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BATTERY TECHNOLOGY RESEARCH

FEASIBILITY ANALYSIS OF ELECTRIC VEHICLE BATTERY REPURPOSING FOR BATTERY ENERGY STORAGE

ENMG680: PROJECT

MASTER OF ENGINEERING IN MANAGEMENT

UNIVERSITY OF CANTERBURY

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FOR: DARC TECHNOLOGIES LTD.

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Abstract

This project reviews the battery technology landscape for energy storage and investigates the feasibility of accelerating the BESS adoption primarily in New Zealand by repurposing electric vehicle batteries. The possibilities and potential issues for recycling battery materials at the ultimate end life are also considered.

This report is submitted as partial fulfillment of the requirements for the degree of Master of Engineering Management at the University of Canterbury for 2019-2020.

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Acronyms and Abbreviations

ALC	Advanced lead carbon
BES	Battery energy storage
BESS	Battery energy storage system
C-rate	Charge/discharge rate
C&I	Commercial and industrial
DoD	Depth of discharge
EV	Electric vehicle
FC	Fuel cell
ICB	Iron chromium battery
LCO	Lithium cobalt oxide
LCOS	Levelized cost of storage
LFP	Lithium iron phosphate
Li-air	Lithium air
LIB	Lithium-ion battery
Li-ion	Lithium-ion
LiS	Lithium sulphur
LMO	lithium manganese oxide
LTO	Lithium titanate
NaS	Sodium sulphur
NCA	Lithium nickel cobalt aluminum oxide
NiCd	Nickel cadmium
NiFe	Nickel iron
NiH	Nickel hydrogen
NiMH	Nickel-metal-hydride
NiZn	Nickel-zinc
NMC	Lithium nickel manganese cobalt oxide
NPV	Net present value
P/E ratio	Power to energy ratio
PHS	Pumped hydro storage
PV	Photovoltaics
SoC	State of charge
SoH	State of health
SSB	Solid state battery
ToU	Time-of-Use
UPS	Uninterrupted power supply
VRB	Vanadium redox battery
VRE	Variable renewable energy
ZnBr	Zinc-bromine

Executive Summary

The adoption of electric vehicles (EVs) is an effective means to alleviate energy crisis and air pollution. However, the increasing number of end-of-life EV lithium-ion batteries (LIBs) poses an imminent threat to environmental sustainability due to the limitations of EV LIB recycling.

Battery energy storage systems (BESS) based on LIBs have recently witnessed vigorous growth due to their unique merits in facilitating the integration of renewable energy and strengthening power system resilience. However, the further adoption of BESS is hindered by multiple barriers including high battery costs and regulatory obstacles.

By applying various engineering management tools, such as system thinking, strategic planning and economic evaluation, this research achieves the objective of alleviating the potential environmental threats from end-of-life EV LIBs and accelerating the adoption of battery energy storage, particularly in New Zealand, through investigating the feasibility of EV LIB repurposing. The key tasks and findings of this research can be concluded as follows.

- Analyse the pros and cons of various battery chemistries for energy storage, explain the dominance of Lithium-ion (Li-ion) chemistries and identify the potential threats from substitute chemistries.

  Key findings: the dominance of LIB for BESS can be explained by its low cost due to the ramp-up of EV production and the performance flexibility achieved through a wide range of different chemistries. It is estimated that LIB will still dominate battery energy storage since no imminent threats from substitute chemistries exist.

- Analyse the landscape of battery energy storage applications. Evaluate the profitability, future prospects, market regulations and battery technical requirements for several of the most widely adopted applications.

  Key findings: While some BESS applications such as ancillary service are highly profitable, other applications including renewable integration cannot yet break even and are thus reliant on incentives. Although their market prospects vary from one another, an increasing popularity of BESS can be expected, particularly due to a foreseeable higher penetration of

variable renewable energy on the global scale. Li-ion chemistries are used widely for various BESS applications with different technical requirements. LIB-based BESS can also be flexibly sized to cater for different needs.

- Identify the barriers and enabling factors of EV battery repurposing for BESS.

  Key findings: Despite the existence of a favorable environment for EV battery repurposing on the global scale, there still exist numerous barriers from regulatory, legal, economic and technical perspectives. Nevertheless, multiple enabling factors such as non-separation of the rights and obligations of responsibility attribution, advanced battery testing and management technologies, collaboration with third parties who have market resources and stable client relations can be identified and are chosen by repurposing facilities according to their own circumstances.

- Provide a feasible solution for EV battery repurposing in New Zealand through economic analyses that focus on both the operation of a repurposing facility and the profitability of second-use BESS under certain usage scenarios.

  Key findings: The operation of a repurposing facility is economically feasible when selecting Nissan Leaf Gen.1 batteries for repurposing. The second-use BESS based on these repurposed batteries may possess price advantage over first-use BESS if the extra costs besides the battery can be well-controlled. However, when applying second-use BESS for load-shifting applications, Cost recovery within 10 years is still unachievable under conventional tariff structures for both household and C&I users. Therefore, besides efforts focusing on BESS technology improvement and price reduction, closer attention should also be paid to the identification of suitable applications.

Finally, it is concluded that the New Zealand-based high-tech companies should actively participate in EV battery repurposing for stationary use, as it contributes to environmental sustainability, facilitates the adoption of BESS and offers unique opportunities from a business perspective.

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1. Introduction

1.1 The Global Landscape of Battery Energy Storage

Although the global energy storage market is still dominated by pumped hydro storage (PHS), the electrochemical technology, also known as battery energy storage (BES), has enjoyed a rapid growth from an accumulated market share of 1.1% in 2016 to 4.1% in mid-2019, with a total installed capacity of 7.43 gigawatts (Fig.1).

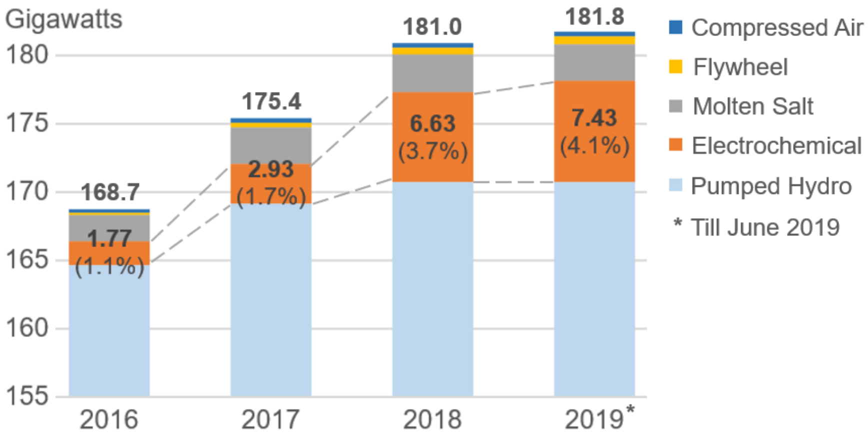


Figure 1: Accumulated global energy storage capacity by technology

Source: adapted from [1] [2] [3] [4]

The increasing popularity of BESS is driven by multiple factors. In comparison to other technologies, BESS has better flexibility, can be deployed quickly, leaves smaller footprints and enjoys fast falling costs. Its performance has also been constantly improved due to evolving technologies. Besides, it is suitable for multiple applications, especially those that can contribute to renewable energy adoption and grid modernization. Therefore, BESS is generally regarded as one of the key technologies for the global shift towards low-carbon and resilient power systems [5].

1.2 Battery Energy Storage in New Zealand

In New Zealand, applications of BESS are relatively limited. On the one hand, batteries are still expensive despite rapidly falling costs. On the other hand, New Zealand has a unique energy structure with renewable sources (hydro in particular) account for an overwhelming large portion of the electricity generation. The dominance of hydroelectricity, together with battery's high cost, poses the following obstacles for BESS adoption in New Zealand [6]:

- **Lower value of ancillary service**: procurement costs for ancillary services (largely from hydro generators) have decreased drastically.
- **Limited potential for renewable integration**: no policy incentives to promote the development of variable renewable energy (VRE) sources such as wind and solar.

- **Lower value of energy arbitrage**: flexible hydro generation reduces the volatility of electricity prices.

As a result, although BESS could contribute to New Zealand's goal of achieving 100% renewable generation in 2035 and increasing the resilience of its power systems, it is not yet economic for most applications [6]. In fact, besides a low level of residential uptake typically alongside PV generation and a limited number of utility-scale pilot projects [7], BESS hasn't enjoyed widespread adoption in New Zealand.

1.3 EV Battery Disposal in New Zealand

In New Zealand, EV registrations have experienced exponential growth from 235 in 2013 to 18,186 in 2019. It is expected that 64,000 EVs will be on the road by 2021 [8]. As EVs gain popularity, the disposal of end-of-life EV LIBs becomes an important issue. Firstly, the disposal of LIBs adopted by most EVs are complicated and cost-ineffective. Besides, the below listed New Zealand-specific features may further increase the possibility that EV LIBs are improperly disposed of.

- **Used EVs account for more than 60% of all the EVs** [8]. More batteries will come to the end-life earlier, with an imminent need of disposal [9] [10]. Limited warranties for used EVs also means defective or end-of-life batteries may not be collected and properly handled by authorized vehicle dealers.
- **No specific legislation for the disposal of EV batteries**. In comparison, some countries such as China have established regulations that urge EV or battery manufacturers to bear the main responsibilities for EV battery disposal [11].
- **Nascent stage of EV battery recycling**. Lack of economies of scale and New Zealand's geographic isolation (for batteries that are exported [12]) means EV battery recycling is not yet economic and battery owners bear a disposal cost in most cases.

Currently, less than 1% of the LIBs are being recycled in New Zealand [12]. This may not be a severe issue while the number of batteries is small, however, as over 80,000 EV batteries are estimated to come to the end-life in 2030 [13], the negative environmental impacts will be enormous if these batteries are improperly disposed of.

1.4 Project Objective

While the dominance of used EVs, the loose regulatory environment and the nascent stage of EV LIB recycling have brought environmental concerns, they could also facilitate the participation in EV battery repurposing by New Zealand-based companies through the below-listed facts.

- EVs will come to their end life earlier with more batteries being collectable sooner [13].
- No market access barriers.
- Possibility to collect batteries at low prices, for free or even get paid.

Besides good business opportunities, EV battery repurposing will also contribute to environmental sustainability and promote the adoption of BESS. This report aims to investigate the feasibility of EV battery repurposing in New Zealand and it is broken down into the following steps.

- Identification of battery chemistries that are suitable for BESS.
- Identification of energy storage applications which are suitable for BESS utilising repurposed EV batteries.
- Identification of the barriers and enabling factors of EV battery repurposing.
- Economic analysis of EV battery repurposing in New Zealand.
- Case studies of second-use BESS applications based on repurposed EV batteries under several New Zealand-specific usage scenarios.

2. Suitable Battery Chemistries for Battery Energy Storage

In this chapter, the criteria for selecting the suitable battery chemistries, particularly for BESS, are introduced. Through the understanding of the technical landscape of battery chemistries, the major considerations for selecting the battery chemistry for BESS, whether the EV battery chemistries are suitable for BESS and whether they are likely to be challenged by other chemistries in the short and long term can be clarified.

2.1 Criteria for Selecting Battery Energy Storage Chemistry

Energy density describes the energy stored per unit mass or volume. It is a key factor for EVs, since the installation space is limited and the driving range can only be effectively extended through the increase of battery energy density. Although BESS is less sensitive to energy density in general, it can also be an important factor where installation space is expensive or restricted.

Power to energy ratio (P/E ratio) describes the duration that the battery can operate while injecting or absorbing energy at the rated power. This criterion can also be described through charge/discharge rate (C-rate). P/E ratio is prioritized differently for different BESS applications. Generally, “load shifting” applications require the battery to be discharged over several hours while “variability-damping” applications require higher power to be absorbed or injected in minutes or seconds [14].

Response time indicates how quickly a battery can respond to the need of power injection or absorption. A short response time is crucial for EVs as acceleration needs to be implemented instantaneously. For BESS however, while a fast response is required by “variability-damping” applications, slower response times are tolerated by others such as “load-shifting” [14].

Round-trip efficiency describes the ratio of energy output to input during a storage cycle. While DC efficiency deals with the energy losses within the battery, AC efficiency also considers the energy losses during power conversion and is thus frequently used for grid-connected BESS. Besides, the parasitic loads including battery monitoring, cooling and heating should also be considered during BESS design and selection. Round-trip efficiency is an important economic indicator especially when BESS are frequently cycled.

Operating temperature: while some batteries function properly over a wide temperature range, for others the operating temperature must be well-controlled in a narrower range to ensure battery performance, health and safety. There are also high-temperature batteries which operate at over 300°C and this presents difficulties for some applications such as EVs or household BESS. Operating temperature should be considered especially according to the geographic location of the BESS. Temperature-robust chemistries are better suited for extreme environments, otherwise more rigid requirements for battery heating and ventilation will be essential, and extra energy will be required as parasitic loads during battery temperature control. In comparison to EV batteries, optimized temperature control for BESS is more achievable as there are less weight and size constraints [15].

Battery management: different chemistries require varying degrees of management. Some chemistries cannot tolerate over-charge/discharge or overcurrent, while others are more robust. For some chemistries, the voltage level among different battery cells needs to be balanced during charging, while the cell voltage of other chemistries can be self-equalized [16]. Some chemistries are more sensitive to ambient temperature, so thermal management is essential to provide heating/cooling or to cut off the battery under extreme temperatures. Battery management is also used to estimate the battery state of charge (SoC) and state of health (SoH). The estimation can be difficult for chemistries with flat charge/discharge curves, and more sophisticated algorithms are required.

Cycle life is the number of complete charge/discharge cycles, i.e. at 0%-100% depth of discharge (DoD), that a battery can perform at rated power output/input (i.e. 1C) before the usable capacity falls under 80% of its original capacity. The actual cycle life differs from the standard definition and is influenced by both the actual charge/discharge rate and the DoD range. In general, cycle life is prolonged with lower C-rate and narrower DoD range [17]. Besides, the sensitivity level also differs among not only different chemistries, but also the same chemistries by different battery manufacturers [18]. EV LIBs are exposed to harsher operating conditions due to a rapid fluctuating discharge rate, which is dependent on the driver's ever-changing demands for acceleration and deceleration [15]. Therefore, in some EV applications, batteries are operated under narrower DoD range and lower C-rates through the adoption of a "super-sized" battery pack to prolong cycle life [19] [20]. Although the energy demand for BESS fluctuates less [15], the C-rate and DoD range should still be carefully determined based on battery chemistry, load profile and the pre-planned lifespan for a cost-effective sizing of the BESS.

Safety is another major criterion for chemistry selection. While some chemistries are inflammable and non-toxic in nature, others are corrosive, explosive and prone to catastrophic failures such as thermal runway. For the latter, the onset temperature of thermal runway also differs between different chemistries. Fire explosion accidents have occasionally occurred on both EV and BESS. Therefore, closer attention should be paid to choose safer chemistries and design resilient battery monitoring systems.

Cost is the major indicator for profitability. Besides a huge variance of the battery cost itself, the additional costs for the BESS construction besides the battery also vary significantly according to the chemistry selection and the system configuration (e.g. C-rate) [21]. While initial construction cost is important, round-trip efficiency, cycle life and other factors should also be considered for a complete economic estimation throughout the BESS lifespan. This can be estimated based on the calculation of net present value (NPV) or levelized cost of storage (LCOS) throughout the project lifecycle.

2.2 Lithium-ion Batteries

As revealed in Fig.2, the recent popularity of BESS is mainly due to the rapid expansion of LIB. In 2018, LIB accounted for 86% of the accumulated BESS capacity globally. At 5.72 gigawatts, its installed capacity has almost quintupled over the previous three years.

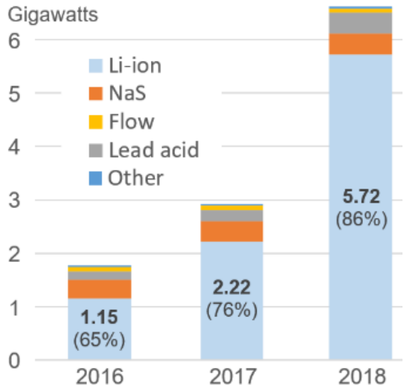


Figure 2: Accumulated global battery energy storage capacity by chemistry
Source: adapted from [1] [2] [3]

The increasing share of LIB has been largely driven by declining costs, which is in turn mainly due to the ramp-up of EV production. It is estimated that EVs will account for 70% of all the rechargeable battery demand in 2020 [22]. In addition to price, the dominance of LIB for BESS can also be justified by high energy density, high round-trip efficiency, rapid response and the performance flexibility achieved through a wide range of different chemistries.

Lithium cobalt oxide (LCO) was widely used in personal electronics due to its high energy density. However, its low P/E ratio, poor thermal stability and high cost due to high cobalt content have strictly limited its application for EV and BESS. Its development perspectives are also limited [23]

Compared with LCO, **lithium manganese oxide (LMO)** has improved thermal stability and P/E ratio, but lower energy density and cycle life [24]. These drawbacks can be compensated by blending LMO with other chemistries [24]. The blended chemistry was adopted by some old versions of EVs such as Nissan Leaf Gen.1 and Mitsubishi Outlander PHEV. Although no examples of commercial BESS with first-use LMO have been found, their suitability is evident from multiple repurposing cases [25].

Lithium nickel cobalt aluminum oxide (NCA) has the highest energy density among currently available Li-ion chemistries and a high P/E ratio. It is therefore favoured by some EV manufacturers such as Tesla. Despite its low thermal stability and limited cycle life, especially at higher discharge rates (e.g. 2C-3C) [26], a long lifespan and high safety fitted for EV can still be achieved through advanced battery management and a “super-sized” pack operating under narrower DoD range and lower C-rates [19] [20]. However, such oversized systems may not be economically applied for BESS and is thus not chosen by Tesla for its Powerpack and Powerwall [27] [28]. As far as the author knows, NCA is seldom used for BESS and no repurposing cases have been reported.

Lithium nickel manganese cobalt oxide (NMC) achieves a balanced performance by combining the merits of nickel (high energy density) and manganese (high thermal stability and P/E ratio). The chemical contents can also be mixed flexibly to meet the needs of different applications requiring high energy or power [24]. Hence, NMC is currently the most widely used Li-ion chemistry for both EV and BESS and is selected by BESS manufacturers including Tesla, Samsung and LG. NMC repurposing case studies for BESS are also frequently reported. To prolong the driving range by increasing the energy density, NMC for EV has evolved towards chemistries with a higher nickel content, with the latest being NMC811 (nickel, manganese and cobalt in a ratio of 8:1:1). However, this comes at the price of shorter cycle life and lower thermal stability [29] and could make future EV NMC chemistries less suitable for BESS repurposing.

Lithium iron phosphate (LFP) has lower energy density compared with cobalt-blended chemistries and is seldom applied by passenger EV. Its higher self-discharge and flat voltage curve also pose challenges for battery management in terms of cell balancing and SoC/SoH estimation [24] [30]. However, due to its longer cycle life, higher safety and lower prices, it is widely adopted by electric buses and BESS, with manufacturers including BYD, CATL, Sony and Sonnen for the latter. Its application prospects for BESS could be further enhanced due to recent development efforts focusing on increasing the energy density [31].

Lithium titanate (LTO) has excellent performance in terms of cycle life, safety and P/E ratio. Its extreme temperature performance is also superior to all other Li-ion chemistries. However, it has restricted applications due to its low energy density and high cost. Nevertheless, Toshiba uses LTO for its commercial BESS offering. LTO has also been adopted by some early EVs including the Honda Fit Gen.1 which may provide repurposing opportunities.

Besides chemistry, battery cell format is another important LIB selection criterion for both EV and BESS.

Cylindrical cell formats are the most mature battery format in terms of standardization and automation. Stability at battery pack level can thus be better guaranteed based on higher consistency of the cells. Due to their smaller cell size, the energy released during thermal runway is also smaller and can be better controlled. This contributes to higher safety over other cell formats. Although cylindrical cells are less ideal in terms of space utilization due to the resultant air cavities when cells are placed side-by-side, this can be compensated for by its higher cell energy density. The empty space between the cells can also be used to improve ventilation and stop fire propagation [32]. However, the smaller energy amount per cell also means a larger number of cells are needed within a battery pack. This raises higher requirements for battery management. Cylindrical cells are used by manufacturers including Tesla and Sony for BESS.

Prismatic cells can be designed flexibly but the manufacture cost is higher due to less product standardization. It has improved space utilization with a larger cell size in a rectangular shape. However, larger cells and higher space utilization also means larger amounts of energy are released and quickly propagated during thermal runaway. This could be mitigated through its metal enclosure combined with extra protection mechanisms (e.g. Samsung's "nail safety device" and "overcharge safety device"). Prismatic cells have been widely adopted by BESS manufacturers including Samsung, Toshiba, CATL, BYD and others. EV battery second-use for BESS based on prismatic cells can also be found, such as the repurposing of the Mitsubishi Outlander PHEV and Honda Fit Gen.1 batteries.

Pouch cells can achieve the highest design flexibly, space utilization and pack level energy density by eliminating the metal enclosure. It has similar drawbacks to prismatic cells, including higher cost due to unstandardized production and extra measures to ensure safety. Pouch cells have been adopted by LG for its BESS products. End-of-life EV pouch cells are also repurposed for energy storage by various vehicle manufacturers including Nissan, Daimler, GM and Hyundai.

To summarize, all the above-mentioned cell formats have both advantages and disadvantages, and are widely applied by EV and BESS (including both first-use and second-use of repurposed EV LIBs).

2.3 Other Established Battery Chemistries

Compared with the EV market, which is dominant by LIB, BESS has a relatively diversified landscape in terms of battery chemistries. Although the market share of non-lithium-ion chemistries are shrinking

(Fig.2), the prospects of LIB and its repurposing for BESS should still be evaluated through the identification of the pros/cons and the development trends of alternative chemistries.

Sodium Sulphur (NaS) is one of the high-temperature batteries (the other less popular one being sodium metal halide, or “Zebra”). As revealed by the name, it has the major drawback of requiring a high operating temperature (above 300 °C) and a long time (2-4 days) for the battery to be cooled down and reheated [33]. This has greatly restricted its application and it is only economically viable for large scale systems with high utilization rates [34]. NaS is also prone to safety risks due to the corrosive and explosive nature of the sodium compounds [35]. Nevertheless, due to its cost-effectiveness achieved through low raw material cost, high round-trip efficiency, long life-cycle and other merits such as high energy density and rapid response, NaS is still commercially adopted by BESS providers such as NGK and is especially suited for long-duration applications. Current development efforts include upgrading the membrane material [36] and reducing the operating temperature [37] may further widen its application prospects.

Flow battery is a generic term for various chemistries including iron-chromium (ICB), zinc-bromine (ZnBr) and vanadium redox battery (VRB), with the latter being the more widely adopted. Flow batteries differ from conventional rechargeable batteries in that the chemical reactants are stored in external reservoirs and pumped through the cells during operation [22]. This brings one key advantage that the power and energy requirements are decoupled, which facilitates an optimal system sizing [34]. Although flow batteries have lower round-trip efficiencies, this can be compensated by their near unlimited cycle life at full DoD range to ensure cost-effectiveness [34]. VRB is particularly favoured due to its safety and cost-effectiveness, since Vanadium is non-flammable, abundant and easily recyclable [38]. However, the low energy density and extra facilities needed (e.g. storage tanks, pumps) suggest that flow batteries have larger footprints and are better suited for large industrial applications with long storage durations (> 3 hours) [34], although smaller-scale applications are also reported [38]. VRBs are commercially developed by BESS providers including Prudent [39] and Bushveld [38] and its market share might be further broadened if efforts to achieve economies of scale [40] and higher energy density [41] are successful.

Conventional lead-based batteries include flooded and sealed types. They are basically made up of similar chemistries that are tailored to cater for various applications including vehicle ignition and uninterrupted power supply (UPS). These batteries, especially the sealed types, possess multiple merits including good extreme-temperature performance, good safety, low price, free of maintenance, high discharge rate and good recyclability. However, disadvantages such as low energy density, narrow usable DoD range, low charge rate and the need to be fully charged periodically make them ill-suited for BESS applications [42]. Nevertheless, conventional lead-based batteries were adopted by some early BESS due to their cost-effectiveness, although the usable DoD range is very restricted (e.g. 80%-100% DoD) to ensure the designed lifespan [43].

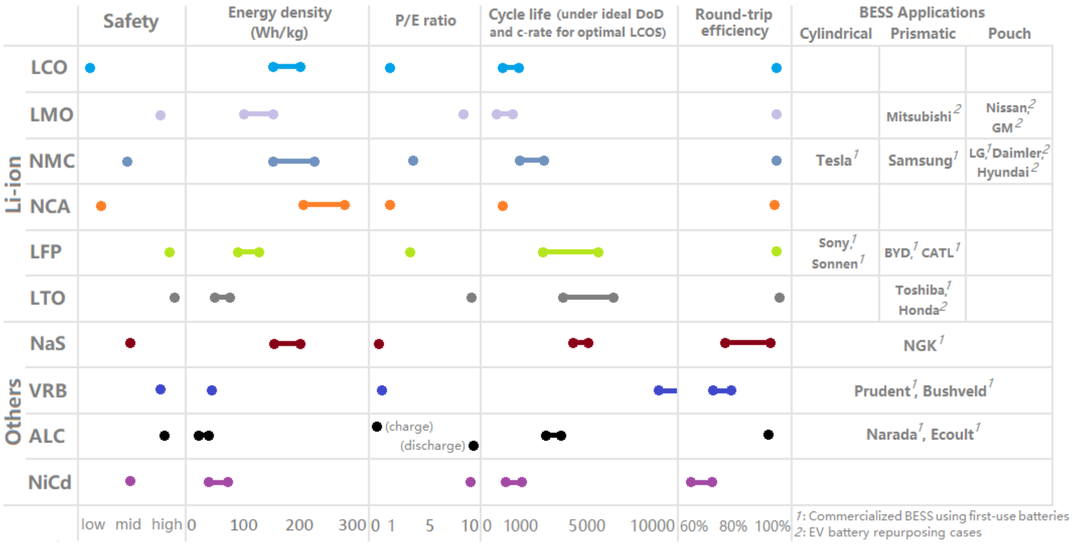
An improved version of lead-based chemistries, known as **advanced lead carbon (ALC)** was developed by adding carbon additives. Although this results in slightly reduced energy density, the charge duration and usable DoD range are significantly improved [44]. The advantages of conventional lead-acid are also inherited. Therefore, ALC is commercially applied by BESS suppliers including Narada and Ecoult for applications with storage durations of 1 to 4 hours [43] [45]. Currently, the adoption of ALC faces obstacles including cost (its average LCOS is still higher than LIB for most applications [22]) and concerns about its cycle life under wide DoD ranges [46].Its applications could be broadened with economies of scale [47] and verified lifecycle performance.

Nickel-based batteries come with different chemistries including nickel-cadmium (NiCd), nickel-metal-hydride (NiMH), nickel-iron (NiFe), nickel-zinc (NiZn) and nickel-hydrogen (NiH). Only NiCd and NiFe have been applied for utility-scale BESS, with the former being more popular [48]. NiCd possesses the advantage of high P/E ratio with the ability of ultra-fast charging in 10-15 minutes and discharging up to 10C for short periods [49]. It also has others merits including long cycle life under a wide usable DoD range, good low-temperature performance, simple implementation without complex management systems and cost-effectiveness in terms of LCOS [34] [50]. However, due to its low energy density, low round-trip efficiency, the memory effect and especially the environmental concerns over the toxicity of Cadmium [34] [48], NiCd has only been used in a limited number of earlier demonstration BESS projects [50] and has limited prospects.

Table 1 provides a visual comparison of the battery chemistries described above. The BESS applications, including commercialized products using first-use LIB and EV LIB repurposing cases are also listed. For Li-ion chemistries, the applications are further classified according to their cell formats. The popularity of LIB can be seen through the performance flexibility and the abundance of BESS providers. Its suitability for repurposing is also evident from multiple cases.

Table 1: Technical comparison and BESS applications of the established battery chemistries

Source: adapted from Appendix A



2.4 Emerging Battery Chemistries

Besides the established battery chemistries, emerging chemistries should also be considered in order to identify and assess their potential impacts on repurposing LIB for energy storage.

Solid state batteries (SSB) adopt solid or semi-solid electrolytes instead of liquid materials to achieve higher levels of energy density and safety. However, non-liquid electrolytes also bring inherent drawbacks such as lower ionic conductivity and higher interface impedance. This presents obstacles for the achievement of ideal cycle life and P/E ratio. To tackle these issues, numerous established companies and startups (e.g. Toyota, CATL, BYD, Solid Power, Prologium and Ganfeng Lithium) have developed different electrolyte chemistries including polymer, inorganic oxide and inorganic sulfide, with promising results. For example, a cell energy density of 240Wh/kg with 90% capacity retention after 1000 cycles is achieved by Ganfeng Lithium and it is estimated that the energy density can be further increased to 500Wh/kg by 2025-2030 [51]. Meanwhile, prototype EV adopting SSB has also been demonstrated by Enovate [52]. Although SSB is generally regarded as the most promising emerging chemistry in the short term, it is still uncertain whether economies of scale can be promptly achieved to decrease the cost and make it commercially competitive against LIB.

Lithium sulphur batteries (LiS) have a practical achievable energy density of 600Wh/kg, which is 2-3 times higher than the currently available Li-ion chemistries. They also possess other advantages over Li-ion such as the abundance and environmental friendliness of Sulphur, a full usable DoD range and the ability to be stored at 0% SoC without degradation. However, LiS also suffers from multiple complex degradation mechanisms which lead to short cycle life, low P/E ratio and safety concerns [53]. Although

LiS is near commercialization due to the improvement efforts by OXIS, its cycle life is still limited and is unlikely to be significantly improved within the coming years [54]. This indicates that while it could be suitable for certain applications such as aviation, its prospects for BESS might be limited.

Lithium air batteries (Li-air) belong to the metal-air technologies and have the most attractive feature of very high theoretical energy density up to 3,460Wh/kg. However, its practical application still faces major hurdles including low cycle life (e.g. 90 cycles) and low round-trip efficiency (e.g. 50%) due to the low reaction efficiency and multiple uncontrollable side-reactions between lithium and the airborne chemicals [34] [55]. Therefore, although Li-air has a high potential contribution to the storage of renewable generation [56], its application is still unclear for the foreseeable future.

While batteries have separate charge / discharge cycles and can only deliver previously stored energy in a short time span of hours, **fuel cells (FCs)** have the advantage that electricity can be continuously produced as long as fuel is available. FCs can also be refueled during operation with a separately-placed tank [57]. This makes FCs ideal for bulk energy storage and other applications that require a continuous discharge up to months. FC also possesses other merits including environmental-friendliness (hydrogen can be generated and consumed without carbon footprint), high energy density and ease of transportation when hydrogen is compressed. Therefore, FC is regarded as the key technology to leverage New Zealand's advantage in renewable generation not only by maximizing self-consumption through the damping of seasonal/yearly fluctuation, but also by delivering extra revenue through energy export [58]. However, the wide adoption of FCs still faces obstacles such as a costly and underdeveloped infrastructure for hydrogen transportation / storage, low energy conversion efficiency and safety concerns [58] [59]. Despite multiple efforts to tackle these issues (e.g. through the increase of conversion efficiency [60]), the inherent character of FC still makes it unsuitable for short duration applications, especially those that require constantly switching between power injection and absorption. Therefore, although FC could bring new opportunities, it is unlikely to compete directly with the current BESS technologies.

Based on analysis of the emerging chemistries, it is revealed that they are still in the development stage, with different maturity levels. Some of the chemistries are also mainly targeted for other applications such as aviation and bulk energy storage. Besides, whether economies of scale can be achieved brings another uncertainty for their popularization. Therefore, it can be concluded that the emerging chemistries pose little threat to LIB and its repurposing for BESS, at least in the short term.

3. Battery Energy Storage Applications

Energy storage applications can be classified in multiple ways based on different perspectives. They can be broadly classified into three groups, i.e. on-grid, behind-the-meter and off-grid services [61]. The grid services can be further divided into several categories across the generation, transmission and distribution of electricity [14]. They can also be classified according to the frequency and duration of the applications [48]. Another classifying method based on discharge duration and power requirement [62] is more suited for the selection of BESS, and is thus adopted by this report. As shown in Fig.3, besides discharge duration and power requirement, other criteria are also taken into consideration, such as whether an application is applied for “variability-damping” or “load shifting”, whether it is deployed “behind the meter” or “on-grid”, and whether it is associated with renewable generation. The purpose of this chapter is to describe the working principle, evaluate the profitability, market accessibility and future trends of the most widely adopted BESS applications (i.e. applications highlighted in Fig.3 in colours). The battery operational requirements for these applications are also identified, which provide basis for the choice of suitable chemistries.

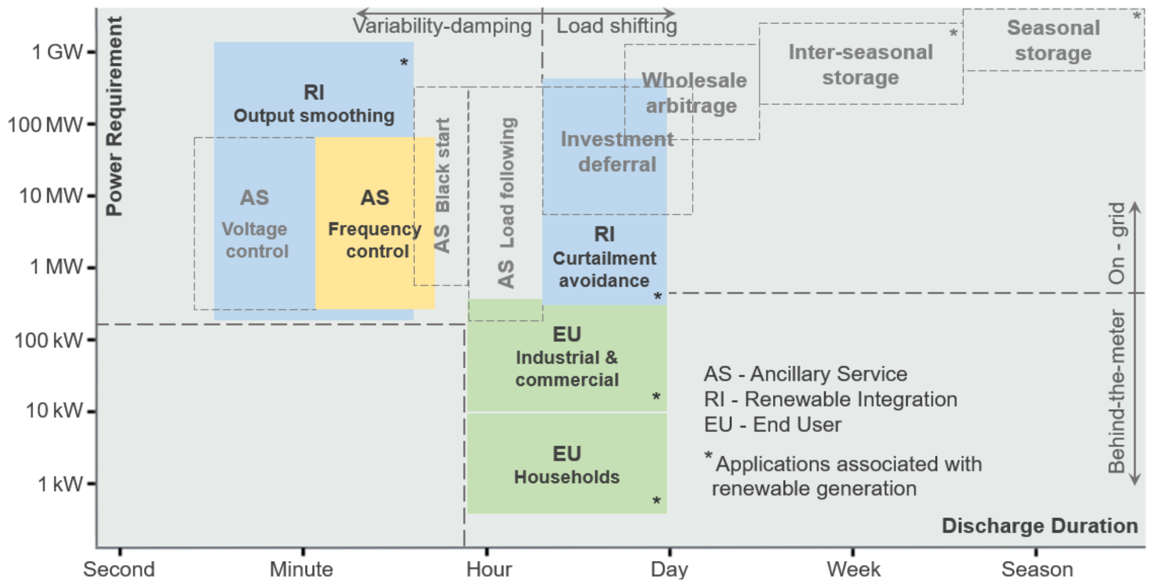


Figure 3: BESS applications

Source: adapted from [62]

3.1 Ancillary Service - Frequency Control

Ancillary service is a general term for a variety of applications including frequency control, voltage control, black start and load following. Frequency control is by far the most prevalent ancillary service utilizing BESS, as it accounted for 50% of all the global BESS capacities in mid-2017 [63]. By injecting or absorbing power from the grid, the frequency fluctuation can be effectively regulated through the alleviation of power demand / supply imbalance. This provides a vital tool to stabilize the grid. According to its working principle, frequency control can be classified as an “on-grid” application providing “variability-damping” service.

BESS is particularly favoured by frequency control due to its unmatched advantage in response speed and accuracy over traditional service providers such as thermal and hydro generators [64]. As power can be injected and absorbed in milliseconds, power blackout and load shedding can be effectively avoided [65]. The introduction of BESS into the frequency control market also intensifies competition and results in a drastic cost decrease [65]. However, even with reduced cost, the frequency control market is still lucrative, especially under favorable price structures such as availability fees [66] or a price slope that encourages quicker response [67]. For example, roughly 90% of the record-high monthly revenue in September 2019 of the Hornsdale Power Reserve BESS in Australia was generated through frequency control [68]. In other markets such as the California Independent System Operator (CAISO), BESS owners can also quickly recover their initial capital investment by providing this service [69].

The adoption of BESS for frequency control depends greatly on market accessibility, which varies among different regions. Market access for BESS can be improved not only by offering incentives [70], but more importantly through clear regulations which acknowledge BESS as a service provider [71], define the minimum capacity required [65] [71], or provide special technical requirements that allow certain degrees of operation freedom for BESS [70]. Despite foreseeable saturation in some markets, the further adoption of the VRE sources may aggravate frequency fluctuation, thus consolidating BESS’s role as a frequency control provider [69].

Although the participation of BESS in the electricity market is encouraged in New Zealand [72], no incentive exists and a clear regulation for BESS providing frequency control is yet to be established. Moreover, due to the dominance of flexible hydro generation, the procurement costs for ancillary services have been greatly decreased [6]. A limited potential revenue could pose a further obstacle to the adoption of BESS for frequency control in New Zealand.

In general, BESS operates at low C-rates within a narrow DoD range when providing frequency control. Analysis revealed that a BESS with a capacity of 1MW/1.2MWh (P/E ratio=0.83) is mostly operated at C-rates below C/5. The SoC is also normally distributed around 50%, with a narrow DoD range rarely exceeding 35%-65% [70]. As shown in Fig.4, BESS for frequency control in Germany are configured at lower P/E ratios due to the requirement that BESS should be able to provide the prequalified power for both charge and discharge for at least 30 minutes [70]. In comparison, the majority of frequency control BESS applied globally are configured with higher P/E ratios above 2. Despite higher P/E ratios, the near normal distribution of C-rate and SoC around 0C and 50% still indicates that deep cycle and high C-rate are not required by frequency control. This facilitates a prolonged battery lifespan. With less degradation concerns, frequency control is not only suited for various Li-ion chemistries including NMC, LFP, LTO in first-use (Fig.4), but also for repurposed EV LIBs [73]. Frequency control can even facilitate the maintenance of new EV LIB spare parts [73]. Although other non-lithium-ion chemistries such as NaS can also provide frequency control due to their fast response [74] [75], the low P/E ratio of these chemistries will result in an over-sized and thus uneconomic system configuration.

3.2 Renewable Integration - Output Smoothing and Curtailment Avoidance

VRE generation suffers from variability due to the fluctuating nature of the power sources (e.g. wind strength fluctuates and clouds pass over solar panels). By injecting or absorbing power on a real time basis, BESS can provide an output smoothing service to smooth the power output and control the ramp rate of the VRE sources [75]. Therefore, BESS can facilitate a better integration of the VRE sources to the grid by effectively reducing the variability of their generation. Similar to frequency control, output smoothing can also be categorized as a “on-grid”, “variability-damping” application.

Besides fluctuations on a real-time basis, the power output level of VRE generation is also uncontrollable on a longer time-scale. This may cause curtailment when excess generation cannot be transported to the grid due to grid constraints, especially during periods of low demand [75]. By storing excess electricity which can be released to the grid when congestion is relieved, BESS can effectively reduce or avoid VRE curtailment by providing “on-grid”, “load-shifting” application.

Despite a rapid growth of installed capacity in recent years [2] [76], analysis reveals that the accumulated earnings throughout BESS lifespan can barely cover its initial installation costs [77]. This indicates that a successful business model is yet to be developed, and most of the existing BESS projects for renewable integration are in the demonstration phase and thus are reliant on incentives [77].

In New Zealand, the adoption of BESS for renewable integration faces further obstacles. Due to the already existing large base of renewables (i.e. hydroelectricity), no incentive exists to encourage VRE installations [6]. There is also little prospect of BESS adoption for grid-scale solar generation, at least in the short term, since solar only represents less than 1% of the total electricity generation and 95% of the capacity is located at business sites or homes [6]. Although wind generation has a larger share of the generation capacity and is mostly deployed on-grid [6], other technologies including hydro generation, improved wind turbine design and wind speed forecasting are preferred for the alleviation of wind generation fluctuation [78]. Nevertheless, analysis revealed that BESS could have the advantage of a lower life-cycle cost than other technologies such as combustion turbine and pumped hydro for renewable integration [79]. A relatively small-scale BESS for wind integration was also already adopted by Dominion Salt [80]. As New Zealand strives to increase the VRE penetration, and as battery price steadily decreases, the adoption of BESS for renewable integration might be broadened.

As a “variability-damping” application, output smoothing can be performed by BESS configured at high P/E ratios up to 2.5 [75]. In comparison, curtailment avoidance, which is “load shifting” by nature, is generally provided by BESS configured at lower P/E ratios. This allows excess energy to be stored and released over a time span of several hours [75]. As two closely associated aspects of renewable integration, both output smoothing and curtailment avoidance are normally performed within the same system. This can be achieved through a hybrid system utilising different chemistries for different applications [77] or through a single low P/E ratio system providing both applications [74] [75] [80], with the latter being more prevalent. As shown in Fig.4, the majority of BESS for renewable integration are configured at P/E ratios lower than 0.5. Similar to frequency control, Li-ion chemistries also currently dominate renewable integration [2], though the adoption of other chemistries including ALC, NaS, VRB and NiCd can also be found. To the author’s knowledge, no cases of EV battery repurposing for renewable integration have been reported.

3.3 End-User Bill Management

Besides on-grid applications, BESS can also be applied behind-the-meter for end-users to reduce their electricity bills. This can generally be realized in two ways, namely through load shifting under flexible price structures (e.g. time-of-use (ToU) rates, demand charges) and load shifting to increase the self-consumption of VRE generation.

ToU is a rate structure by which the electricity price is charged based on the time it is consumed. It can be applied to both households and commercial and industrial (C&I) end-users. Under ToU tariffs, BESS can be applied to store electricity when the price is low during off-peak times. The stored electricity can then be injected from BESS to power the electric appliances at peak hours, thus reducing the import of expensive electricity from the grid. Besides ToU pricing, C&I end-users that consume a large amount of electricity are also subject to demand charges, which can comprise a significant portion of the electricity bills [81]. Demand charges are based on the maximum power drawn from the grid. To reduce demand charges, end-users can use BESS to store electricity when electrical load is low. The stored electricity can then be used at times of high electrical load, thus reducing the maximum power drawn from the grid.

For household and C&I end-users equipped with photovoltaics (PV) or other VRE generation systems, BESS can also be used to increase VRE self-consumption by storing excess electricity at times of peak generation which cannot be immediately consumed. It is worth noting that, the classification between VRE self-consumption increase for end-users and on-grid renewable integration can be rather ambiguous, especially for some large C&I sites, as both applications are based on similar working principles and no clear distinction between end-users and generators exists (e.g. end-users can generate electricity and sell it back to the grid, while generators may also consume the energy generated by themselves. The case of Dominion Salt provides a good example [80]).

Load shifting under flexible price and for VRE self-consumption increase not only benefits the end-users by reducing the amount of electricity purchased from the grid, but also helps to alleviate the load of power network and thus defer infrastructure upgrade, especially through the reduction of peak power. Therefore, this application is also encouraged by distributors delivering power to fast-growing regions [82].

Similar to renewables integration, behind-the-meter BESS also enjoyed huge growth on a global scale [76]. It is estimated that BESS located with PV generation behind the meter will enjoy the fastest growth, accounting for over 60% of the global cumulative energy storage deployment by 2024 [83].

In New Zealand, the adoption of BESS for behind-the-meter applications also possesses huge potential. Firstly, it is analysed that BESS will offer greater value when placed near end-users. Accordingly, various services can be provided not only for BESS owners, but also upstream to the whole network [6]. Secondly, due to its cost-ineffectiveness, BESS is currently not recommended for household PV systems by some installers in New Zealand [84]. However, with an exponential growth of household PV installation in the past several years [85], New Zealand may follow the global trend to adopt “PV + battery storage” when it becomes economic due to steadily declining battery costs.

Despite its cost-ineffectiveness, BESS for behind-the-meter applications is still being commercially exploited globally due to its unique value as UPS for contingencies. There are numerous manufacturers providing BESS with LFP, NMC and other non-lithium-ion chemistries including Lead-acid and VRB. The energy capacity is normally small, which ranges from several kilowatt-hours to several tens of kilowatt-hours, except for some large-scale C&I applications. The BESS P/E ratio is also lower than 0.5 for most applications, thus allowing the battery to be discharged continuously over several hours (Fig.4). Although the landscape of BESS for behind-the-meter applications is more diversified among different battery chemistries, Li-ion still plays a dominant role with a 70% share of the capacity additions in 2017 [2]. Besides a wide adoption of first-use batteries, repurposed EV LIBs are also frequently applied for behind-the-meter applications, with “4R Energy” being a typical example. BESS equipped with second-use Nissan Leaf Gen.1 batteries are commercialized by “4R Energy” for household applications and are sold in the Japanese market at a high price of roughly $34,000 NZD, which is at the same price level of BESS adopting first-use batteries [86]. The “4R Energy” case provides evidence that EV battery repurposing could be profitable and it will be analysed in detail in the next chapter.

3.4 Other Applications

There are also applications including the non-frequency control ancillary services, investment deferral, energy arbitrage, microgrid and seasonal/inter-seasonal storage, which are not discussed in detail. This is not only due to the length limitation of this report, but also because of their limited market prospects on a global scale (e.g. ancillary services including voltage control and black start), the special market condition in New Zealand (e.g. low value in energy arbitrage), the difficulties of economic evaluation (e.g. investment deferral is relevant to other assets), the ambiguity of classification (microgrid applications and investment deferral are sometimes achieved through renewable integration), or a lower degree of relevance to the current battery chemistries and EV LIB repurposing (e.g. seasonal / inter-seasonal storage are more likely to be solved by fuel cells).

It should also be noticed that in some cases, multiple applications are served within one system. For example, a BESS mainly targeted for renewable integration can also be used to stabilize the grid through frequency control (Appendix B, cases 52, 53). By providing multiple services simultaneously or in sequence, BESS can be operated under higher utilization rates and thus create more revenue streams [6]. However, as BESS are normally configured based on the main application (e.g. a low P/E ratio system for both renewable integration and frequency control), and the design of BESS control strategy for multiple applications is beyond the scope of this report, such scenarios are not discussed in detail.

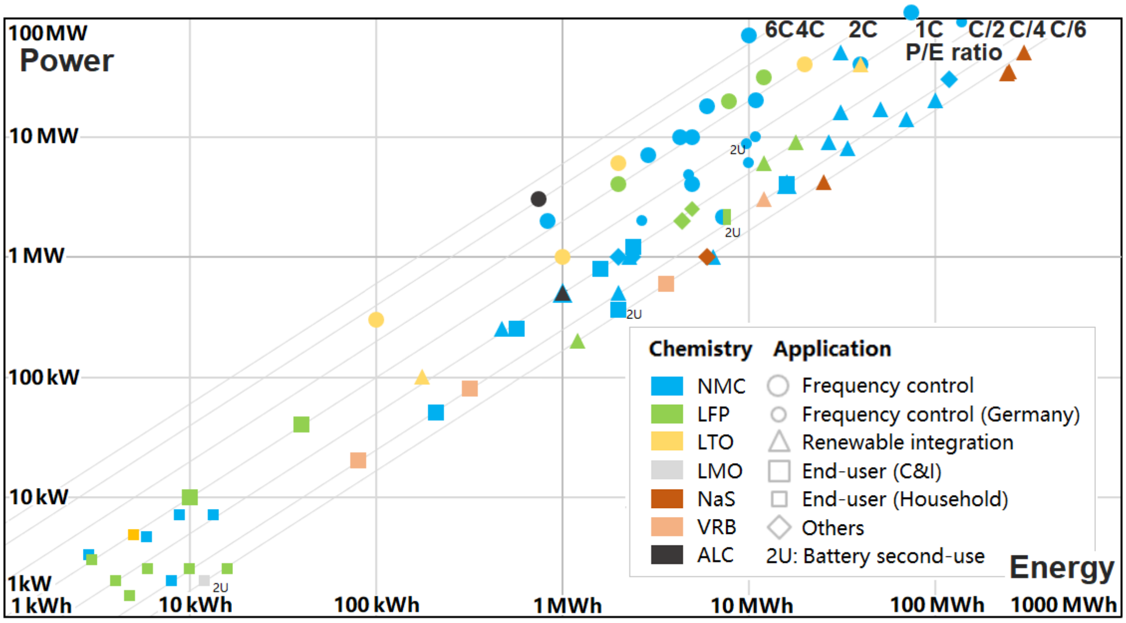


Figure 4: BESS application survey

Source: adapted from Appendix B

Fig.4 shows the result of the BESS application survey (Appendix B) which covers not only the mid- and large-scale BESS projects, but also BESS products for household and C&I use. Each case is plotted as a dot on a logarithmic scale, with energy and power on the horizontal and vertical axes respectively. The battery chemistries and BESS applications are represented through different colors and shapes. The P/E ratio for each case can be inferred with reference to the constant P/E ratios varying from 6C to C/6 presented as grey oblique lines. It can be seen that the Li-ion chemistries are used widely for applications requiring very different P/E ratios. They are also highly adaptable with energy capacities ranging from several kilowatt-hours to more than 100 megawatt-hours. In comparison, the non-lithium-ion chemistries are less flexible, with most applications restricted to mid- and large-scale, low P/E ratio ones.

Through the analysis of BESS applications, the popularity of Li-ion chemistries for energy storage is once again verified. This provides another solid foundation for the repurposing of EV LIBs.

4. EV Battery Repurposing for Battery Energy Storage

With the global trend of vehicle electrification, the number of end-of-life EV batteries is also expected to grow at an accelerating rate. It is predicted that 95 gigawatt-hours of LIBs will be disassembled from EVs by 2025 on a global scale [87]. In New Zealand, it is estimated that 17,094 EV battery packs will be off the road by 2025, and this number may further increase to roughly 84,000 by 2030 [13].

The sheer volume of end-of-life LIBs can partly be disposed of through recycling. However, due to the current limitations of LIB recycling, the recycling rate may not be guaranteed and even so, there still exists considerable environmental concerns. Firstly, the LIB recycling technologies are still evolving and the recycling is not yet profitable in most cases [88] [89], especially for chemistries with low or no cobalt contents [90]. Secondly, while the environmental impacts of battery recycling vary by recycling technology, it is revealed that the dominant recycling methods (i.e. pyrometallurgical and hydrometallurgical) are energy-intensive and thus may increase carbon emissions [91]. The environmental risks could be even greater if the market is under-regulated, leading to potentially numerous small and less-qualified recyclers [92].

It is estimated that LIBs can retain 70% to 80% of the initial capacity after automotive service and be employed in second-use applications with less intensive and fluctuating load profiles for an extra period of 10 years [82] [93]. Therefore, EV LIB repurposing not only delays recycling and gains time for recycling technologies to evolve, but also further reduces carbon emissions by providing extra services without the need of building new devices [15]. From a business perspective, a secured availability of second-use batteries and a promising growth trend of battery energy storage also present new market opportunities worth exploring.

Throughout the globe, regulations and standards are being established to facilitate LIB repurposing and minimize the potential environmental threats. For example, China has launched a management platform to trace EV LIBs throughout their entire lifecycle from production to recycling for both domestically produced and imported EVs. Accordingly, EV manufacturers should bear the main responsibility of LIB repurposing and recycling through establishing and maintaining a network and cooperating with EV dealers, LIB manufacturers and recyclers. It is also required that that the LIB structure design should be standardized and easily removable, in order to increase the automation level of repurposing and recycling. The sharing of communication protocols of the battery control system with third-parties is also encouraged, which facilitates the LIB SoH assessment for repurposing [94] [95].

The US and Canada also jointly published UL1974, a standard for the evaluation of EV LIB repurposing. This facilitates the sorting and grading of LIB packs, modules and cells, the identification of LIB SoH and the determination of their viability for stationary second-use applications [96].

Despite those efforts, the EV LIB repurposing still faces multiple obstacles which should be analysed and addressed.

4.1 Barriers and Competitors

As discussed earlier, battery energy storage in general faces **regulatory obstacles**, especially for large grid-scale applications, such as ancillary service and renewable integration, where multiple stakeholders are involved. In addition to the common hurdles, the regulatory environment for EV LIB repurposing could be more complex due to greater safety and environment concerns. There also exist additional challenges such as the transportation of products based on used EV LIBs, which may be categorized as hazardous goods [97]. **Liability concerns** pose another barrier to repurposing. As former owners of second-use LIBs, the LIB and EV manufacturers may want to avoid their potential liabilities for system malfunctions or safety accidents, by discouraging EV owners from selling end-of-life LIBs to other parties for repurposing.

Besides regulatory and liability concerns, EV LIB repurposing could also be hindered by **economic uncertainties**. Firstly, battery repurposing could be costly since it is labour-intensive (e.g. the manual disassembly of the battery packs, the manual sorting of battery modules with similar remaining capacities). Secondly, the extra costs including battery refurbishing, the balance of system (BOS) (i.e. all components of the BESS other than the battery), permitting, engineering and construction could be high. This means the battery itself may only account for a small portion of the whole system costs. A significant saving by using repurposed LIBs is thus less achievable. Thirdly, most BESS applications are valued by their economic returns, concessions in performance or cycle life could mean sacrifice of profitability. This could make repurposed LIBs less favoured by potential customers [28].

Furthermore, there also exists **technical barriers**. Due to the lack of the battery historical diagnostic data in most cases, repurposing participants lack the knowledge about how the batteries performed under what conditions, and what are the residual capacities [15] [97]. Although data sharing might be facilitated by regulations in certain regions, diagnostic data is mainly used as a reference during SoH assessment and a long testing time may still be required. Besides, even if the SoH can be clearly determined, there still exist technical difficulties to alleviate battery degradation during second-use through the monitoring and controlling of battery performance.

Lastly, it is also worth mentioning that EV LIB repurposing may also face **competition from recycling**, especially when the raw materials reclaimed from end-of-life batteries are highly sought after by LIB manufacturers [13].

4.2 Enabling Factors

Based on literature reviews, a number of case studies of second-use BESS projects utilising repurposed EV LIBs are described in Appendix C. The common enabling factors that contributed to successful repurposing from the view point of the battery repurposing facilities and second-use BESS manufacturers are summarized below, with reference to specific case studies.

Removal of regulatory and legal barriers:

- Non-separation of the rights and obligations of responsibility attribution for EV battery disposal. This can be achieved when LIB manufacturer and BESS manufacturer are subsidiary companies of the EV manufacturer (App. C, cases 1,2,3,4), the BESS manufacturer is the LIB manufacturer itself (App. C, case 7), or the BESS user is a subsidiary company of the BESS or EV manufacturer (App. C, case 2).
- Conduct pilot programs to evaluate BESS performance, before a full-scale implementation takes place. This helps to verify the system and avoid potential liability risks (App. C, cases 2,5).
- Collaborate with EV/ LIB manufacturers or other repurposing companies not only to exploit market opportunities, but also to share potential liabilities (App. C, case 6).
- Operate under favourable regulatory environment, such as frequency control in Germany (App. C, case 3).
- Gain certifications, especially those that are widely accepted and specifically drafted for EV LIB repurposing, such as UL1974 (App. C, case 1).

Removal of economic barriers:

- Minimize the end-of-life battery purchase price (will be discussed in detail in Appendix E).
- Minimize the battery repurposing costs. This can be achieved through:

- Reduce the battery testing time to improve efficiency through various means including battery coding, advanced battery testing and management technologies (App. C, cases 1,4,6,7).
- Only repurpose battery packs with optimal module sizes. Smaller module sizes could prolong the disassembling and testing time needed, while larger module sizes mean more defective modules and lower yield rate under the same cell defective rate [93].
- Use retrofitted battery packs instead of modules to reduce the engineering and BOS costs (App. C, cases 6,7).

- Increase the share of battery cost in the total cost, in order to increase the savings gained through using repurposed batteries instead of new ones. This can be achieved through:
  - An optimal configuration of the BESS P/E ratio. For utility-scale BESS, battery cost can account for more than 50% of the total cost in a 4-hour system (P/E ratio=0.25) but less than 25% in a 0.5-hour system (P/E ratio=2) [21].
- Focus on profitable markets such as frequency control (App. C, cases 3,7) or household BESS in regions prone to natural disasters (App. C, case 1).
- Collaborate with third parties who possess market resources and stable client relations, such as energy solution providers or electricity distributors (App. C, cases 2,5,6).
- Provide battery repurposing as a service for other parties (App. C, case 4).

Removal of technical barriers:

- Improve the traceability throughout battery lifecycle through battery coding. The availability of battery historical diagnostic data facilitates the SoH evaluation (App. C, case 7).
- Adopt advanced battery testing technologies to reduce the time needed for SoH evaluation (App. C, cases 1,4). A new technology for simultaneous measurement of the impedance of multiple LIB cells has also been recently developed by Panasonic [98].
- Adopt advanced battery management technologies such as cell-balancing during BESS operation, in order to prolong the battery lifespan during second-use and reduce the pre-processing needs of battery testing and sorting (App. C, case 6). Besides, a real-time SOH estimation technology developed by Toshiba can also facilitate timely inspections without suspending BESS operation [99].
- Develop second-use BESS of small capacities (App. C, cases 1,6). BESS with a capacity smaller than that of EV battery pack can achieve higher SoH homogeneity when using modules within the same pack. This avoids the technical difficulties when integrating large-scale BESS from several

battery packs with various SoH levels [93].

- Select applications with battery-conserving load profiles, such as frequency control (App. C, cases 3,7).
- Configurate the BESS at low P/E ratios to prolong cycle life through operating at lower C-rates and/or within narrower DoD range [93] (App. C, cases 1,3,7,8).
- Choose robust chemistries with less degradation concerns, such as LTO (App. C, case 5).
- Develop a hybrid system and select different chemistries for different applications in which they are best suited to, when BESS serves multiple applications (App. C, cases 7).
- Collaborate with third parties that possess extensive know-how in BESS research and development (App. C, case 2).

4.3 EV Battery Recycling

Before full implementation of EV LIB repurposing, the impacts of battery recycling should also be considered. Firstly, it helps to evaluate the competitiveness of battery repurposing against recycling and determine the end-of-life battery purchase price. Secondly, it also assists in determining the battery residual value at the ultimate end-life after second-use as the LIB recycling industry evolves.

The large diversity of Li-ion chemistries and LIB design (e.g. cell format, module size, pack structure, etc.) results in a LIB recycling industry that is similarly varied and characterized by complexity. In order to analyse the recycling industry landscape, case studies that include recycling companies both in New Zealand and globally are presented in Appendix D. A summary of the main recycling technologies and companies that use these technologies is illustrated in Fig.5.

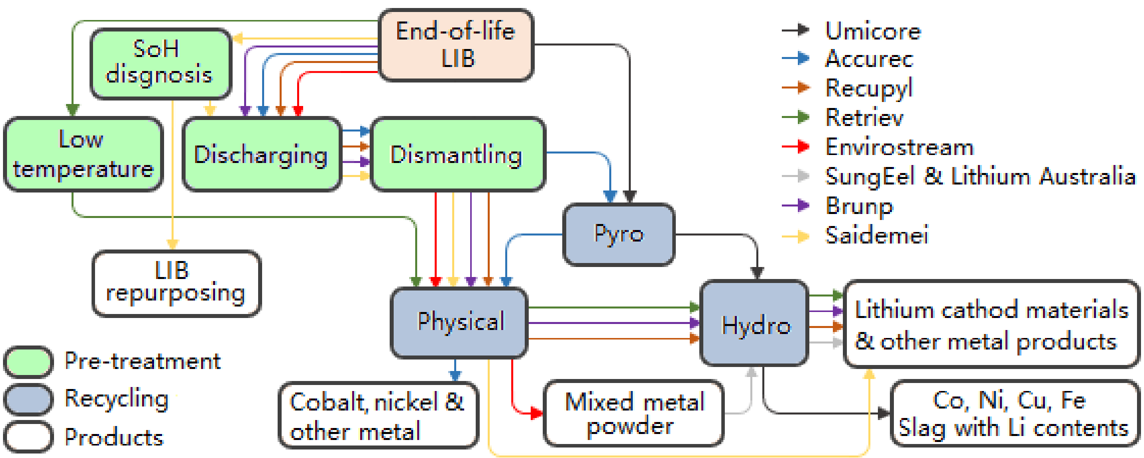


Figure 5: Recycling technology comparison

Source: adapted from Appendix D

The main current features of EV LIB recycling can be summarized as follows:

- Co-existence of multiple technical routes. While pyrometallurgy followed by hydrometallurgy or physical treatment is chosen by Umicore and Accurec (App. D, cases 1,2), there are other recycling companies who prefer physical treatment in combination with hydrometallurgy (App. D, cases 3-8). Recycling technologies that solely rely on physical treatment have also been developed (App. D, case 9). Even within the same route, the technical details adopted may also vary between different recyclers (e.g. Recupyl vs. Retriev, App. D, cases 3,4, [100]).
- Different levels of pre-treatment and different implementation methods. While Umicore eliminates the need for pre-treatment by feeding the battery packs directly into a furnace (App. D, case 1), discharging and dismantling of the batteries is required by other recycling technologies (App. D, cases 2,3,8,9). Some special pre-treatment methods such as liquid nitrogen immersion for battery deactivation have also been developed and patented (App. D, case 4).
- Different products retrieved in different compounds and with different recycling efficiencies. While the high-value metals such as cobalt, nickel and copper are retrievable in most cases, lithium can only be properly collected through non-pyro processes. The purity and forms of the retrieved metals also differ from one another (e.g. cobalt in the form of pure metal, oxides or hydroxides), thus influencing their ability to be re-used for LIB manufacturing.

These features reveal the limitations of the current LIB recycling industry mentioned at the beginning of this chapter, which include environmental-unfriendliness, cost-ineffectiveness and potential safety risks (e.g. manual disassembly of the high-voltage LIB packs). It is also worth mentioning that in some markets with economies of scale, LIB recycling is already profitable for high cobalt-content LIBs through the adoption of advanced recycling technologies. Therefore, LIB recyclers have established collaborations with EV manufacturers to purchase end-of-life LIBs (App. D, cases 8,9). However, in markets such as New Zealand where LIB recycling is nascent, end-of-life LIBs are either cost-neutral or bear a disposal cost (App. D, cases 10,11). Meanwhile, the case studies in Appendix D also reveal the following development trends of EV LIB recycling.

- The prevalence of pre-processing including the pre-treatment and physical disassembly of the LIBs. Most of the recyclers reviewed are engaged in different levels of pre-processing activities. This helps the recyclers to earn more revenue by achieving higher recycling efficiency and obtaining cathode materials of higher purity which can be directly sold to LIB manufacturers. Automation for cell disassembly is evident (App. D, cases 8,9) and automation level could be further increased based on the foreseeable standardization of LIB design [95] [101]. Some recyclers are also beginning to engage in repurposing to further increase profitability (App. D, case 9).

- Supply chain optimization. Strategic relationships have been developed not only around recyclers and EV manufacturers (App. D, cases 1,8,9), recyclers and LIB manufacturers (App. D, cases 1,8), but also among recyclers themselves (App. D, cases 5,6,7). There are also recyclers that seek international growth by establishing multiple facilities around the globe (App. D, cases 3,6). These activities not only facilitate economies of scale, but also help recyclers to concentrate on their core competitiveness, thus avoiding unnecessary investment.

From the view point of end-of-life EV LIB owners, these development trends not only mean the reduction of environmental liabilities, but also a potential increase in battery residual value after second-use, as EV LIB recycling becomes increasingly profitable due to the evolvement of both the recycling technology and the industry landscape. This is particularly the case for New Zealand, where economies of scale might be achieved in the coming years based on an estimated rapid increase in the number of end-of-life LIBs [13].

5. Feasibility Analysis of EV Battery Repurposing for Battery Energy Storage in New Zealand

When analysing the feasibility of EV LIB repurposing in New Zealand, besides the consideration of general enabling factors adopted by various repurposing participants throughout the globe, closer attention should also be paid to the New Zealand-specific market conditions such as low EV volumes, large market share by a single EV brand /model (e.g. Nissan Leaf), dominance of used EVs and a under-developed EV LIB recycling industry.

The first section of this chapter will focus on the selection of LIBs used by various EV brands based on their availability in the New Zealand market and their suitability of repurposing. After choosing the EV battery, economic analysis will be performed to evaluate the feasibility of running a repurposing facility based on the determination of the battery purchase and selling prices.

In the second section, the usability of second-use BESS based on repurposed EV batteries and their potential advantages against first-use BESS will be evaluated based on two typical application scenarios for New Zealand-based consumers.

Finally, the feasibility of EV battery repurposing in New Zealand will be concluded in the last section. Several recommendations which could further facilitate EV battery repurposing in New Zealand in both the short and long term will also be provided.

5.1 Economic Analysis of EV Battery Repurposing

In Appendix E, the economic feasibility of EV battery repurposing in New Zealand is analysed in detail. The key findings can be concluded as follows:

- Economies of scale can only be achieved by repurposing Nissan Leaf Gen.1 batteries due to its market dominance and the availability of a relatively large number of end-of-life batteries in the coming years.
- Besides quantitative advantage, the repurposing of Nissan Leaf Gen.1 batteries is also facilitated by the availability of battery diagnostic data, good capacity retention after first-use and a small module size (i.e. each module contains four cells) that improves the cell SoH homogeneity within the module.

- Due to the lack of scale of EV battery recycling in New Zealand, repurposing facilities may acquire end-of-life EV batteries at lower prices compared with other markets such as the US and China.
- The battery selling price should be determined based on the price offered by other repurposing facilities, the estimated price of new batteries for energy storage on a yearly basis and the usable DoD range of repurposed batteries during second-use. It is estimated that the ideal selling price is $163/kWh in 2020 and will be steadily decreased to $96/kWh in 2025.
- Initial investment for the purchase of battery testing equipment and the annual employment costs, particularly the latter, will account for an overwhelmingly large portion of the expenses for the operation of a repurposing facility.
- Although it is estimated that the repurposing facility will incur losses in the first several years, a positive cumulative present value could be reached in 2025 or earlier as more and more end-of-life batteries become available.
- Although the adoption of conventional and time-consuming battery testing technologies and an annual increase of the battery purchase price can negatively influence the repurposing profitability, they could still be tolerated to a certain degree when an abundant supply of end-of-life batteries can be secured.

5.2 Case studies of BESS applications based on repurposed EV batteries

In Appendix F, the economic feasibility of BESS applications based on repurposed EV batteries in New Zealand is analysed through two typical usage scenarios. The key findings can be concluded as follows:

- With lower battery costs, second-use BESS based on repurposed EV batteries possess potential price advantage over first-use BESS, if the other costs besides the battery can be well-controlled. Although the determination of BESS cost structure is beyond the scope of this report and thus not analysed in detail, it is still revealed that the second-use BESS cost control can be facilitated if they are configured at lower P/E ratios.
- While low P/E ratios alleviate BESS degradation and reduce costs, it is also revealed that under typical household and C&I load profiles, BESS profitability is mostly determined by the BESS energy capacity and barely influenced by power capacity. This provides another reason for the adoption of lower P/E ratios.
- It is found that the variation of battery degradation within a certain level only has a limited negative impact on BESS profitability. Therefore, a potential higher degradation of second-use BESS

compared with first-use ones can be tolerated.

- Under typical and simple tariff structures (e.g. ToU rate for household users at $0.17/kWh off-peak and $0.25/kWh on-peak; fixed rate for C&I users at $0.21/kWh and feed-in tariffs for PV generation sold back to the grid at $0.08/kWh), neither the first-use nor the second-use BESS can achieve cost recovery within 10 years. Therefore, the repurposing of EV batteries alone cannot facilitate the widespread of BESS. Instead, besides the efforts for BESS performance improvement and cost reduction, repurposing facilities and second-use BESS manufacturers should also pay close attention to the identification of suitable applications.

5.3 Conclusion and Recommendations

Based on the above analysis, the feasibility of EV battery repurposing in New Zealand can be verified based on the following reasons.

- The Li-ion chemistry not only takes up an overwhelming large share of the global BESS installation currently, but is also expected to dominate the BESS market in the foreseeable future. Therefore, EV battery repurposing can be facilitated by a stable environment without imminent threat from substitute chemistries.
- The Li-ion chemistry is suitable for a variety of different BESS applications. Analysis of numerous EV battery repurposing cases also reveals a huge application diversification for second-use BESS. Therefore, EV battery repurposing can be further facilitated based on the application flexibility.
- Despite being a small market, EV battery repurposing in New Zealand could still enjoy a positive cumulative present value within a relatively short time span due to New Zealand-specific factors that facilitate repurposing. These factors include low end-of-life battery purchase price, a large base of used EVs and the market dominance of a single EV brand/model.
- Second-use BESS based on repurposed EV batteries is particularly suited for load-shifting applications in which the profitability is highly relevant to BESS energy capacity. With lower unit prices for batteries per kilowatt-hour, larger energy capacities can be achieved under the same price level through adopting repurposed EV batteries. The extra costs of the BESS beside the batteries can also be better controlled for load-shifting applications which generally only require low P/E ratios.
- It should also be mentioned that external factors beyond battery technologies (e.g. the electricity tariff structure) can cause enormous impacts on the BESS profitability during operation. Therefore, repurposing facilities and second-use BESS manufacturers should also pay close attention to the

identification of suitable applications, as the electricity market evolves.

As a conclusion, it is suggested that the New Zealand-based high-tech companies should actively participate in EV battery repurposing for energy storage, as it not only contributes to environmental sustainability, facilitates the adoption of BESS and hence the transition towards low carbon and resilient power systems, but also offers unique opportunities from a business perspective. To further promote EV battery repurposing in New Zealand, the following activities for both short and long terms are also recommended.

- Apply for government funds which encourage the low-carbon transition, such as the Waste Minimization Fund and the Low Emission Vehicles Contestable Fund. Although most of the funding of the latter currently goes to EV charging, an EV LIB refurbishing project by Blue Cars Ltd has also been funded [102].
- Conduct pilot programs, preferably for self-use, in order to verify the second-use BESS performance and avoid potential liability risks.
- Gain certifications such as ISO14001 (environmental harm minimization) and UL1974.
- Acquire advanced battery testing and management technologies through self-development or technology import (e.g. from Relectrify for cell-balancing [103], Toshiba for real-time SoH estimation [99] or Panasonic for simultaneous SoH measurement for multiple LIB cells [98]).
- Extend the battery categories for repurposing based on more advanced and flexible battery testing technologies and the availability of other battery types other than Nissan Leaf Gen.1 as New Zealand's EV market evolves.
- Seek collaborating opportunities with EV manufacturers or other repurposing companies to secure sources of end-of-life batteries and to share potential liabilities. For example, Relectrify has established collaboration with Volkswagen and 4R Energy [104] [105].
- Extend the use of second-use BESS to other applications besides load shifting for household and small-scale C&I users through the increase of BESS energy capacity. This could be achieved based on more advanced battery management technologies that tolerate greater SoH inhomogeneity and thus facilitate the integration of battery modules from multiple packs.
- Seek collaborating opportunities with electricity distributors, especially those who face pressures of infrastructure upgrade and have interest in second-use BESS, such as Vector [13].

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Appendix A Battery Chemistry Survey

Table 2: Battery chemistry survey

Abbre-viation	Chemistry and working principle	Energy density (Wh/kg)	Charge rate	Discharge rate	Cycle life	Round-trip efficiency	Safety	Applications	Source
LCO	Cathode: Lithium cobalt oxide Anode: Graphite. The layered structure of LCO is less stable and has higher resistance, compared with the spinel structure of LMO.	150-200	0.7-1C	1C	500-1000	95%	Low, thermal runaway at 150°C	Personal electronics	[14] [24]
LMO	Cathode: Lithium manganese oxide Anode: Graphite The spinel structure of LMO improves ion flow on the electrode, lower internal resistance increases C-rates and improves safety.	100-150	0.7-1C (typical) 3C (max)	10C	300-700	95%	High, thermal runaway at 250°C	EV, power tools, medical devices	[14] [24]
NMC	Cathode: Lithium nickel manganese cobalt oxide; Anode: Graphite or Graphite + Silicon Nickel has high energy density but low stability; manganese has lower energy density but the spinel structure can lower the internal resistance. NMC combines the merits of both nickel and manganese	150-220	0.7-1C (typical) 4-5C (max)	1-2C (typical) 5-10C (pulse)	1000-2000	95%	Middle, thermal runaway at 210°C	EV, BESS, medical devices, industrial applications	[14] [24] [106]
NCA	Cathode: Lithium nickel cobalt aluminum oxide; Anode: Graphite or Graphite + Silicon	200-260	0.7-1C	1C	500	92%	Low, thermal runaway at 150°C	EV, medical devices, industrial applications	[24] [34] [63]
LFP	Cathode: Lithium iron phosphate Anode: Graphite The olivine crystal structure of LFP has better thermal stability than layered cathode materials. However, it has the disadvantage of poor Li-ion conductivity due to stronger binding forces	90-120	1-2C	1-2C 4C (pulse)	2000-6000	95%	High, thermal runaway at 270°C	EV, BESS, vehicle starter battery	[14] [24] [107]
LTO	Cathode: LMO or NMC Anode: Lithium-titanate nanocrystals By replacing the graphite with the spinel structure LTO, anode surface area increases from 3 to 100 m2/g, allowing electrons to enter and leave the anode more quickly. It helps LTO to achieve a high P/E ratio and excellent thermal stability	50-80	1-5C	10C	3000-7000	96%	Very high	EV, BESS, UPS, medical devices, vehicle starter battery	[14] [24] [34] [63]

NaS	Cathode: molten sulphur Anode: molten sodium NaS works on the reversible electrochemical reaction between sodium / sulfur and sodium polysulfides. The electrodes are separated by a solid ceramic sodium alumina, which acts as the electrolyte.	>150	C/8-C/4	C/8-C/4	4000-5000	75%-92%	Middle, high operating temperature, sodium polysulfides highly corrosive	BESS	[14] [34] [108]
VRB	Hydrogen ions are exchanged through a membrane across the two types of vanadium electrolytes (V2+/V3+ and V4+/V5+).	40	C/8-C/2	C/8-C/2	>10000 Theoretically unlimited	70-80%	High, the electrolytes are inflammable, but leaking could be a concern	BESS	[50] [109] [22]
ALC	Cathode: Lead dioxide Anode: carbon/lead composite Adding carbon-based material to the anode lowers sulfation (a typical failure mode of the classic lead-acid chemistry), improves conductivity and increase charge acceptance	20-30	C/10-C/5	Theoretically unlimited	2000-3000	90-92%	High	BESS, vehicle starter battery	[44] [110]
NiCd	Cathode: Nickel oxide hydroxide Anode: metallic cadmium	45-80	4C-6C	10C	500-1000	60-70%	Middle, nickel electrodes are susceptible to thermal runaway	Personal electronics, BESS, telecom UPS, aviation	[14] [34] [49] [48]

Appendix B BESS Application Survey

Part 1: Mid- and large-scale BESS projects

Table 3: Mid- and large-scale BESS projects

Case No.	Power (MW)	Energy (MWh)	Battery chemistry	Manufacturer	Application	Site	Description	Source
1	70	10	NMC	Tesla	Frequency control	Hornsdale, Australia	70MW/10MWh of the whole capacity (100MW /129MWh) is dedicated to grid stabilization by providing FCAS regulation /contingency and SIPS participation	[65]
2	30	119	NMC	Tesla	Wholesale arbitrage	Hornsdale, Australia	30MW/119MWh of the whole capacity (100MW /129MWh) participates in the Australian Electricity Market for energy arbitrage	[65]
3	1	2.4	NMC	Tesla	Investment deferral	Auckland, New Zealand	Growing electricity demand in Auckland urges equipment upgrade for electricity transition and distribution. BESS applied by Vector is 70% less costly ($5mil vs. $12mil) compare to traditional upgrades and serves as backup source during power outages.	[77] [111]
4	0.8	1.6	NMC	Tesla	End user (C&I)	Multiple sites, USA	Retail company "Target" uses BESS at some stores to provide electricity during periods of high energy consumption and relieve stress on the power grid	[112]
5	1.2	2.4	NMC	Tesla	End user (C&I)	California, USA	Jackson Family Wines uses BESS to store electricity from the grid or PV panels during off-peak times and use it during periods of high energy consumption to avoid high demand charges	[112]
6	0.5	2	NMC	Tesla	Renewable integration, Microgrid	Malolo, Fiji	An off-grid project which facilitates diesel abatement and renewable consumption	[111]
7	4	16	NMC	Tesla	End user (C&I)	Colorado, USA	BESS is connected to the grid to be charged at night and discharged in the afternoon during peak hours	[22]

8	0.25	0.475	NMC	Tesla	Renewable integration	Oklahoma, USA	A distribution company "Central Electric Cooperative" uses BESS to mitigate the impact of solar intermittency and maximize its consumption.	[113] [22]
9	0.5	1	NMC	Tesla	Renewable integration, Microgrid	North Carolina, USA	Bess is applied by "North Carolina Electric Membership Corporation" on Ocracoke Island to smooth the input of renewable sources and reduce peak demand by increase renewable self-consumption.	[22]
10	1	2	NMC	Tesla	Wholesale arbitrage, R&D,	Auckland, New Zealand	A pilot project by Mercury is directly connected to the high voltage grid and participates in the energy and reserves markets. With an investment of $3mil, a break-even might only be reached after many years. "Research" is emphasized to draw lessons from market participation, which can then be used when battery technology evolves and price decreases.	[114]
11	0.25	0.57	NMC	Tesla	End user (C&I), Renewable integration	Lake Grassmere, New Zealand	BESS is applied for Dominion Salt to maximise the wind self-consumption through load shifting. Output smoothing of the wind power can also be provided.	[80]
12	20	100	NMC	Samsung	Renewable integration	Hawaii, USA	BESS is applied to mitigate the intermittency of the solar generation and increase its self-consumption (65% of the nighttime peak load might be supplied by renewable energy by the end of 2019)	[22]
13	14	70	NMC	Samsung	Renewable integration	Hawaii, USA	Same as above	[22]
14	8.6	9.8	NMC	Daimler	Frequency control	Elverlingsen, Germany	EV LIB spare parts are used for frequency control which can provide battery-conserving loads. This add value at the beginning of battery life. Besides, there is another 17.4MWh EV LIB spare part BESS project and a 12.8MWh EV LIB second-use BESS project (power capacities of both projects unrevealed)	[73]
15	90	140	NMC	LG	Frequency control	Saarland, Germany	Unrevealed	[115]

16	10	11	NMC	LG	Frequency control	Feldhiem, Germany	Unrevealed	[115]
17	6	10	NMC	LG	Frequency control	Wunsiedel, Germany	Unrevealed	[115]
18	4.8	4.8	NMC	LG	Frequency control	Heilbronn, Germany	Unrevealed	[115]
19	2	2.7	NMC	LG	Frequency control	Dresden, Germany	Unrevealed	[115]
20	109	75	NMC	LG	Frequency control	England	Unrevealed	[115]
21	10	5	NMC	LG	Frequency control	Northern Ireland	Unrevealed	[115]
22	40	40	NMC	LG	Frequency control	New Jersey, USA	Unrevealed	[115]
23	20	11	NMC	LG	Frequency control	Rosecoe, US	Unrevealed	[115]
24	18	6	NMC	LG	Frequency control	Meyersdale, US	Unrevealed	[115]
25	4	5	NMC	LG	Frequency control	Surprise, US	Unrevealed	[115]
26	10	4.3	NMC	LG	Frequency control	Cumberland, US	Unrevealed	[115]
27	7	2.9	NMC	LG	Frequency control	Minster, US	Unrevealed	[115]
28	2	0.83	NMC	LG	Frequency control	New Richmond, US	Unrevealed	[115]
29	16	31	NMC	LG	Renewable integration	Reunion	Unrevealed	[115]
30	17	51	NMC	LG	Renewable integration	Yeongyang, Korea	Unrevealed	[115]
31	9	27	NMC	LG	Renewable integration	Jeju, Korea	Unrevealed	[115]
32	4	16	NMC	LG	Renewable integration	Yeongheung, Korea	Unrevealed	[115]
33	50	31	NMC	LG	Renewable integration	Hokkaido, Japan	Unrevealed	[115]
34	1	6.4	NMC	LG	Renewable integration	Cook Islands	Unrevealed	[115]
35	8	34	NMC	LG	Renewable integration	Tehachapi, USA	Unrevealed	[115]
36	1	2.3	NMC	LG	Renewable integration	Cedartown, USA	Unrevealed	[115]
37	6	12	LFP	Lishen	Renewable integration	Anoka, Greece	BESS is applied to provide solar energy during peak hours by Connexus Energy	[22]
38	9	18	LFP	Lishen	Renewable integration	Athens, Greece	Same as above	[22]
39	2	4.4	LFP	BYD	Microgrid	Glacier, USA	Unrevealed	[116]
40	19.8	7.865	LFP	BYD	Frequency control	Multiple sites, USA	Unrevealed	[116]
41	31.5	12.06	LFP	BYD	Frequency control	Multiple sites, USA	Unrevealed	[116]
42	2.5	5	LFP	BYD	Renewable integration	California, USA	Unrevealed	[116]

43	0.2	1.2	LFP	BYD	Renewable integration	South Africa	Unrevealed	[116]
44	4	2	LFP	BYD	Frequency control	Ontario, Canada	Unrevealed	[116]
45	40	40	LTO	Toshiba	Renewable integration	Minamisoma, Japan	BESS stores surplus electricity during excess renewable energy generation and release it at times of high demand	[117]
46	40	20	LTO	Toshiba	Frequency control	Nishisendai, Japan	BESS is applied to reduce the fluctuation of grid frequency due to the increasing use of variable renewable sources	[117]
47	0.3	0.1	LTO	Toshiba	Frequency control	Yokohama, Japan	BESS is applied to stabilize the electricity grids through frequency control and peak-load shifting	[117]
48	0.1	0.176	LTO	Toshiba	Renewable integration	Miyako, Japan	BESS is applied to increase PV self-consumption	[117]
49	6	2	LTO	Toshiba	Frequency control	Cincinnati, USA	BESS is applied to provide ancillary service through the frequency regulation market operated by PJM	[117]
50	1	1	LTO	Toshiba	Frequency control	Sardinia, Italy	As grid stabilization becomes more crucial due to an increasing use of renewable energy, BESS provide effective solutions to stabilize the grid through frequency control	[117]
51	50	300	NaS	NGK	Renewable integration	Fukuoka, Japan	BESS is applied to optimize the balance of supply and demand and avoid curtailment by absorbing excess solar power generation for later use	[74]
52	34.8	250	NaS	NGK	Renewable integration, Investment deferral, Frequency control	Italy	BESS is applied to avoid wind curtailment by absorbing excess generation for later use. By doing so, the investment of new transmission capacity can also be avoided. Ancillary services including primary / secondary reserves can also be provided	[74] [75]

53	34	244.8	NaS	NGK	Renewable integration, Frequency control	Aomori, Japan	BESS is applied to avoid wind curtailment by absorbing excess generation for later use. Beside time-shifting, immediate smoothing can also be provided. Besides, grid services such as frequency control is also available.	[74] [75]
54	4.2	25.2	NaS	NGK	Renewable integration	Shimane, Japan	BESS is applied to absorb fluctuations of solar and wind power generation, thus adding more renewables to the grid	[74]
55	1	6	NaS	NGK	UPS, Investment deferral	British Columbia, Canada	BESS is applied to supply backup power to a remote aera in the case of a power outage. The system load during periods of high demand can also be reduced, thus delaying the infrastructure upgrade	[74]
56	3	12	VRB	Prudent	Renewable integration	Hubei, China	The currently largest PV + VRB project in China can increase the consumption of PV generation through load-shifting	[118]
57	0.6	3.6	VRB	Prudent	End user (C&I)	Oxnard, USA	BESS is applied to absorb cheap electricity during off-peak periods and inject it during on-peak periods for up to six hours. Spikes in usage can also be avoided to reduce demand charges	[39]
58	0.08	0.32	VRB	VSUN	End user (C&I)	Victoria, Australia	Meredith Dairy uses BESS to achieve self-sufficiency and quit the grid by maximizing solar self-consumption	[38]
59	0.02	0.08	VRB	VSUN	End user (C&I)	Victoria, Australia	A Victorian apple farm uses BESS to maximize solar self-consumption	[38]
60	0.5	1	ALC	Ecoult	Renewable integration	New Mexico, USA	BESS is applied to smooth the volatile ramp rates of solar generation and facilitates better alignment of PV output and system peaks through load shifting	[43]
61	3	0.75	ALC	Xtreme Power	Frequency control, Microgrid	Alaska, USA	BESS is applied to provide frequency control due to the increasing use of wind generation on an island in Alaska	[43]

Part 2: BESS products for household and C&I use

Table 4: BESS products for household and C&I use

Case No.	Usable Energy (kWh)	Power (kW)	Battery chemistry	Manufacturer	Application	Product model	Round-trip efficiency	Warranty (years)	Capacity retention	Approximate price ($NZD) *	Price Status	Source
62	210	50	NMC	Tesla	End user (C&I)	Powerpack	88%	10	>60%	126,500 **	2016	[111] [119] [120]
63	13.5	7	NMC	Tesla	End user (Household)	Powerwall 2	89%	10	>70%	17,000	2019	[121]
64	4	2	LFP	Sonnen	End user (Household)	ECO 8.2/4	86%	10	>70%	11,200	2019	[121]
65	6	2.5	LFP	Sonnen	End user (Household)	ECO 8.2/6	86%	10	>70%	13.600	2019	[121]
66	10	2.5	LFP	Sonnen	End user (Household)	ECO 8.2/10	86%	10	>70%	18,500	2019	[121]
67	16	2.5	LFP	Sonnen	End user (Household)	ECO 8.2/16	86%	10	>70%	25,500	2019	[121]
68	2.9	3.3	NMC	LG Chem	End user (Household)	RESU 3.3	95%	10	>60%	Not stated	-	[121]
69	5.9	4.6	NMC	LG Chem	End user (Household)	RESU 6.5	95%	10	>60%	9,500 **	2019	[121]
70	8.8	7	NMC	LG Chem	End user (Household)	RESU 9.8	95%	10	>60%	Not stated	-	[121]
71	8	2	NMC	Panasonic	End user (Household)	LJ-SK84A	86%	10	>60%	13,000	2019	[121]
72	12	2	LMO	4R Energy	End user (Household)	EHB-240	90%	15	>50%	38,000 ***	2019	[86]
73	5	4.8	LTO	Toshiba	End user (Household)	ENG-B5022C4-B1	96%	10	>60%	25,000 ***	2019	[86]
74	4.8	1.5	LFP	Sharp	End user (Household)	JH-WB1402	Not stated	10	>60%	21,000 ***	2019	[86]
75	3	3	LFP	BYD	End user (Household)	Mini ES	Not stated	Not stated	Not stated	Not stated	-	[122]
76	40	40	LFP	BYD	End user (C&I)	Commercial ESS	Not stated	Not stated	Not stated	Not stated	-	[122]
77	10	10	LFP	BYD	End user (C&I)	B-Box 10.0	Not stated	Not stated	Not stated	Not stated	-	[122]

* Exchange rates in January 2020 are adopted

** Prices excluding invertor and other BOS

*** Prices in the Japanese market

Appendix C EV Battery Repurposing Case Studies

Table 5: EV battery repurposing case studies

Case No.	**Stakeholders** 1: Battery manufacturer 2: EV manufacturer 3: BESS manufacturer 4: BESS user	EV model	Battery Chemistry	Battery Specification	BESS capacity	Application	**Lessons Learned (how the barriers are overcome)** 1: Regulatory and legal barriers 2: Economic barriers 3: Technical barriers	Source
1	AESC[1], Nissan[2], 4R Energy[3], Households[4]	Nissan Leaf Gen.1	LMO (NMC blended)	24kWh pack; 48 modules; 4 pouch cells per module	2kW / 12kWh	End-user bill management (Household)	AESC and 4R Energy are both subcompanies of Nissan (joint ventures between Nissan and other companies), thus reducing the liability uncertainties [1]; 4R Energy is the first repurposing company that earns the UL1974 certification. This helps to build customer trust and reduce regulatory restrictions [1]; BESS for households are sold at high prices in the Japanese market, thus reducing the economic uncertainties [2]; Based on advanced SoH testing technology, all 48 modules in each battery pack can be analysed in just 4 hours[3]; BESS product is configured at a low P/E ratio (0.17), a low C-rate can prolong battery cycle-life during second-use [3].The small BESS capacity (12kWh) achieves higher SoH homogeneity when using modules from the same battery pack and avoids the technical difficulties when integrating large BESS from several packs with various SoH levels [3].	[86] [123] [124]
2	SK Innovation[1], Hyundai[2], Hyundai, Wartsila[3], Hyundai Steel Co.[4]	Hyundai Ioniq EV, Kia Soul EV	NMC	28kWh pack; 8 modules; 10 or 14 pouch cells per module	1MWh	End-user (C&I) pilot program	Hyundai is not only the EV manufacturer, but also the BESS builder and user, thus reducing the liability uncertainties and regulatory barriers [1]; Wartsila is a renowned energy solution provider with advanced energy storage technologies and software, customers and channel networks across 177 countries. This advantage can reduce the economic uncertainties and technical difficulties [2,3].	[125]

3	Deutsche Accumotive[1], Daimler[2] A joint venture between Daimler and other companies[3,4]	Smart electric Gen.3	NMC	17.6 kWh pack; 3 modules; 31 pouch cells per module	3 projects: 8.96MW/ 9.8MWh; 17.4MWh (spare parts) 12.8 MWh (second-use)	Frequency control	The LIB manufacturer and BESS manufacturer/owner are both subcompanies of Daimler (Joint ventures between Daimler and other companies), thus reducing the liability uncertainties [1]; The Germany market has favorable regulatory environments for grid-connected BESS, thus reducing the regulatory barriers [1]; Due to the high profitability of frequency control, the economic uncertainties can be reduced [2]; Whole battery pack used, thus reducing the labor cost and time for battery disassembly and testing [2]; Frequency control has battery-conserving load profiles, especially in Germany where BESS are configured at a lower P/E ratio based on the "30-min criteria". This reduces the risk of battery degradation [3].	[70] [73] [126]
4	Primearth EV Energy[1], Toyota[2], TTK Logistics Thailand[3]; Households, C&I users[4]	Toyota hybrids (various models)	NiMH Li-ion	various	Unrevealed	End-user bill management (Household, C&I)	The battery manufacturer and BESS manufacturer/owner are both subcompanies of Toyota (The battery manufacturer is a joint venture between Toyota and Panasonic), thus reducing the liability uncertainties [1]; Battery repurposing will not only serve Toyota hybrids, but also other EV brands and electric devices, thus broadening the economic prospects [2]; The battery SoH can be rapidly and accurately evaluated based on advanced testing technology [3].	[127] [128]
5	Toshiba[1], Honda[2], Honda, American Electric Power[3], Households[4]	Honda Fit EV	LTO	20 kWh	Unrevealed	End-user bill management (Household)	Through a pilot program at the initial stage, the liability uncertainties could be reduced [1]; By partnering with American Electric Power, a major electricity distributing company in the US which has access to millions of end-users, the economic prospects might be broadened [2]; LTO has ideal cycle life and extreme temperature performance, thus reducing the degradation concerns [3].	[129] [130]

6	AESC[1], Nissan[2], Relectrify, Vector[3], Household, C&I users[4]	Nissan Leaf Gen.1	LMO (NMC blended)	24kWh pack; 48 modules; 4 pouch cells per module	10kW/ 15kWh	End-user bill management (Household, C&I)	Relectrify seeks collaboration with EV manufacturers and other repurposing companies, this could reduce the potential liability risks [1]; By partnering with Vector, a major electricity distributing company in New Zealand, the economic prospects might be broadened [2]; By developing BESS based on retrofitted battery packs, the extra BOS costs might be reduced [2]; With advanced battery SoH monitoring and controlling, cells/modules with less homogeneity could be used. This could prolong the BESS lifespan and reduce the pre-processing needs of end-of-life battery SOH evaluation [3]. The small BESS capacity (15kWh) achieves higher SoH homogeneity when using modules from the same battery pack [3].	[131] [103] [104] [105]
7	BAK[1], Unrevealed[2]; BAK[3]; C&I user[4]	unrevealed	NMC & LFP	Unrevealed	2.15MW/ 7.27MWh	End-user bill management (C&I), Frequency control	BAK is both the battery and second-use BESS manufacturer, thus reducing the liability risks [1]; Whole battery pack is directly applied, thus reducing the labor cost for battery disassembly [2]; Besides load shifting for bill management, ancillary services are also provided, thus broadening the revenue streams [2]; NMC and LFP batteries are both used to cater for different applications [3]; All the batteries are coded, better traceability facilitates the SoH evaluation [3]; BESS is configured at a low P/E ratio (0.3), lower C-rate can prolong cycle life [3].	[132]
8	Unrevealed[1], Changan[2], Huizhi Energy[3], C&I user[4]	Changan EV	NMC	Unrevealed	360kW/ 2MWh	End-user bill management (C&I)	BESS is configured at a low P/E ratio (0.18), lower C-rate can prolong cycle life [3].	[133]

Appendix D EV Battery Recycling Case Studies

Table 6: EV battery recycling case studies

Case No.	Recycling company	Location	Pre-treatment	Recycling technology Pyro: pyrometallurgy Hydro: hydrometallurgy Physical: physical treatment	Products	Customers 1. suppliers 2. buyers	Battery purchase price	Source
1	Umicore	Belgium	none	Pyro + Hydro	Co, Ni, Cu, Fe, Slag with Li contents (external cooperation needed for Li recovery)	Saft, Toyota[1]; Samsung SDI, LG[2]	unrevealed	[100] [134] [135] [136]
2	Accurec	Germany	Sort by chemistry (NMC/LCO/LFP); Discharge to <60v; Dismantle to cell level	Pyro + Physical	Co, Ni, Cu, Fe, Al	unrevealed	unrevealed	[137]
3	Recupyl	France, US, Singapore	Discharge; Dismantle to module level	Mech + Hydro	Cu, Al, Cobalt oxide, iron oxide, Lithium carbonate	unrevealed	unrevealed	[100] [138]
4	Retriev	US	Low temperature treatment using liquid nitrogen	Mech + Hydro	Cu, Al, Carbon, Lithium cathode materials with Nickel and Cobalt contents	unrevealed	unrevealed	[100] [139]
5	Envirostream	Australia	unrevealed	Physical	Cu, Al, Fe, mixed metal compound with cobalt, nickel, lithium and graphite contents	LG[1], SungEel[2]	unrevealed	[140]
6	SungEel	Korea, Malaysia, US Hungary, India	unrevealed	Hydro	Co, Ni, Li, Mn, Cu	Envirostream[1]	unrevealed	[141]
7	Lithium Australia	Australia	unrevealed	Hydro	Cathode material including Lithium phosphate	Envirostream[1]	unrevealed	[142]
8	Brunp	China	Automatic cell dismantling	Physical + Hydro	Cu, Al, Fe, cathode materials (nickel-cobalt-manganese hydroxide)	SAIC-VW, BMW, Toyota, Nissan, etc[1]; CATL[2]	~$25 NZD/kWh	[143] [144] [145]
9	Saidemei	China	Automatic cell dismantling	Physical	Cu, Al, Fe, Carbon, cathode materials	Enovate[1]	~$45 NZD/kWh	[146]
10	Ecotec	New Zealand	unrevealed	unrevealed	unrevealed	unrevealed	0	[147]
11	Upcycle	New Zealand	Dismantling to cell level; ship overseas for recycling	none	unrevealed	Toyota NZ[1]	battery owners are charged	[11] [148]

Appendix E Economic Analysis of EV Battery Repurposing

The initial step of EV battery repurposing is to determine the usability of end-of-life EV batteries for BESS applications through testing and sorting. Therefore, the feasibility of EV battery repurposing should first be evaluated through economic analysis for the running of a battery repurposing facility.

By determining the battery types for repurposing and estimating the number of end-of-life batteries that can be collected and processed each year, the initial capital investment for the testing equipment, the annual expenses (e.g. battery purchase and transport, labour, electricity for battery testing and facility daily running, facility rental, etc.) and the annual revenue through the sales of repurposed batteries can be estimated. These estimations are used to calculated the NPV, which determines whether and when the battery repurposing business can become profitable.

It is also worth mentioning that although the concept of "battery selling price" is introduced, it does not necessarily mean that the batteries after testing are sold to others to produce second-use BESS. This concept is only adopted as a tool to decide whether it is worthwhile to run a repurposing facility instead of buying repurposed batteries from others and whether repurposed batteries can compete against new batteries whose costs are steadily decreasing.

Since it is difficult to make reasonable assumptions for longer terms, the economic analysis is only performed within a period of 6 years, from 2020 to 2025.

1. Selection of Battery Types and Estimation of Numbers of Batteries Collectable

The New Zealand EV registrations published by Ministry of Transport [149] is a key reference to determine the availability of the batteries by different EV brands. It is revealed that with 8,273 EVs being registered, Nissan currently accounts for 58% of the New Zealand EV market share and is by far the most popular EV brand. Besides Nissan, the market share is scattered among various other brands, with the second and third popular brand (i.e. Mitsubishi and Hyundai) only take 13% and 7% of the market share respectively.

Besides the percentage-wise figure, the absolute numbers of the batteries of different EV brands that are collectable should also be estimated. In this analysis, the estimation is based on the numbers of end-of-life batteries estimated by Vector [13], the distributions of EVs among different regions published by Ministry of Transport [150] along with the following assumptions.

- The New Zealand EV market share by brands will remain the same till 2025;
- The distribution of end-of-life EV batteries among different regions follows the same distribution of EV registration, and it will remain the same till 2025;
- 50% of the end-of-life EV batteries in South Island can be collected. It is assumed that the repurposing of the North Island batteries in South Island is less economic due to the extra costs of sea freight. The establishment of another North Island-based facility could be more feasible;
- Batteries from Nissan Leaf Gen.1 account for nearly 100% of all the end-of-life Nissan EV batteries in New Zealand till 2025.

Table 7: Estimation of the numbers of collectable end-of-life batteries

Brand / Model	Numbers of end-of-life batteries collectable					
	2020	2021	2022	2023	2024	2025
Nissan Leaf Gen.1	41	62	155	258	340	530
Mitsubishi	9	14	35	58	76	119
Hyundai	5	7	18	30	39	61
BMW	4	5	14	23	30	46
Toyota	3	5	13	21	28	43
Tesla	3	5	12	21	27	42
VW	1	2	5	8	10	16
Others	4	5	16	30	38	59

Based on these assumptions, the numbers of end-of-life batteries that can be collected from 2020 to 2025 for each EV brand is estimated in Table 7. It is shown that only the collection of Nissan Leaf Gen.1 batteries has the potential to achieve economies of scale, which will be further verified in the next section. Besides volume, the following factors also facilitate Nissan Leaf Gen.1 repurposing.

- **Availability of onboard diagnostic data**. Battery scanning which reveals important diagnostic data (e.g. the overall SoH of the battery pack, the voltage level of each battery cell, the numbers of quick and slow charges) can be easily performed through OBD2 devices [151]. Due to the availability of diagnostic data, the adoption of conventional and time-consuming test protocols that evaluates the battery SoH through full charging / discharging circles at low C-rates (e.g. C/5 [152] or C/3 [93]) can be avoided [93]. Instead, the battery SoH can be quickly evaluated through a partial charging circle with higher C-rates based on advanced SoH identification algorithms [93].

- **A general healthy state of the Nissan Leaf Gen.1 batteries**. According to Flip the Fleet, more than 50% of the 2011 Nissan Leaf Gen.1 surveyed have a SoH of above 72% and less than 5% having a SoH lower than 66% [153]. As it is assumed that two thirds of the EV batteries in New Zealand will reach end-of-life after 9 to 11 years [13], an optimal DoD range of 50% for the maximization of the second-use battery energy throughput [93] can be applied under these SoH levels.

- **Small module size**. It is assumed that module-level repurposing will be performed, as it minimizes total costs [154]. The small module size of Nissan Leaf Gen.1 (4 cells per module, 48 modules per pack [155]) can reduce the number of faulty modules under a certain cell fault rate [93] and also increase the homogeneity of cell SoH within each module. Although this comes at the cost of reduced testing efficiency [93], it could be compensated by the adoption of advanced SoH identification algorithms.

2. Determination of the Battery Purchase and Selling Prices

In some markets outside New Zealand, a huge amount of end-of-life EV batteries can be collected and economies of scale is thus already achieved by recyclers. Therefore, the end-of-life EV batteries are purchased at relatively higher prices. For example, Chinese EV manufacturers including SAIC-VW and Enovate have signed agreements with battery recyclers. Under these agreements, recyclers will purchase end-of-life batteries at a price of roughly $25-45/kWh [145] [146]. It is also estimated that battery purchase cost will account for the largest portion of the operating expenses for US-based repurposing facilities [93].

In comparison, battery recycling is not yet economic in New Zealand due to its small market scale and less advanced technologies. Therefore, recyclers can either acquire the battery for free or even get paid [147] [148]. This provides a unique opportunity for New Zealand-based repurposing facilities to get end-of-life batteries at low prices. Accordingly, the battery purchase price is initially set at $10/kWh for economic calculation. The purchase price will also be adjusted for sensitivity analysis.

As mentioned above, the repurposed battery selling price determines whether it is worthwhile to run a repurposing facility and whether repurposed batteries can compete against new batteries. Therefore, the price will be determined based on the following criteria.

- Firstly, the battery selling price should not be higher than the prices of repurposed batteries offered by other companies. For example, used Nissan Leaf Gen.1 modules are sold at $250NZD/kWh by Blue Cars Ltd in New Zealand [156]. A US-based repurposing company Greentec Auto also sells Nissan Leaf Gen.1 modules at roughly $240NZD/kWh for modules and $180NZD/kWh for packs [157].

- Secondly, the battery selling price should also be lower than the new battery prices for energy storage. It is estimated that the EV battery module costs will reach $94USD/kWh in 2024 [22], which can be derived based on a price of $176USD/kWh in 2018 [22] and an annual price decrease of 10%. It is also estimated that battery for energy storage is 51% more expensive due to the much lower order volumes [5]. It should also be noticed that new Li-ion batteries are normally operated at a DoD range of 90% or higher. In comparison, an optimized DoD range for second-used batteries is only 50% [93]. This means repurposed batteries should be at least 50% less expensive than new batteries because the usable energy capacity of repurposed batteries is only half of their nameplate energy during first use. Besides, new batteries in New Zealand could also be more expensive due to the smaller market demand and geographic isolation. This means the price estimation could be conservative since this factor is not taken into consideration.

Table 8: Estimation of the battery selling price

Battery selling price	2018	2019	2020	2021	2022	2023	2024	2025
New ($USD*/kWh, EV)	176	158	143	128	115	104	94	84
New ($NZD*/kWh, BESS)	403	363	326	294	264	238	214	193
Second-use ($NZD/kWh, BESS)	201	181	163	147	132	119	107	96

**It is assumed a USD to NZD exchange rate of 1.52 in January 2020 is adopted*

Based on the second criterion, the targeted second-use battery selling price does not remain constant but decrease steadily from $201/kWh in 2018 to $96/kWh in 2025 (Table 8). Since the current price determined by this criterion (i.e. $163/kWh for 2020) in not higher than the selling price offered by other repurposing companies (i.e. $180-250/kWh for 2020), this set of value will be adopted for the following economic analysis.

3. Estimation of Revenue and Expenses

Revenue is generated annually from the selling of repurposed batteries. It can be derived based on the annual throughput, the yield rate of the repurposed batteries and the battery selling price.

The expenses can be divided into the initial investment for the establishment of a repurposing facility (i.e. the purchase of test equipment, work stations, conveyors, forklifts, storage racks, etc.) and the regular annual expenses which are spent to maintain the facility's operation. The annual expenses can be further classified as direct costs (i.e. battery purchase and transport, labour, rent, etc.) and indirect costs (i.e. insurance, general and administrative (G&A), warranty, research and development (R&D)).

Based on the following assumptions, the revenues and expenses can be estimated by using the NREL's repurposing cost calculator [154].

- The equipment purchased and the facility layout are planned according to both the recommendations by NREL's calculator [154] and the actual operational plan. This means the facility should be big enough and there should be enough equipment for the estimated throughput for 2025.

- Due to the availability of battery diagnostic data, it is supposed that advanced SoH evaluation technology can be adopted. As suggested by NREL [154], 75 minutes will be needed for electrical testing, which includes battery charging at 1C for 60 minutes.

- There are three types of permanent positions. Module test technicians are responsible for the inspection of the modules before and after electrical testing, the connection / disconnection of the modules and initiation of the test programme. Pack technicians oversee the inspecting and dismantling of the battery packs. Forklift drivers are employed for the logistics within the facility. It is also assumed that no additional managers or engineers will be appointed, at least in the short term, for an already established company that wants to expand its business. The numbers of employees employed each year are determined by both the handling time needed for each operation suggested by NREL [154] and the estimated annual throughput of the facility[1].

- Various New Zealand-based price indicators are used for financial calculation (e.g. the employment costs, the rental price, the electricity price, tax rate, discount rate, etc.). For example, an annual discount rate of 7% suggested by New Zealand Treasury [158] is adopted. If New Zealand specific prices are not available (e.g. price of the test equipment), prices suggested by NREL [154] are adopted.

- It is assumed that end-of-life battery modules averagely possess 70% capacity retention at the time of repurposing. It is also assumed that the average yield rate is 98%. This means one cell within each battery pack is defective, and 1 of the 48 modules within each pack will be discarded.

Table 9: Economic analysis for the operation of a repurposing facility

	2020	2021	2022	2023	2024	2025
Number of packs processed	41	62	155	258	340	530
Facility annual throughput (kWh)	984	1488	3720	6192	8160	12720
Number of module test technicians	1	1	2	3	4	6
Number of pack technicians	1	1	1	1	1	1
Number of forklift operators	1	1	1	1	1	1
Total employment cost ($)	189380	189608	261012	332529	403705	546512
Battery purchase cost ($)	9840	14880	37200	61920	81600	127200
Facility rental cost ($)	36600	36600	36600	36600	36600	36600
Transportation cost ($)	768	1024	2560	4224	5504	8576
Electricity cost - testing ($)	162	245	613	1020	1344	2095
Electricity cost - facility running ($)	403	403	403	403	403	403
Total direct cost ($)	237154	242760	338387	436696	529156	721386
Insurance (direct cost * 3%) ($)	7115	7283	10152	13101	15875	21642
G&A (direct cost * 5%) ($)	11858	12138	16919	21835	26458	36069
R&D (direct cost * 3%) ($)	7115	7283	10152	13101	15875	21642
Warranty (revenue *5%) ($)	7856	10692	24058	36040	42745	59969
Total indirect cost ($)	33943	37396	61280	84077	100952	139322
Initial investment	201566					
Expenses ($)	472663	280156	399668	520773	630108	860707
Revenue ($)	157128	213847	481156	720803	854906	1199382
Taxes ($)			12223	30005	33720	50801
Net Profit ($)	-315536	-66309	69265	170026	191078	287874
NPV ($)	-315536	-61668	59907	136761	142936	200270
Cumulative Present Value ($)	-315536	-377203	-317296	-180535	-37599	162672

[1] A conservative approach for the estimation of employment cost is adopted, as full wages are paid to the staffs who are not fully occupied.

The result of the economic analysis is shown in Table 9. It is revealed that an initial investment of roughly $200,000 is needed for the running of a repurposing facility with an annual capacity of 530 Nissan Leaf Gen.1 battery packs. The employment costs account for an overwhelming majority of the annual expenses throughout the next six years. The maximum loss at nearly $380,000 will occur in 2021. Afterwards, annual revenues will exceed expenses as more and more battery packs become collectable. The cumulative present value is estimated to be positive in 2025, with an accumulated earning of $162,672 in the same year. it is concluded that although initial losses are inevitable, the EV battery repurposing can still be profitable in the long run.

Besides the baseline scenario, there are also potential variables which may influence the profitability of repurposing. Therefore, a sensitivity analysis is performed to estimate the potential impacts based on the following assumptions, with the results shown in Fig.6.

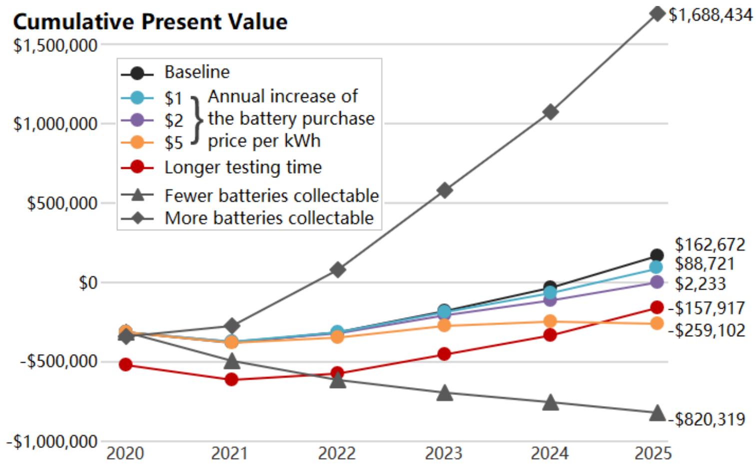

Figure 6: Sensitivity analysis of EV battery repurposing

- **Higher battery purchase price**. As more and more end-of-life EV batteries becomes available, battery recycling in New Zealand may achieve economies of scale and higher prices may be offered by recyclers. Therefore, the battery purchase price for repurposing may also need to be increased to compete with recycling.

  - When the battery purchase price increases moderately by $1/kWh or $2/kWh annually, the cumulative present value could still become positive in 2025, but it will be decreased to $88,721 and $2,233 respectively.

  - With an annual battery purchase price increase of $5/kWh (i.e. battery purchase price at $35/kWh in 2025, which is similar to the current price level in the Chinese market), it is estimated that the cumulative present value not only remains negative in 2025, but will also unlikely to be positive in the long run, as it shows a downward trend from 2024.

- **Longer battery testing time**. Conventional and time-consuming testing methods need to be adopted if advanced SoH technology is unavailable. Accordingly, the electrical testing is assumed to last 190 minutes, which includes battery charging at C/3 for 180 minutes. It is revealed that in comparison to the baseline scenario, the cumulative present value will decrease but its growing trend will remain the same. This can be explained through the fact that only the initial investment will increase and the employment cost will remain the same, as more battery testing equipment will be needed and the time length of manual operation by technicians (i.e. inspection, connection, disconnection and initiation of the electrical test) remains unchanged.

- **More or fewer batteries collected**. The sensitivity to volume of batteries collected is tested by the following assumptions:

  - A similar repurposing facility is established in North Island to collect more end-of-life batteries. Based on the same assumptions described in the first chapter of Appendix E, it is estimated that the numbers of Nissan Leaf Gen.1 batteries collected each year in North Island will be more than twice the numbers of batteries collected in South Island. Accordingly, the cumulative present value can become positive in 2022 and will reach $1,688,434 in 2025, which is more than 10 times higher than that of the baseline scenario.

  - The numbers of batteries collected decrease to roughly one fifth of the baseline volume (i.e. the same level of the estimated numbers of Mitsubishi batteries in Table 7). As a result, the cumulative present value decreases steadily and an enormous loss of over $800,000 will be incurred in 2025 due to lack of scale.

By combining all the factors, it can be concluded that the repurposing is economically feasible only when a relatively large volume of end-of-life batteries can be secured. Based on this premise, the adoption of conventional and time-consuming SoH estimation methods and a modest annual increase of the battery purchase price can be tolerated, particularly when an abundant supply of end-of-life batteries is foreseeable.

Appendix F Case studies of BESS applications based on repurposed EV batteries

Due to the uncertainties of input parameters (e.g. different load profiles from different household and C&I users, different electricity tariff structure, fluctuation of the solar irradiance for PV + storage systems, availability of the subsidy schemes, etc.), the economic evaluation for battery storage applications in real-life is also characterized by its complexity.

Therefore, besides focusing on the initial capital investment, it is also of vital importance to minimize the LCOS through an optimal sizing of the storage system, in order to shorten the payback period. There are various BESS sizing studies for different application scenarios, including household PV + storage [159] and industrial BESS for peak shaving [160]. There are also web tools such as REopt Lite [161] that facilitate the integration and optimization of renewable energy.

However, although a tailored BESS sizing for each usage scenario is indispensable for minimizing the payback time, it will not be analysed in detail as it is beyond the scope of this report. Instead, the evaluation of the second-use BESS profitability will be performed based on two typical usage scenarios (i.e. Household under ToU tariff, C&I PV + storage), the pre-determined BESS sizes (e.g. 2kW/12kWh for household, 40kW/240kWh, 80kW/240kWh and 80kW/480kWh for C&I) combined with sensitivity analysis. Despite a large number of assumptions, the case studies can still evaluate the usability of second-use BESS for these usage scenarios, prove its cost-effectiveness against first-use ones and identify the enabling factors that consolidate its application.

1. Usage Scenario One: Household Users under ToU Tariffs

In this scenario, BESS is applied by household users to absorb cheap electricity from the grid during off-peak hours, thus reducing or avoiding the consumption of expensive peak electricity. The economic evaluation is performed based on the following assumptions.

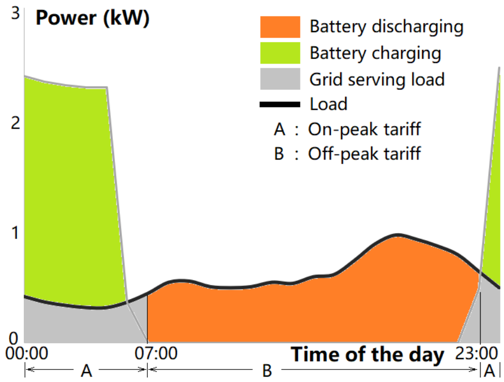

Figure 7: Example of BESS operation profile (2kW/12kWh system)

- The average yearly electricity demand profile of a typical Australian household on an hourly basis [162] is used (Fig.7). The daily electricity consumption is 13.93kWh. The load variations between weekdays / weekends and among seasons are not considered.

- A typical New Zealand ToU tariff structure of $0.17/kWh off-peak and $0.25/kWh on-peak [6] is used. The off-peak and on-peak hours are 11pm to 7am and 7am to 11pm respectively, for both weekdays and weekends [163].

- BESS is charged at its maximum power when the off-peak electricity is available (i.e. charging starts at 11pm) to ensure the absorption of cheap electricity as quickly as possible (Fig.7). The absorbed electricity is then injected to power the household during on-peak times at its required load, when not exceeding the BESS's maximum power output.

- The BESS capacity degrades according to the warranty terms. The annual degradation rate remains constant and the energy capacity level remains the same within each year. (e.g. a BESS with a 10-year warranty for 70% capacity retention is expected to have an annual capacity degradation of 3.5%). It is also assumed that BESS possesses an AC round-trip efficiency of 90% throughout lifespan.

- The economic analysis is performed within a time span of 10 years. An annual discount rate of 7% suggested by New Zealand Treasury [158] is adopted. A 1% annual inflation rate of the electricity prices is estimated based on historical electricity price provided by MBIE [164].

- For the second-use BESS, 48 modules (24kWh) of the repurposed Nissan Leaf Gen.1 batteries are used, with a price of $163/kWh (battery selling price for 2020 determined in Appendix E).

The usable DoD range is limited to 50%, so the usable energy capacity is 12kWh. It is also assumed that the maximum power output/input is 2kW and there is 70% capacity retention after 10 years.

Besides the second-use BESS, the economic evaluation also covers some of the commercial BESS products listed in Appendix B, in order to compare both the technical and economic aspects between first- and second-use BESS.

Table 10: Input parameters for economic evaluation (household user, ToU)
Source: adapted from Appendix B

Brand	Tesla Powerwall 2	Sonnen ECO 8.2/4	LG Chem RESU 6.5	Panasonic LJ-SK84A	Second-use BESS
Usable capacity (kWh)	13.5	4	5.9	8	12
Power (kW)	7	2	4.6	2	2
Round trip efficiency	90%	90%	90%	90%	90%
Approx. Price ($NZD)	13450	11200	9500	13000	3912*
Warranty (years)	10	10	10	10	10
Capacity retention at warranty end	70%	70%	60%	60%	70%
Yearly capacity degradation	3.5%	3.5%	5.0%	5.0%	3.5%

* battery module price only

As shown in Fig.8, it is revealed that the cumulative present value inflow throughout a lifespan of 10 years fluctuates greatly among different BESS from $547 to $1807. None of the systems, including the second-use BESS, can recover the initial BESS purchase cost, as the cumulative present value inflow only accounts for roughly 5% to 14% of the cumulative present value outflow (i.e. the BESS purchase). This result is in accordance with the evaluation by Transpower that BESS for household ToU is currently not cost-effective [6].

However, second-use BESS can be competitive against first-use BESS in price, if the other costs besides battery module (e.g. BMS, BOS, profit, etc.) can be kept low. Cost control can be facilitated by the low P/E ratios since some of the BOS components including the inverter are priced based on power rather than energy capacity [21].

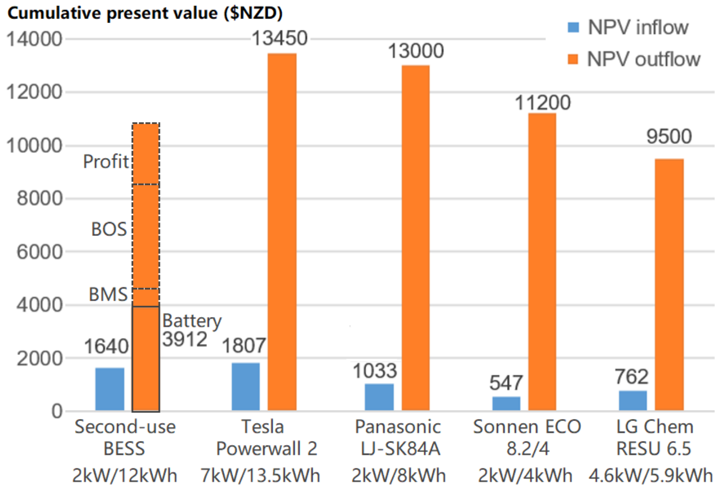

Figure 8: Cumulative present value throughout BESS lifespan (household user, ToU)

By analysing the yearly NPV inflow (Fig.9), the favorable factors for second-use BESS can be more clearly explained.

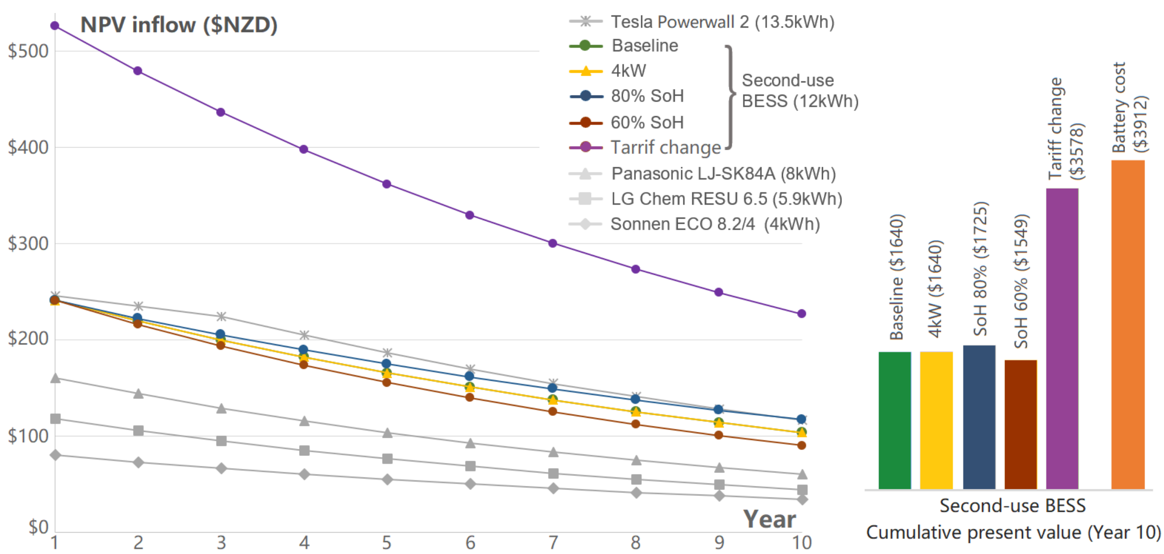

Figure 9: Yearly NPV inflow, second-use BESS cumulative present value (household user, ToU)

- NPV inflow is hugely influenced by energy capacity. This means, NPV inflow is higher if a larger portion of the on-peak grid electricity consumption can be avoided. As the BESS energy capacity drops from 13.5kWh to 4kWh, the NPV inflow in Year 1 also decreases dramatically from roughly $250 to $80.

- Power capacity barely influences NPV inflow. A long off-peak period (i.e. 8 hours from 11pm to 7am) in the pre-described typical household load profile means that there's ample time for the battery to be fully charged at low C-rates. The peak load during on-peak hours also rarely exceeds the maximum BESS power when ignoring the short-term fluctuations, thus allowing it to be fully covered by BESS. As a result, it is estimated the annual NPV inflow of the second-used BESS will remain identical at a doubled power capacity of 4kW.

- Capacity degradation only exerts limited influence on NPV inflow. If the 10-year capacity retention of the second-use BESS drops from 70% to 60%, the cumulative present value inflow will only incur a decrease of 5.5% from $1640 to $1549. Therefore, even if the second-use BESS capacity degradation is more severe than estimated, the negative impacts on BESS profitability will be limited. As second-use BESS are designed to operate at a partial DoD range with low C-rates, it is also likely that the actual degradation is less severe than estimated. At a 10-year capacity retention of 80%, an extra cumulative present value inflow of $85 (i.e. a 5.2% increase) can be generated by the second-use BESS.

- The ToU tariff structure has a significant impact on profitability. If the average ToU tariff of $0.17 off-peak, $0.25 on-peak is replaced by a tariff of $0.15 off-peak, $0.30 on-peak, the cumulative present value inflow will be more than doubled from $1,640 to $3,578 and can almost cover the battery cost of $3,912. This result verifies Transpower's finding that value of BESS for household users can be better realized through the introduction of a cost-reflective tariff structure [6].

Based on the analysis above, it can be concluded that although a payback period of 10 years is currently unreachable for household users under the above-mentioned ToU tariff structures, second-use BESS can still compete against first-use BESS due to its potential cost advantage, by offering a low P/E ratio system with a large energy capacity which can reduce or fully avoid the consumption of expensive on-peak grid electricity. The potential capacity degradation has limited impact on BESS profitability, this presents other favorable factor for second-use BESS. Besides, it is also revealed that the profitability is more reliant on the tariff structure itself rather than the choice of BESS.

2. Usage Scenario Two: C&I Users, PV + Battery Storage

In this scenario, BESS is applied by C&I users to increase the self-consumption of PV generation by storing the excess generation for later use, which would otherwise be abandoned or sold back to the grid at cheap prices.

For load profiles with demand peaks that do not match with times of solar generation, the value of

BESS will be higher as storage reduces the amount of electricity that needs to be imported. Therefore, a typical load profile of a dairy farm that has low power demand during peak solar generation [165] is adopted for economic evaluation, with the following assumptions.

- Since this report only focuses on the economic analysis of BESS, it is assumed that a PV system is already installed and only the additional costs and benefits from adding a BESS to the PV system will be considered.
- The analysis only focuses on an optimal summer day when the solar irradiance reaches the yearly maximum and solar generation reaches its theoretical maximum output (i.e. no sunshine blocked by the clouds throughout the day). It is also assumed that the peak PV generation is roughly 90kW with a distribution curve of summer PV generation downloaded from NIWA [166] with the following parameters:
  - Location: Christchurch; Panel tilt: 44 degrees; Panel bearing: 0 (facing north).
- Repurposed Nissan Leaf Gen.1 battery modules are used. The unit module price is $163/kWh (battery selling price for 2020 determined in Appendix E). The usable DoD range is limited to 50%.
- Several scenarios are considered during economic analysis.
  - Scenario (a): no BESS is applied;
  - Scenario (b): 960 repurposed Nissan Leaf Gen.1 battery modules are used for a BESS of 40kW/240kWh;
  - Scenario (c): 960 repurposed Nissan Leaf Gen.1 battery modules are used for a BESS of 80kW/240kWh.
  - Scenario (d): 1920 repurposed Nissan Leaf Gen.1 battery modules are used for a BESS of 80kW/480kWh;
- The analysis only focuses on the first year of BESS operation. Throughout the whole year, no BESS capacity degradation happens. It is also assumed that all the BESS have an AC round-trip efficiency of 90%.

- BESS will be cycled daily. PV generation will first be used to serve load, when excess generation is available, it will be used to charge the BESS. After BESS being fully charged, the extra excess PV generation will then be sold to the grid.

- A fixed electricity price rate of $0.21/kWh, which is the average electricity price for agriculture sector revealed by MBIE [164], is adopted. The excess PV generation is sold back to the grid at a price of $0.08/kWh, as estimated by Transpower [6].

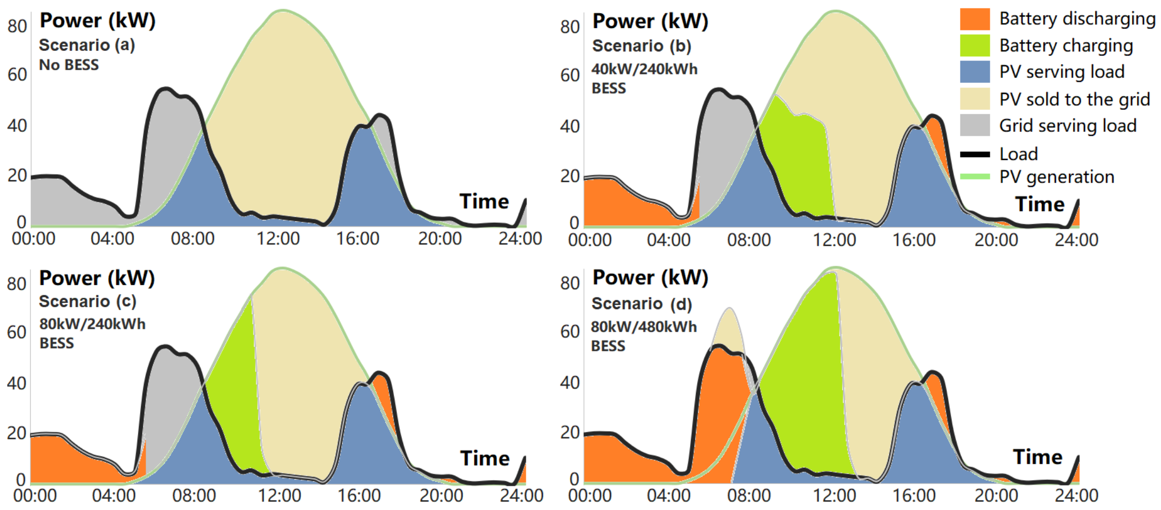

Figure 10: Daily load profiles of a typical dairy farm (PV only vs. PV+BESS)

Table 11: Daily load statistics of a typical dairy farm (PV only vs. PV+BESS)

	Scenario (a)	Scenario (b)	Scenario (c)	Scenario (d)
BESS nominal capacity (kWh)	-	240	240	480
BESS power (kW)	-	40	80	80
PV generation (kWh)	643.5	643.5	643.5	643.5
Load demand (kWh)	397.9	397.9	397.9	397.9
PV self-consumed (kWh)	200.25	318.15	318.15	416.9
PV sold to the grid (kWh)	443.25	325.35	325.35	226.6
Grid serving load (kWh)	197.65	90.25	90.25	5
PV self-consumption rate	31%	49%	49%	65%
Electricity self-sufficiency rate	50%	77%	77%	99%
Savings (reduction of grid load) ($)	42.05	64.60	64.60	82.50
Earnings (PV sold to the grid) ($)	35.46	26.02	26.02	18.12
Extra benefit through BESS ($)	-	13.12	13.12	23.12
Total benefit (10years, optimal*) ($)	-	33 062	33 062	58 262
Battery module costs ($)	-	78 240	78 240	156 480

** without the consideration of solar irradiance fluctuation and battery degradation, operational on weekdays*

The daily load profiles and the statistics for all the scenarios are shown in Fig.10 and Table 11 respectively. The key findings can be concluded as follows.

- Both PV self-consumption rate and electricity self-sufficiency rate increase with the BESS energy capacity. the PV self-consumption rate increases from 31% to 49% through the adoption of a 240kWh BESS, and it further increases to 65% when the energy capacity is doubled to 480kWh. Electricity self-sufficiency rate also rises from 50% to 77% and 99% through the adoption of 240kWh and 480kWh BESS. With lower battery module prices, second-use BESS possess advantage over first-use BESS in that a larger energy capacity can be achieved at the same price, if the other costs beside the battery modules remain identical.

- Both PV self-consumption rate and electricity self-sufficiency rate are barely influenced by the BESS power capacity. This can be deemed as a favorable factor for second-use BESS which are preferably configured at low P/E ratios to prolong life span. However, for C&I users who are also subject to demand charges, higher power capacities may be required, in order to fully cover the peak load.

- Similar to the analysis for household users under ToU tariff structure, despite a potentially lower price compared with first-use BESS, second-use BESS still cannot provide a cost-effective solution for C&I users under low electricity prices and simple tariff structures. It is estimated that even under optimal conditions, which is practically unachievable, the total 10-year extra benefit from the adoption of BESS still cannot cover half of the battery module costs, let alone the total BESS costs. Therefore, the repurposing of EV batteries alone cannot facilitate the widespread of BESS. Instead, more attentions should also be paid in finding the suitable applications (e.g. C&I customers who are subject to more cost-reflective tariff structures such as highly volatile ToU rates or expensive demand charges).