transformer-enabled PV farms. IEEE Transactions on Energy Conversion, 38 (4), 2596-2611, doi:10.1109/TEC.2023.3291661.

Energy Efficiency and Conservation Authority, 2025. Regional energy transition accelerator | EECA. Accessed 26 August 2026 from: https://www.eeca.govt.nz/co-funding-and-support/products/about-reta/.

Etaveni M, Nukala NVSB, 2026. Extreme fast charging using solid state transformer. Communications in Computer and Information Science, 2613, 325-338, doi:10.1007/978-3-032-00983-8_25.

Fang Z, Shek JKH, Sun W, 2025. A review of grid-connected hybrid energy storage systems: Sizing configurations, control strategies, and future directions. Journal of Energy Storage, 118, 116226, doi:10.1016/j.est.2025.116226.

Firstlight Network, 2023. Firstlight Network | Asset management plan 2023. Accessed 26 August 2026 from: https://firstlightnetwork.co.nz/assets/Documents/Firstlight-Network-AMP-2023.pdf.

Flow Batteries Europe, n.d. The Volterion stack - flow batteries tour. Accessed 26 August 2026 from: https://flowbatterieseurope.eu/the-volterion-stack-flow-batteries-tour/.

Gabriel MT, Mansour DEA, Shoyama M, Abdelkader SM, 2025. Design and performance evaluation of a battery-integrated PV system utilizing triple-active bridge based solid-state transformer topology. Journal of Energy Storage, 114, 115646, doi:10.1016/j.est.2025.115646.

Granata S, Di Benedetto M, Terlizzi C, Leuzzi R, Bifaretti S, Zanchetta P, 2022. Power electronics converters for the internet of energy: A review. Energies, 15 (7), 2604, doi:10.3390/en15072604.

Han L, Li B, Gu H, Liu D, Jiao Y, Deng F, Xu D, 2025. Operation of medium-voltage modular multilevel converter with hybrid Si and SiC half-bridge sub-modules. IET Power Electronics, 18 (1), doi:10.1049/pel2.70093.

Hossain MS, Islam MR, Sutanto D, Muttaqi KM, 2025. A modular multi-port hybrid solid-state transformer for large-scale renewable power applications. IET Electric Power Applications, 19 (1), e70021, doi:10.1049/elp2.70021.

Huang J, Wang Y, Li Z, Zhu H, Li K, 2024. A Si IGBT/SiC MOSFET hybrid isolated bidirectional DC-DC converter for reducing losses and costs of DC solid state transformer. Electronics, 13 (4), 801, doi:10.3390/electronics13040801.

Ilyushin P, Volnyi V, Suslov K, 2025. Review of approaches to creating control systems for solid-state transformers in hybrid distribution networks. Applied Sciences, 15 (20), 10970, doi:10.3390/app152010970.

Imperiali L, Wang R, Anurag A, Barbosa P, Kolar JW, Huber J, 2025. Comparative analysis of carbon footprints and material usage of solid-state transformers and low-frequency-transformer-based MVac-LVdc interfaces for high-power EV charging. 2025 IEEE Applied Power Electronics Conference and Exposition (APEC), 1318-1325, doi:10.1109/APEC48143.2025.10977184.

International Renewable Energy Agency, 2025. Sodium-ion batteries: A technology brief. Accessed 26 August 2026 from: https://www.irena.org/Publications/2025/Nov/Sodium-ion-batteries-A-technology-brief.

Jayabal R, 2025. Decarbonizing transportation with flywheel energy storage systems: Current trends and future prospects in sustainable mobility. Energy Storage, 7 (4), doi:10.1002/est2.70197.

Joglekar C, Mortimer B, Ponci F, Monti A, De Doncker RW, 2022. SST-based grid reinforcement for electromobility integration in distribution grids. Energies, 15 (9), doi:10.3390/en15093202.

Joshi A, Mishra DK, Singh R, Zhang J, Ding Y, 2025. A comprehensive review of solid-state batteries. Applied Energy, 386, doi:10.1016/j.apenergy.2025.125546.
Ju S, Zhang M, Bo Y, Shi T, 2025. Research on active distribution network power flow optimization method based on energy storage regulation. Recent Advances in Electrical & Electronic Engineering, 18, doi:10.2174/0123520965372066250203050550.
Kala H, Rawat MS, Uniyal A, 2025. Optimal allocation and technoeconomic analysis of solid state transformer in distribution network. Computers and Electrical Engineering, 125, doi:10.1016/j.compeleceng.2025.110417.
Karlis A, Piromalis D, Xiao H, Prasad K, Kilby J, 2025. A review of solid-state transformer-based ultra-fast charging station technologies: Topologies, control, and grid interaction. Energies, 18 (17), 4705, doi:10.3390/en18174705.
Khan S, Rahman K, Tariq M, Hameed S, Alamri B, Babu TS, 2022. Solid-state transformers: Fundamentals, topologies, applications, and future challenges. Sustainability, 14 (1), doi:10.3390/su14010319.
Kim DU, Park JH, Lee SH, Kim S, 2025. Development of medium voltage single-phase solid-state transformer for high-speed railway vehicles: Reduced scale verification results. High Voltage, 10 (3), 555-569, doi:10.1049/hve2.70061.
Leba Akman A, Arslan MZ, Farsak M, 2025. The rise of vanadium redox flow batteries: A game-changer in energy storage. Journal of Alloys and Compounds, 1038, 182869, doi:10.1016/j.jallcom.2025.182869.
Lee HP, 2026. Integrating distributed energy resources in power distribution systems: A comprehensive review of impacts, challenges, and opportunities from a distribution system operator's perspective. Applied Energy, 403, 127052, doi:10.1016/j.apenergy.2025.127052.
Liu J, Liu Y, Dai Z, Yang F, Rao H, Pan L, Xu X, Han M, Zeng L, Li Y, Leung P, An L, Wei L, 2025. Simultaneously enhancing energy density and reducing cost of vanadium redox flow batteries via the dual role of tetravalent vanadium ions as both active species and redox mediator. Small, 21 (37), e05171, doi:10.1002/smll.202505171.
Mandal A, Muttaqi KM, Islam MR, Sutanto D, 2025. Solid-state power substations for future power grids. IEEE Transactions on Industry Applications, 61 (1), 1055-1067, doi:10.1109/TIA.2024.3477447.
Mishra DK, Ghadi MJ, Li L, Hossain MJ, Zhang J, Ray PK, Mohanty A, 2021. A review on solid-state transformer: A breakthrough technology for future smart distribution grids. International Journal of Electrical Power and Energy Systems, 133, doi:10.1016/j.ijepes.2021.107255.
Mo H, Li C, Liu N, Zhao B, Dong H, Liu H, Zio E, 2025. Energy storage systems for carbon neutrality: Challenges and opportunities. Frontiers of Engineering Management, 12 (2), 305-329, doi:10.1007/s42524-025-4190-3.
Mojlish SAK, Sutanto D, Muttaqi KM, 2025. Impacts of ultra-fast charging of electric vehicles on power grids: State-of-the-art technologies, case studies, and a proposed improvement using a solid-state transformer. Journal of Energy Storage, 107, doi:10.1016/j.est.2024.114913.
Mollik MS, Hannan MA, Reza MS, Abd Rahman MS, Lipu MSH, Ker PJ, Mansor M, Muttaqi KM, 2022. The advancement of solid-state transformer technology and its operation and control with power grids: A review. Electronics, 11 (17), 2648, doi:10.3390/electronics11172648.
Mugyema M, Botha CD, Kamper MJ, Wang RJ, Sebitosi AB, 2023. Levelised cost of storage comparison of energy storage systems for use in primary response application. Journal of Energy Storage, 59, doi:10.1016/j.est.2022.106573.

Njema GG, Ouma RBO, Kibet JK, 2024. A review on the recent advances in battery development and energy storage technologies. Journal of Renewable Energy, 2024, 1-35, doi:10.1155/2024/2329261.
Olabi A-G, Dassisti M, Zhang Z, Hutchinson AJ, Gladwin DT, 2024. Standalone and hybridised flywheels for frequency response services: A techno-economic feasibility study. Energies, 17 (11), 2577, doi:10.3390/en17112577.
Pathak AD, Cha E, Choi W, 2024. Towards the commercialization of Li-S battery: From lab to industry. Energy Storage Materials, 72, 103711, doi:10.1016/j.ensm.2024.103711.
Powerco, 2023. Electricity asset management plan. Accessed 26 August 2026 from: https://www.powerco.co.nz/-/media/project/powerco/powerco-documents/who-we-are---pricing-and-disclosures/disclosures/electricity-disclosures/2-electricity-asset-management-plans/2023-electricity-asset-management-planpdf.pdf.
Predescu D-M, Roșu Ș-G, 2025a. Solid state transformers: A review—Part I: Stages of conversion and topologies. Technologies, 13 (2), 74, doi:10.3390/technologies13020074.
Predescu D-M, Roșu Ș-G, 2025b. Solid-state transformers: A review—Part II: Modularity and applications. Technologies, 13 (2), 50, doi:10.3390/technologies13020050.
PwC New Zealand, 2024. Electricity line business 2024 information disclosure compendium. Accessed 26 August 2026 from: https://www.pwc.co.nz/assets/2024-assets/pwc-nz-electricity-compendium-2024.pdf.
Rahman MdA, Islam MdR, Muttaqi KM, Sutanto D, 2021. Modeling, design, and control of solid-state transformer for grid integration of renewable sources. In: Emerging Power Converters for Renewable Energy and Electric Vehicles, 1-36, doi:10.1201/9781003058472-1.
Rana MM, Mo H, Shafiullah GM, Qiao L, Dong D, 2026. Optimal sizing of battery storage for cost-effective peak shaving in regional distribution networks. Journal of Energy Storage, 141, 119502, doi:10.1016/j.est.2025.119502.
Rashed Hassan Bipu M, Montes O, Teng F, Wang D, Awal MA, Yu W, Husain I, Lukic S, 2025. Design, control, and protection of a 13.2 kV, 1 MVA solid state transformer for electric vehicle extreme fast charging station. IEEE Transactions on Transportation Electrification, 11 (1), 4469-4481, doi:10.1109/TTE.2024.3462920.
Ravindran R, Massoud AM, 2025. An overview of wide and ultra wide bandgap semiconductors for next-generation power electronics applications. Microelectronic Engineering, 299, 112348, doi:10.1016/j.mee.2025.112348.
Reber D, Jarvis SR, Marshak MP, 2023. Beyond energy density: Flow battery design driven by safety and location. Energy Advances, 2 (9), 1357-1365, doi:10.1039/d3ya00208j.
Reeve D, Barton B, 2020. Low voltage monitoring primer and guideline. Accessed 26 August 2026 from: https://www.ena.org.nz/home/document/805.
Reeve D, Comendant C, Trill R, Batstone S, 2024. Potential uses of battery energy storage systems for industrial consumers: A report for EECA. Accessed 26 August 2026 from: https://www.eeca.govt.nz/assets/EECA-Resources/report-2024-potential-uses-of-battery-energy-storage-storage-systems-for-industrial-consumers.pdf.
Ren X, Jiang Y, Weng H, Long T, Xu D, 2024. Design and testing of a soft-switching solid-state transformer module. IEEE Journal of Emerging and Selected Topics in Power Electronics, 12 (6), 5977-5989, doi:10.1109/JESTPE.2024.3447455.
Rezaei F, Esmaeili S, 2024. An enhanced sensitivity-based combined control method of battery energy storage systems for voltage regulation in PV-rich residential distribution networks. IET Renewable Power Generation, 18 (14), 2641-2657, doi:10.1049/rpg2.13109.

Roger D, Napieralska-Juszczak E, Komeza K, Napieralski P, 2021. Solid-state transformers of smart high-power battery charger for electric vehicles. 2021 IEEE International Conference on Environment and Electrical Engineering and 2021 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe), doi:10.1109/EEEIC/ICPSEurope51590.2021.9584723.

Roy TK, Oo AMT, 2024. Enhancing grid frequency regulation in low inertia modern multi-area power systems using cascaded non-integer control approaches with BESS-based virtual inertia. IET Renewable Power Generation, 18 (S1), 4602-4620, doi:10.1049/rpg2.13169.

Schmaltz T, Hartmann F, Wicke T, Weymann L, Neef C, Janek J, 2023. A roadmap for solid-state batteries. Advanced Energy Materials, 13 (43), 2301886, doi:10.1002/aenm.202301886.

Schwanninger R, Stöcklein N, Weitz N, Yang X, März M, 2025. A path to configurable solid state transformers and energy routers: Introduction to modular active cell control. IEEE Transactions on Power Electronics, doi:10.1109/TPEL.2025.3621885.

Shadfar H, Ghorbani Pashakolaei M, Akbari Foroud A, 2021. Solid-state transformers: An overview of the concept, topology, and its applications in the smart grid. International Transactions on Electrical Energy Systems, 31 (9), doi:10.1002/2050-7038.12996.

Sharmoukh W, 2025. Redox flow batteries as energy storage systems: Materials, viability, and industrial applications. RSC Advances, 15 (13), 10106-10143, doi:10.1039/d5ra00296f.

Simic Z, Topic D, Dubravac M, Knezevic G, 2022. Application of battery storage in low voltage distribution network for improving integration of distributed generation. 2022 18th International Conference on the European Energy Market (EEM), doi:10.1109/EEM54602.2022.9920983.

Stathatos A, Queiroz SS, Li C, Costa LF, Fecarotti C, Papafotiou G, 2025. Assessing the benefits of redundancy in solid-state transformers: An extended total cost of ownership model. IEEE Transactions on Power Delivery, doi:10.1109/TPWRD.2025.3605723.

Sunny AC, Muttaqi KM, Sutanto D, 2025. A multioutput DC-DC converter for solid-state transformer-based fast electric vehicle charging stations with batteries of different ratings. Electric Power Systems Research, 249, 112066, doi:10.1016/j.epsr.2025.112066.

Takagi M, Fukushima K, Tagashira N, Okada K, Asano H, 2024. Cost-effectiveness analysis method for voltage stabilization in case of combining storage battery and reactive power compensator. Journal of Energy Storage, 93, 112065, doi:10.1016/j.est.2024.112065.

Thokar RA, Gupta N, Niazi KR, Swarnkar A, Meena NK, Yang J, 2024. Optimal coordinated energy management in active distribution networks considering battery energy storage and price-responsive demand. IET Generation, Transmission and Distribution, 18 (9), 1743-1756, doi:10.1049/gtd2.12989.

Transpower, 2025. System operator strategy: Key trends and issues. Accessed 26 August 2026 from: https://static.transpower.co.nz/public/bulk-upload/documents/SO%20Strategy%20initial%20engagement.pdf.

Tsareva PE, Avdeev BA, Markovkina NN, Epifantsev IR, Zhilenkov AA, 2022. Simulation of the operation of a three-phase solid-state transformer under variation of load. Russian Electrical Engineering, 93 (6), 420-423, doi:10.3103/S1068371222060086.

Unison Networks Limited, 2025. Asset management plan 2025. Accessed 26 August 2026 from: https://www.unison.co.nz/media/a3nevg2u/2025-ramp-website.pdf.

Valedsaravi S, El Aroudi A, Martínez-Salamero L, 2022. Review of solid-state transformer applications on electric vehicle DC ultra-fast charging station. Energies, 15 (15), 5602, doi:10.3390/en15155602.

Volterion GmbH & Co, 2024a. Data sheet vanadium stack. Accessed 26 August 2026 from: https://www.volterion.com/files/volterion/datasheets/Data%20Sheet_vanadiumStack_EN.pdf.

Volterion GmbH & Co, 2024b. Data sheet smart stack. Accessed 26 August 2026 from: https://www.volterion.com/files/volterion/datasheets/Data%20Sheet_smartStack_EN.pdf.

Voß P, Gruber B, Mitterfellner M, Plöpst JD, Degen F, Schmuch R, Lux S, 2025. Benchmarking state-of-the-art sodium-ion battery cells - modeling energy density and carbon footprint at the gigafactory-scale. Energy and Environmental Science, 18 (17), 8104-8129, doi:10.1039/d5ee00415b.

Wald F, Hrishikesan VM, Gomis-Bellmunt O, Ji H, Davoudi M, Bidram A, Syed M, Josevski M, Bruske S, Kumar C, Alzola RP, Colak I, Pannala S, Liserre M, De Carne G, 2025. Applications and services of solid-state transformers in active distribution networks - a critical review. IEEE Transactions on Smart Grid, 16 (5), 3615-3637, doi:10.1109/TSG.2025.3574007.

Wangmo S, Helwig A, Bell J, 2024. What energy storage technologies will Australia need as renewable energy penetration rises? Journal of Energy Storage, 95, doi:10.1016/j.est.2024.112701.

Wei J, Feng H, Ran L, 2023. Multidimensional design of DC-link for two-stage solid-state transformer cell considering second-order harmonic current distribution. IEEE Transactions on Power Electronics, 38 (8), 10244-10255, doi:10.1109/TPEL.2023.3272477.

WEL Networks, 2023. Asset management plan Mahere Whakahaere Rawa. Accessed 26 August 2026 from: https://www.wel.co.nz/media/etafw1tf/11111136-amp-web-version.pdf.

Wellington Electricity Lines Limited, 2025. Wellington Electricity 10 year asset management plan. Accessed 26 August 2026 from: https://www.welectricity.co.nz/disclosures/asset-management-plan/document/398.

Xu W, Rajendran S, Guo Z, Vetrivelan A, Huang AQ, 2023. 7.2kV/100kVA solid state transformer based on half bridge LLC resonant converter and 15kV SiC AC switch. 2023 IEEE Applied Power Electronics Conference and Exposition (APEC), 1516-1522, doi:10.1109/APEC43580.2023.10131549.

Zheng L, Marellapudi A, Chowdhury VR, Bilakanti N, Kandula RP, Saeedifard M, Grijalva S, Divan D, 2022. Solid-state transformer and hybrid transformer with integrated energy storage in active distribution grids: Technical and economic comparison, dispatch, and control. IEEE Journal of Emerging and Selected Topics in Power Electronics, 10 (4), 3771-3787, doi:10.1109/JESTPE.2022.3144361.

Zhou Y, Li J, Huang S, Wang J, Coelho S, Afonso JL, Monteiro V, 2026. An SST-based emergency power sharing architecture using a common LVDC feeder for hybrid AC/DC microgrid clusters and segmented MV distribution grids. Electronics, 15 (3), 496, doi:10.3390/electronics15030496.