

# Electric Vehicle Battery Life

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For the New Zealand Energy Efficiency and Conservation Authority (EECA) – April 2017

## Summary

The vast majority of modern electric vehicles (EVs) use lithium-ion batteries, which are designed to allow motorists to drive and recharge their EVs for many years with high reliability.

While these batteries can be recharged several thousand times, and still be useful after ten or more years of operation, the performance from these batteries naturally degrades slowly. Therefore, it is important to understand why EV batteries degrade, what the potential consequences are for the motorist, and how these batteries can be managed best to maximise their useful life.

This document considers the lifetime performance and cost of EV batteries by describing the underlying technology to help answer some of the frequently asked questions such as:

- How long do EV batteries last, and what influences this?
- What should be considered in relation to battery life when buying an EV?
- What are some best practices for using EVs in normal operation?
- What are the options to restore performance once a battery becomes degraded?
- Can spent EV batteries be repurposed or recycled?
- How does battery degradation influence the total cost of ownership for an EV?

A case study is used to show that, even with the full extra cost of battery replacement included, some EVs can still compete with petrol cars in New Zealand in terms of overall cost of ownership.

Recommended practices are also outlined to show how EV motorists can act proactively to get the best long-term results from EV ownership.

A survey of the New Zealand EV industry activity has found that many brands already have facilities in place, or are working quickly to establish facilities, for the recovery, repair and recycling of EV batteries in anticipation of significant future growth in the local market.

While the local market is still in its early stages, consumers should feel confident that they may choose to own and operate an EV in New Zealand without the battery becoming a prohibitive liability, and with professional industry support for their battery throughout the life of their EV.

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## Part 1: Understanding EV Battery Performance Degradation and Life

### How are electric vehicle batteries designed and built?

Electric vehicle (EV) batteries are extremely-sophisticated, high-performance devices designed to allow motorists to drive and recharge their EVs for many years with high reliability. Compared to other battery applications you may have prior experience with (such as rechargeable toy batteries, consumer electronics such as smart phones and laptops, or lead-acid starter batteries in your car or boat), EV batteries are an entirely new breed.

The vast majority of traction batteries in modern-day EVs are of lithium-ion chemistry. This is because, relative to other chemistries popular in other applications (such as lead-acid starter batteries), lithium-ion offers the right combination of attributes to make EVs competitive in the marketplace. These desirable attributes include:

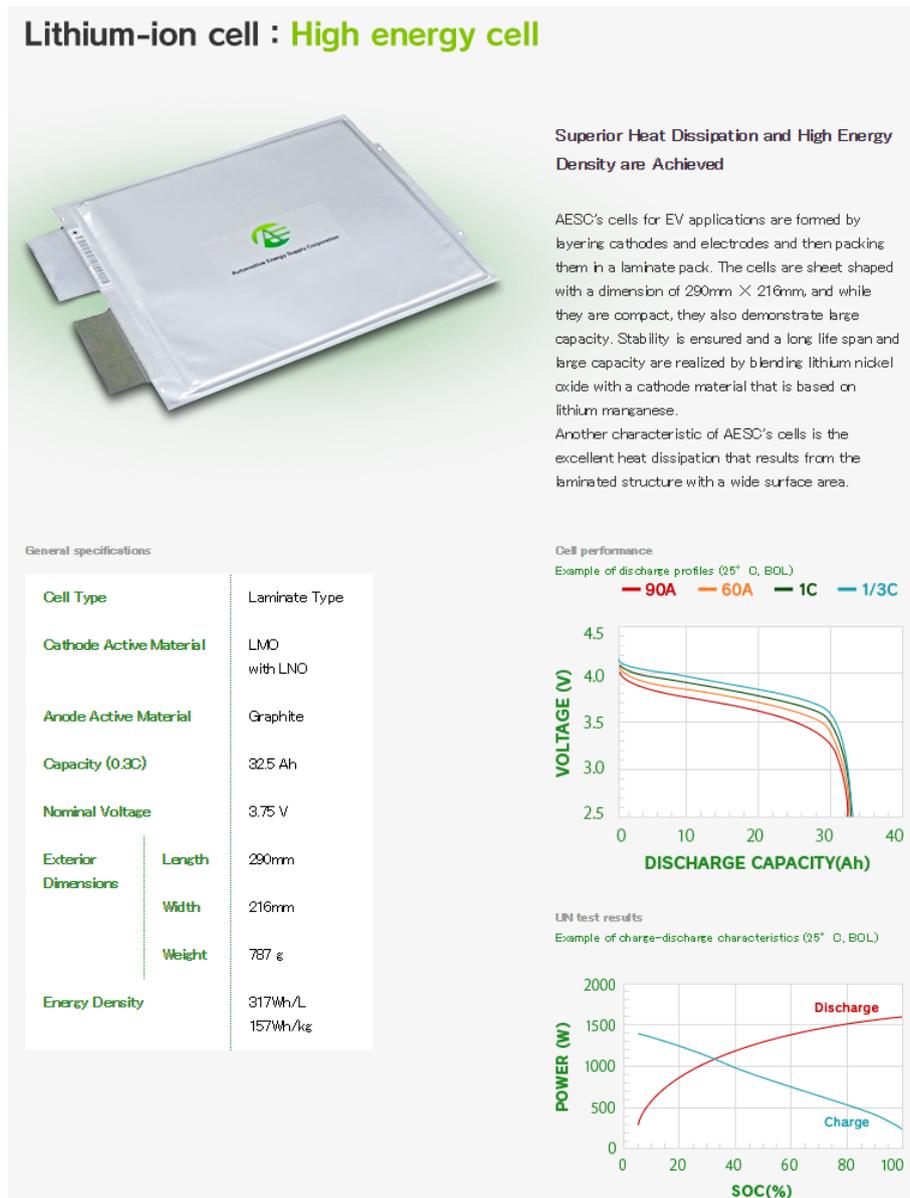
- **High performance:** enough energy density to provide a long driving range combined with enough power delivery to provide for fast acceleration
- **Long life:** durability that provides reliable operation for many years (potentially a decade or more) and without much preventative maintenance needed to achieve this reliability
- **Affordable cost:** such that EVs are projected to cost roughly the same as conventional vehicles, once manufactured in the same volumes (millions of vehicles per year).

To deliver this impressive combination of attributes, automotive manufacturers go to great lengths to select the right battery cells for their products and then to engineer them into high-performance, high-reliability, low-cost battery packs for mass-production in their quality-controlled factories.

From a systems perspective, an EV battery is assembled in three key levels:

1. The battery **cell** is made from a sandwich of electrochemical materials that generate a certain amount of electrical voltage and current. These cells are relatively fragile and are manufactured in specialised “clean-room” environments similar to those for making semiconductor chips. Figure 1 provides an example of a high-energy “pouch” cell manufactured by Automotive Energy Supply Corporation (AESC) and used in EVs sold by Nissan and Renault.
2. The cells are assembled into **modules** that constitute the building blocks for complete EV batteries. These modules are more physically robust and also contain components to help manage the health of the cells, such as electrical sensors and cooling channels. Figure 2 shows the module that is assembled from four of the cells shown in Figure 1.
3. The modules are then physically interconnected and packaged inside a rugged enclosure to create the overall assembly known as a battery **pack**. In addition to containing all of the battery cells (within the modules), the pack also includes charge and thermal management systems that are controlled and optimised by a built-in computer, using measurements

provided by the sensors contained within the modules. The rugged enclosure also provides the mounting points so that the battery pack can be firmly attached to the vehicle chassis. Figure 3 provides an example of battery packs assembled from 48 of the modules in Figure 2, and Figure 4 provides a schematic diagram of how the battery control systems work. The completed battery pack is a very large device, with the Nissan Leaf battery pack shown in Figure 3 having a total weight of approximately 300kg.



**Figure 1: the lithium-ion cell used in the Nissan Leaf EV (AESC, 2016)**

## Module : High energy module

A Compact Shape that Increases the Efficiency of Loading in Vehicles

The modules for EV use are formed by connecting 4 cells in a 2-series, 2-parallel formation and then housing the unit in metal case. The case functions to protect the cells from vibration and such and also increases the flexibility of the pack design because of its simple, compact shape.

The EV modules adopted in the Nissan Leaf and other vehicles feature a 2-series, 2-parallel formation, but applications with a 4-series formation are also possible.



General specifications

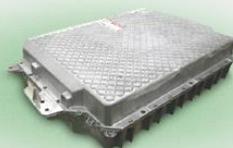
Number of Cells	4	
Structure	2 parallel, 2 series	
Exterior Dimensions	Length	308 mm
	Width	223mm
	Height	35mm
Weight	3.8 kg	

Figure 2: the lithium-ion module used in the Nissan Leaf EV (AESC, 2016)

## Pack : High energy battery pack



For the Nissan Leaf



For the Renault Kangoo

Vehicle Tailored Designs are Possible

The pack is formed by connecting multiple modules to sensors, a controller, and other components and then housing the unit in a case custom designed for each vehicle model.

The battery packs for both the Nissan Leaf and the Renault Kangoo are formed by connecting 48 modules in a series.

AESC's modules can be installed vertically or flat, and the pack can be designed with a shape that is tailored to the shape under the vehicle floor.

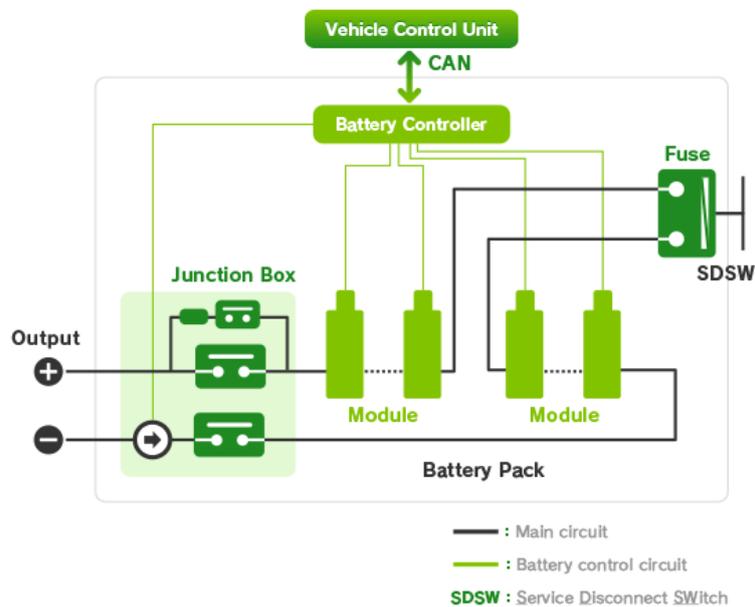
The packs for both the Nissan Leaf and the Renault Kangoo are designed with a voltage of 360V and a capacity of 24kWh and can store electric power that is equivalent to 2 days of electric power used by a standard home.

General specifications

Number of Modules	48
Nominal Voltage	360V
Capacity	24kWh

Figure 3: the lithium-ion battery pack used in the Nissan Leaf EV (AESC, 2016)

## Composition



Voltage, temperature, and such are constantly monitored by sensors attached to the modules in the pack. The data is sent from the battery controller to the vehicle control unit via a CAN (Controller Area Network).

When a vehicle is maintained at a service factory, the circuit is interrupted by operating the SDSW (Service Disconnect Switch) so that work can be safely performed.

**Figure 4: a schematic diagram of the Nissan Leaf battery pack (AESC, 2016)**

The battery pack for one model of the Nissan Leaf (as shown in Figure 3) has a total electrical energy storage capacity of 24kWh, which in simple terms is equivalent to the gross thermal energy content of approximately 2.5L of petrol (but noting that this is not necessarily a fair comparison, since the petrol burns in the engine with relatively poor efficiency – such that 24kWh battery storage is actually the equivalent of approximately 10L of petrol in terms of energy propulsion at the wheels).

It has become a common EV industry practice to describe battery life relative to when the batteries degrade to 80% of original capacity, but note this is a somewhat arbitrary definition that originally arose from laboratory testing protocols for battery cells. An EV battery may continue to provide significant utility and value below 80% residual capacity (depending on the application), and also battery degradation can manifest itself in other ways such as loss of current/power that may be of greater consequence in determining the true “end of life” in the real world.

Nevertheless, the residual capacity convention provides an objective way to quantify EV battery life, such that manufacturer’s warranty documents often describe the warranty coverage in terms of a certain percentage of residual capacity after a certain period of ownership (in time or distance).

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## What levels of warranty coverage do EV battery manufacturers provide?

There are a range of EV battery warranties provided in the New Zealand marketplace, and there are some important distinctions to be made for the sake of consumer awareness.

**Workmanship warranties** protect consumers against defects in the manufacture, assembly, delivery and servicing of their EV. For example these defects could be something as simple as a loose screw, or in more-severe yet highly-unlikely cases, a faulty battery cell.

For new EVs in New Zealand at the time of writing, the workmanship warranties ranged between five years/100,000km and eight years/160,000km.

**Performance warranties** protect consumers against deterioration of their EV battery, since the battery health is paramount in the driving range and acceleration performance of the vehicle. This is a new type of warranty not previously associated with petrol/diesel vehicles, but is considered especially relevant for EVs since even a healthy battery will still degrade over time to some extent. While EV performance warranties are not mandatory in New Zealand, there is a global trend to increasingly provide warranties of this type to help consumers feel more confident about the new EV battery technology.

At the time of writing, some manufacturers did not provide a performance warranty for their new EVs on sale in New Zealand. Of those that did, the performance warranty was specified as guaranteeing between 75-80% of original battery capacity after a specified period of time, usually at least five years, with one company offering 10 years unlimited km high voltage battery warranty for their EV.

The warranty offerings for **used-imported vehicles** are quite mixed. Some brands are providing reduced warranty cover for imported used vehicles, whereas some are not providing any cover. Nevertheless, most New Zealand EV brands say they will provide support for used-import EVs, even if this comes at the cost to the owner due to lack of cover. It should be noted however that some third parties are importing used EV models that are different to the official range currently provided and supported by New Zealand vehicle representatives, which may make it more difficult to get support for these EV models.

An established insurance company operating in New Zealand now offers EV breakdown and collision policies that cover the high voltage battery, and other insurers may follow suit.

Just like the manufacturer's warranty on the vehicle as a whole, it is also important to realise that a battery warranty statement is absolutely not the same thing as the expected life for the battery. Several overseas manufacturers have indicated an expectation that their EV battery will probably last the life of the vehicle, although at the time of writing these statements have not yet been made officially by any of the New Zealand EV manufacturers' representatives.

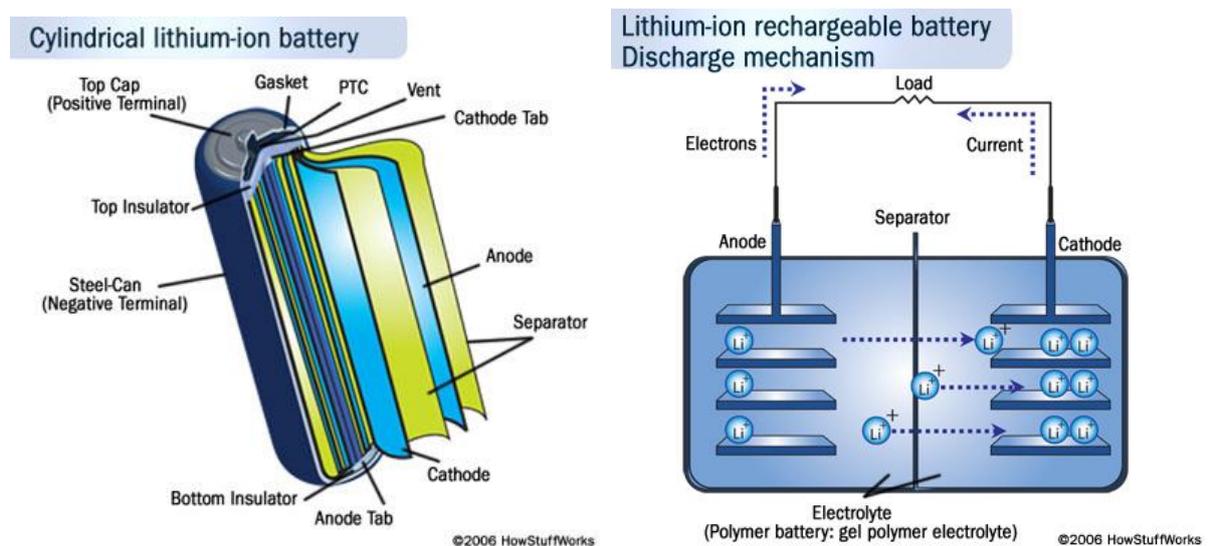
## Why do EV batteries fail?

EV batteries do not always fail or deteriorate due to the battery cells alone. There are many minor reasons why a battery fault can arise that may result only in the illumination of dashboard light, whereas in more severe cases there may be a loss of battery performance (with or without a dashboard warning light). Minor reasons can include poor connections of fasteners and ancillary monitoring components, or faults in cooling systems, etc. It is understood these minor faults can be relatively easily repaired by authorised personnel without loss in battery performance, either under warranty coverage or at relatively low cost to the consumer.

Whereas some degree of battery cell deterioration will always occur over the life of an EV, and the potential for “unacceptable” degradation (as well as the motorist’s liability for it) naturally goes up beyond the warranty coverage period. Therefore it is important to understand why EV batteries degrade and how they can best be managed to maximize their useful life.

## What is EV battery degradation and why does it occur?

Batteries are charged and discharged via a series of “primary” chemical reactions that occur within the active materials inside the battery. However, no battery is perfect and thus there are always some “side reactions” occurring that gradually cause the battery to wear out by altering the internal structure of the battery and converting some of the active materials into unusable forms.



**Figure 5: Diagrams showing how a lithium-ion battery cell is constructed, as well as the basis of its electrochemical operating principles – images courtesy of howstuffworks.com (Brain, 2016).**

For lithium-ion batteries predominant in modern plug-in vehicles, the chemical degradation mechanisms are extremely varied and complex (see Table 2) and it is far beyond the scope of this document to describe them all here. For a more-thorough description in this context, the reader is referred to a recent engineering report by FEV (Merichko, 2016). However, these degradation mechanisms can be relatively-easily described and understood in relation to the Solid Electrolyte Interface (SEI) – a thin layer that sits inside the battery at the precise location at which the primary reactions occur.

The SEI layer is always present inside the battery, given that it forms the moment the battery cell is first assembled, and it is a purely passive material that does not help the battery to generate power. The problem is that formation of the SEI layer consumes some of the battery’s active materials, and its location creates a barrier to the flow of electrical charge – both of which degrade overall battery performance. Battery degradation gets worse as various operating circumstances cause the SEI layer to grow further, and this degradation in battery performance can be observed in two ways:

- Loss of useable capacity as active materials are irreversibly converted or made inaccessible
- Loss of available current as the flow of electrical charge is increasingly hindered by the layer

**Table 2: Electrochemical degradation mechanisms in lithium-ion batteries (Merichko, 2016)**

Cause	Effect	Leads to	Reduced by	Enhanced by
Electrolyte decomposition (→SEI)(Continuous side reaction at low rate)	Loss of lithium Impedance rise	Capacity fade Power fade	Stable SEI (additives) Rate decreases with time	High Temperatures High SOC (low potential)
Solvent co-intercalation, gas evolution and subsequent cracking formation in particles	Loss of active material (graphite exfoliation) Loss of lithium	Capacity fade	Stable SEI (additives) Carbon pre-treatment	Overcharge
Decrease of accessible surface area due to continuous SEI growth	Impedance rise	Power fade	Stable SEI (additives)	High temperatures High SOC
Changes in porosity due to volume changes, SEI formation and growth	Impedance rise Overpotentials	Power fade	External pressure Stable SEI (additives)	High cycling rate High SOC
Contact loss of active material particles due to volume changes during cycling	Loss of active material	Capacity fade	External pressure	High cycling rate High DOD
Decomposition of binder	Loss of lithium Loss of mechanical stability	Capacity fade	Proper binder choice	High SOC High temperatures
Current collector corrosion	Overpotentials Impedance rise Inhomogeneous distribution of current and potential	Power fade Enhances other aging mechanisms	Current collector pre-treatment (?)	Over discharge Low SOC
Metallic lithium plating and subsequent electrolyte decomposition by metallic Li	Loss of lithium (loss of electrolyte)	Capacity fade, power fade	Narrow potential window	Low temperature High cycling rates Poor cell balancing Geometric misfits

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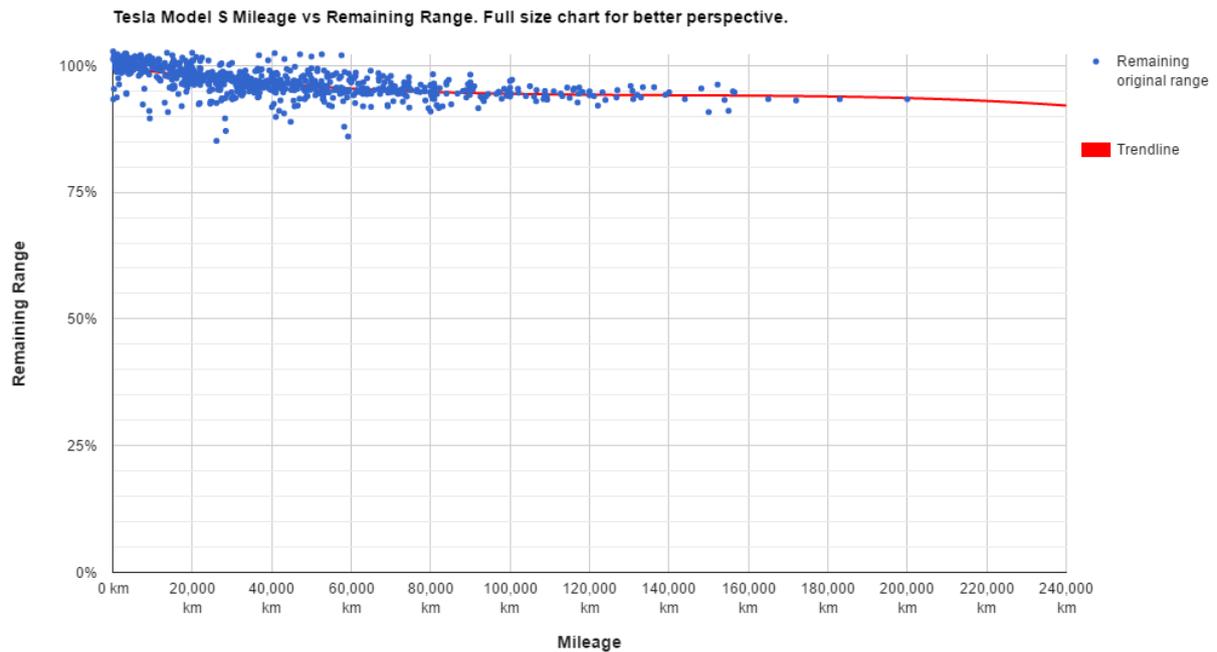
For an EV battery, this means that both the usable energy (range) and available power (acceleration) will lessen as the battery degrades. Fortunately, these degradation mechanisms typically occur at a very slow rate, such that a well-designed automotive battery will typically provide suitable performance for many years (if not decades) under intended operating conditions.

## How does EV battery degradation translate into useful EV battery life?

The rate of EV battery degradation, and how it translates into the useful EV battery life for the motorist, is influenced by three key factors in the real world:

- 1) How the EV/battery is typically operated** – this includes both the way the EV/battery is driven and recharged, as well as the ambient climate that the EV/battery resides within. This operating environment can be more or less degrading for the battery (based on growth of the SEI layer etc.) depending on a huge range of circumstances that vary between different motorists and climates.
- 2) How the EV/battery is designed** – this includes the attributes of the exact cells chosen by the manufacturer, the way these cells are designed into a larger battery pack, and the management systems that are incorporated to maintain optimum battery health. The design of the battery will determine how well it can handle the motorist’s operating environment, as well as how much tolerance it has for any undesirable operation outside the intended operating envelope.
- 3) How much EV performance is required by the motorist** – this recognises that a new EV/battery typically has more performance than the motorist typically needs, and that a degraded EV/battery (with less range, less acceleration, etc.) may still be able to meet the motorist’s daily needs. The ultimate definition of battery “end-of-life” is when it has degraded to the point that it can no-longer deliver the required performance, noting that different EV motorists have significantly different needs for range and acceleration.

Figure 6 provides an example of real-world battery degradation within a sample fleet of Tesla Model-S EVs (Lambert, 2016). The variance in the sample set is arguably due the first factor – differences in the operating patterns and ambient climates for different motorists. The shape of the trend line is arguably due to the second factor – how the Model S battery pack is designed and built – as this trend line shows the Model S range stabilising after a running-in period over the first 80,000km. Finally, the relatively slow degradation rate (only 5% degradation after 100,000km) is arguably due to the third factor – the Model S has a very large battery with a very high real-world range, and assuming a real-world range of 400km, the 80,000km running-in period equates to only 200 full discharge-recharge cycles, which is a relatively short time in the overall life of an EV battery.



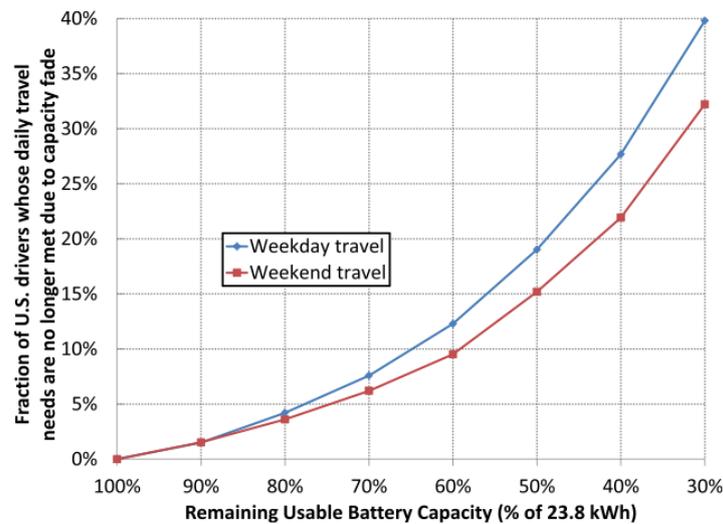
**Figure 6: Real-world EV battery degradation in a sample of Tesla Model S EVs (Lambert, 2016)**

There are also some interesting compounding effects (negative feedback loops) that may factor into how quickly an EV battery reaches its “end of life”:

- For example, a motorist who drives their EV very hard on a daily basis by using lots of performance is likely to cause their battery to degrade faster. However, because this motorist requires such high performance on a daily basis, the available battery performance is likely to fall to a level unacceptable to them much sooner as well.
- Furthermore, battery degradation is irreversible and cumulative, which means that as the battery performance declines it becomes more vulnerable to further degradation causing the overall trend to accelerate towards end of life. In other words, a worn-out battery degrades faster than a new one does – all else being equal.

Figure 7 shows the results of an insightful US study (Saxena et al, 2016) that sought to understand how battery degradation in EVs of more-modest performance (Nissan Leaf as opposed to Tesla Model S) could hamper their ability to meet the driving needs of the broader population. For the new battery capacity of 24kWh they found that only a negligible population would be affected, but as the degradation fell to 80% residual capacity, almost 5% of drivers would be affected – which is not a devastating result, but it could be enough to make some prospective buyers hesitate or cause some existing owners to become quite dissatisfied with their EV purchase.

Of these three key factors, it is only the first factor (how the EV is used) that can be affected by the motorist’s daily actions, so it is pertinent to understand how EV operation can affect EV battery degradation, with a view to outlining recommended practices to maximize EV/battery useful life.



**Figure 7: A study by Lawrence Berkeley National Laboratory (USA) to assess EV battery capabilities relative to the driving needs of the US population (Saxena et al, 2015).**

## How does EV operation influence battery degradation?

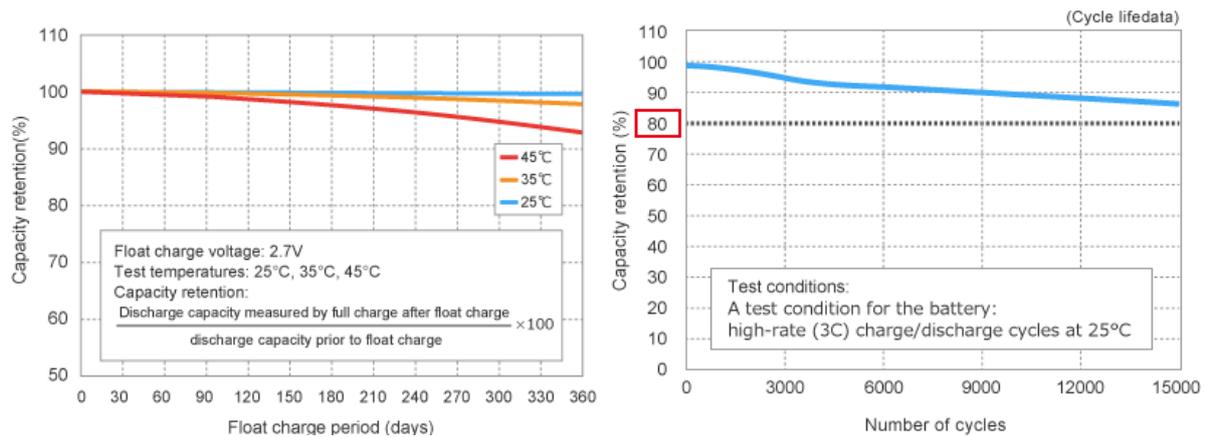
In simplified terms, there are two degradation mechanisms (that cause the SEI layer etc. to grow and battery performance to deteriorate) that may be influenced by how a motorist operates their EV:

1. Calendar Degradation
2. Cyclic Degradation

Both of these mechanisms cause the battery to lose its energy capacity and power delivery, and their effects are cumulative. Even though these two effects may be identified and tested for separately under laboratory conditions, in-practice they arise inseparably in real-world applications.

**Calendar Degradation** arises primarily when the battery is at rest (not being used). The rate of degradation via this mechanism depends on the temperature and voltage that the battery rests at, as well as the amount of time spent in this condition (hence “calendar” life). Calendar degradation occurs at a disproportionately higher rate for higher temperatures or higher voltages (the latter which occur with high states of battery charge), and the worst possible scenario is simultaneously high temperatures and voltages for extended periods of time.

For example, an EV that spends most of its time parked in a hot location (e.g. a rooftop carpark in full sun), with the battery simultaneously plugged-in and fully charged most of the time, is likely to experience a higher rate of calendar degradation.



**Figure 8: Laboratory testing of calendar degradation (left) vs. cyclic degradation (right) for a 20Ah lithium-ion EV battery cell manufactured by Toshiba Corporation (2016).**

**Cyclic Degradation** arises primarily when the battery is being used (charged or discharged). The rate of degradation via this mechanism depends on the amount of charge that has flowed through the cells (the cumulative number of equivalent full cycles), as well as the rate at which this charge has flowed (the currents). Deep energy-intensive cycles are more degrading than an equivalent number of partial/shallow cycles, and higher currents (in both directions, for charging and discharging) are more degrading than lower currents, especially at low temperatures. Furthermore, high discharge currents at low states of charge (when discharge impedance is worst), as well as high charge currents at high states of charge (when charge impedance is worst), can be particularly degrading. Another extremely damaging (and sometimes irreversible) scenario is when self-discharge causes the battery to discharge to a completely empty state.

For example, an EV that typically travels many kilometres relative to its range (i.e. lots of deep cycles), and is driven hard to empty (i.e. high discharge currents at low state of charge), and is fast-charged on a regular basis (i.e. high charge currents at high state of charge), is likely to experience higher rates of cyclic degradation.

Of these two degradation mechanisms, it is typically **Calendar Degradation** that matters most for pure EVs. This is because a typical EV has ample excess range and acceleration relative to its typical daily driving requirements. (For example an EV with 160km range might only be driven 40km per day on average, and rarely at full throttle due to speed limits or traffic.) Whereas a typical EV sits stationary for many hours in the day and EV drivers are inclined to keep their EVs fully-charged as a practical matter. Therefore EVs are more likely to suffer calendar than cyclic degradation.

For example, a series of real-world fast-charging tests on Nissan Leafs (Figure 9a) by the Idaho National Laboratory (Shirk & Wishart, 2015) concluded that it was actually the hot climate in the testing location of Phoenix, Arizona that caused the most degradation in the batteries, rather than fast-charging that only caused slightly more degradation relative to the “control” EVs that were slow-charged (Figure 9b, with AC slow charging results in blue consistently indicating higher battery capacity than the DC fast charging results in red).

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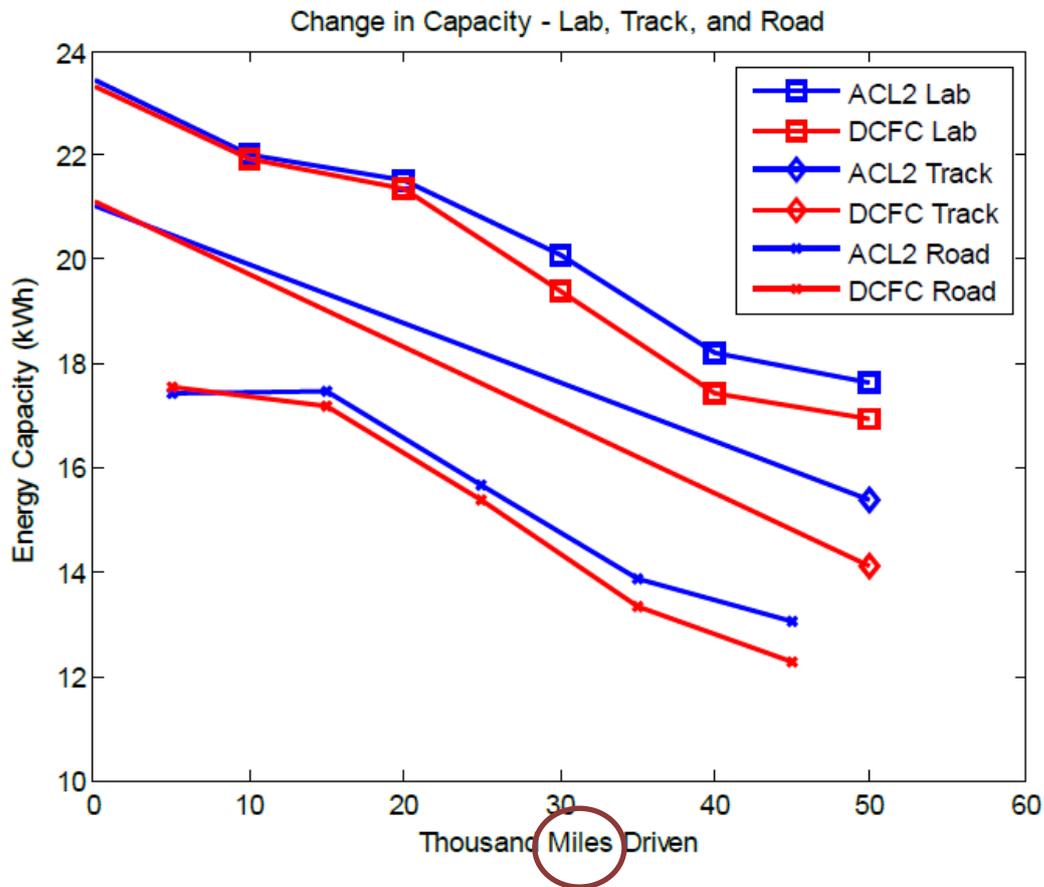
PHEVs are a more challenging situation given that the electric range of most PHEVs is a close match with typical daily driving distances (meaning typically deep cycles). Similarly, the typical currents experienced by PHEV batteries are larger relative to the smaller size of these batteries. This makes cyclic degradation more of an issue in PHEVs, and manufacturers compensate for this by selecting batteries that are more tolerant to cyclic degradation (but tend to have lower energy density), and also by using the control system to restrict the battery's operation to a more favourable regime (which is enabled by the combustion engine also being available to power the vehicle when required).

Also note the above scenario for EVs is the exact opposite to the lithium-ion batteries used in consumer electronic devices such as smart phones and laptops. These devices often experience multiple deep cycles in a single day, at a rate that is considered fast relative to the battery capabilities, and these devices also spend relatively less time sitting idle at full charge. Thus consumer electronic devices suffer relatively more cyclic degradation.

Note however that **Cyclic Degradation** in EVs can readily become more significant due to compounding effects. As the battery degrades and its range/acceleration performance diminishes, the susceptibility to cyclic degradation becomes more pronounced. Furthermore, the conditions that give rise to cyclic degradation (deep cycles, especially at high currents) will also cause more self-heating of the battery due to its internal losses. Hot batteries suffer from greater calendar degradation, and can be slow to cool down again due to their significant thermal mass. Fast charging can be potentially damaging in this regard, given that it simultaneously drives the battery to a high temperature and voltage, which may then be held for an extended period of time.



**Figure 9a:** The fleet of Nissan Leafs tested by the Idaho National Laboratory (USA) in Phoenix, Arizona (Shirk & Wishart, 2015).



**Figure 9b:** Slow-charging (in blue) vs. fast-charging (in red) degradation test results obtained by the Idaho National Laboratory (USA) for the fleet of Nissan Leafs operating in Phoenix, Arizona (Shirk & Wishart, 2015).

Long-term battery degradation and end-of-life is inevitably the result of a “death by 1,000 cuts” caused by cumulative and compounding effects of both calendar and cyclic degradation. Therefore, the long-term management of EV battery degradation is all about making trade-offs and finding the right balance on a day-to-day basis:

- EV motorists get the most utility from their EVs if they can keep them fully charged as much as possible, without having to worry about the climate in which they’re parked. But due to calendar degradation, some motorists need to be mindful of their charging patterns, especially if they live in hot climates. Manufacturers assist by including software features to artificially limit the level of a “full” charge and/or to postpone the completion of the charging cycle until needed, as well as by including cooling systems to protect batteries from high temperatures.
- EV motorists get the most utility from their EVs if they can drive lots of kilometres relative to the range of their vehicles, which may be further enabled by driving and recharging relatively fast. But due to cyclic degradation, some motorists need to be mindful of the

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number of cycles they're logging on their battery packs, especially if those cycles are at currents that cause their batteries to heat up. Manufacturers assist by including software features that artificially limit the vehicle performance to protect the battery when necessary, as well as by including thermal management systems to protect batteries from cold temperatures.

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## Part 2: Recommended Best Practices for EV Buyers and Owners

In terms of EV battery degradation, there are universally-agreed best practices to help get the most battery life and hence the most long-term value out of your EV. These include questions you should ask while shopping for your EV to help manage your expectations, as well as good habits you can develop as an EV owner to minimise the battery's degradation and maximise its useful EV battery life.

### Best practices for buying an electric vehicle

#### When buying an EV (whether new or used):

- Do your product research to understand the technical specifications and warranty coverage for the EV you are looking to buy. Also get in touch with existing owners of your intended EV to understand their anecdotal experiences and recommendations. There are several EV-user forums already active in New Zealand.
- Think about how you intend to use the EV, and compare that to the EV's performance specifications. For example, if your typical daily driving distance is closely matched to the range of your EV (e.g. 100km daily travel in an EV with only 120km range), then it is likely you will experience noticeable battery degradation. If you have the option to upgrade to a larger battery, consider how this might alleviate your battery degradation as well as improve performance. If you're looking at a PHEV, consider whether your operating requirements might cause the engine to come on "too often" (for example by exceeding the PHEV's electric range on a daily basis, or by regularly towing heavy loads), as this is also a good indicator of a PHEV battery being worked too hard. Also consider how practical it would be to make use of opportunity charging at convenient locations during the day if your daily range is close to, or exceeds that, of a single charge.

#### If buying a used EV:

- Ask the seller to provide you a measure of the battery's residual capacity:
  - Some EVs provide this data via the in-vehicle display
  - Others require a technician to connect diagnostic equipment to the vehicle (note some dedicated EV enthusiasts have also attained this capability via third-party equipment)
  - A private seller may share anecdotal experiences about changes to the performance
  - If the seller cannot provide the above types of information, be cautious!
- Also try to find out where the EV was previously located and how it was used:

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- Find out whether the EV resided in extreme hot/cold environments
  - Check the odometer reading and compare to the vehicle's age
  - If the EV has fast-charge capability, try to find out how often this was used
  - Find out if the vehicle has been in accidents or if battery parts have been replaced
- Find out what local servicing support will be available for your used EV

## Best practices for owning and operating an electric vehicle

### Following Manufacturer's Guidance

Review your EV owner's manual and always follow the guidance contained therein:

- Always abide by the battery warranty conditions. Not only will this ensure you retain warranty coverage, but it will also help to maximise your battery life (even after the warranty period has expired).
- Some EV manufacturers provide smart phone apps to help track and manage your EV battery status remotely – make use of them.

### Efficient driving habits

Learn how to “eco-drive” in your EV and make it a daily habit. Efficient driving reduces stress on your EV battery, which reduces degradation rates to help maintain battery performance, which also helps to avoid compounding effects in a weakened battery that further accelerate degradation.

Understand that by driving efficiently you will continue to extract the most daily utility and long-term battery life from your EV, even after the performance has degraded noticeably.



**Figure 10:** The user interface in your EV, such as this one in the Mitsubishi Outlander PHEV, may help you learn how to drive more efficiently, to reduce stress on your battery and prolong its life.

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## Managing Cyclic Degradation of a daily basis

Limit battery stress while driving, especially when operating at low states-of-charge:

- For pure EVs, try to avoid deep-discharging your battery pack by doing partial recharges on a frequent basis (but also consider the note above about full charging too often).
- For plug-in hybrids, pre-emptively use the engine to avoid rapidly depleting the battery in demanding driving conditions, such as during extended hill climbing or towing a trailer.

Also minimise use of fast charging (where applicable).

## Managing Calendar Degradation on a daily basis

Avoid full charging whenever you can:

- Don't recharge to full every day unless you need to.
- Use software/timers to minimise the time spent at a high state of charge

Keep your battery comfortable as best you can:

- Always try to park in the shade, rather than in full sun.
- During extreme hot or cold weather, park in a sheltered garage, rather than outdoors.
- If the weather is extreme (i.e. below freezing), plug in whenever you can to take advantage of your EV's battery thermal management systems.



***Figure 11: Your EV battery doesn't like extreme weather any more than you do, but plugging in can allow the EV thermal management systems to help keep the battery comfortable.***

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## **Parking and storing your EV for longer periods**

Plan ahead for periods of extended storage of one month or more:

- Store the vehicle in a sheltered location that will not get too hot or too cold.
- If your EV comes equipped with a “storage” charging mode – use it and keep it plugged in.
- Otherwise, don’t store the EV with a battery that’s too full or too empty:
  - A good compromise is just above half full (~60%) – which provides enough tolerance to long periods of self-discharge, but also enough range for a short drive if needed.
  - Also never let the vehicle sit unused for more than three months, and don’t let the state-of-charge in storage drop below 20%, without applying a “refresher” charge (back to ~60%).

### Part 3: Dealing with a Degraded EV Battery

As an EV owner seeking to maximise their battery life, it's important to understand you have many options to provide both preventative maintenance on your EV as well as ways to respond to battery degradation if/when it becomes a noticeable problem for you.

All New Zealand EV brands have reported that they either have facilities in place in New Zealand, or that they were in the process of establishing such facilities in New Zealand, that can fully service and replace EV batteries as necessary. For example, Figure 12 demonstrates that Mitsubishi Motors New Zealand has established a central handling facility in Porirua to assist the repair, recovery and recycling of EV battery packs in partnership with its dealer network (Mitsubishi Motors, 2016).

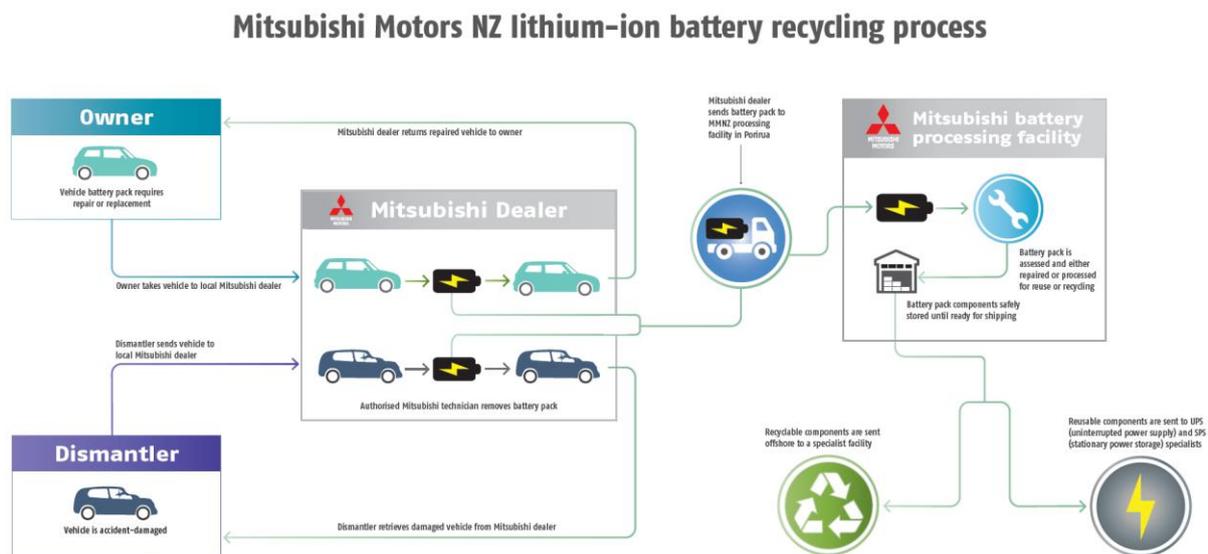


Figure 12: Mitsubishi Motors New Zealand lithium-ion battery recycling process

There are also third parties investigating the provision of battery maintenance and repair services and, while these may become available in the near- to medium-term, such providers will also need a strategy to stay current with the range of batteries present in the market over time.

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## Battery Warranty Claims

If your EV battery has a problem while still under warranty coverage, then the dealer/importer will determine the best course of action as per the specific terms of your warranty. Note that this does not necessarily mean you will get a brand-new replacement battery. Instead your dealer/importer might choose from one of the other options described below (repair, refurbishment, etc.) to get you back on the road with a fully-functioning battery.

As always, you should read the fine print in your warranty documents to fully understand the details of your cover, and always adhere to your warranty conditions to ensure you retain maximum coverage.

## Battery Servicing & Repair

The best protection against EV battery failure is regular servicing by an authorised technician (Figure 13).

**Motorists should never try to service or repair their own EV batteries** (unless they have the necessary qualifications and training). EV batteries contain lethal voltages that should not be risked! Furthermore, the battery cells, sensors, etc. may be vulnerable to damage from mishandling by unqualified persons.

If you've bought a new EV, be sure to follow your manufacturer's recommended service intervals, which are also typically required anyway as a condition of your manufacturer's battery warranty. As far as the battery is concerned, these services are typically a diagnostic inspection to verify that the battery is operating in good health, as well as a general inspection of contacts, connectors and battery case, with no other maintenance required unless a fault is detected.

If you've bought a used EV through a dealer/importer, be sure to find out what servicing support is available for your used EV. If you've bought your EV privately, try to find a local dealership who can service your EV. In many cases, a dealership that is authorised to sell/service new EVs will also be happy to service your used EV for a modest fee.

If something does go wrong with your EV battery, then your authorised service provider is the best person to ask because they have the appropriate diagnostic equipment and training to figure out the issue. Sometimes battery cells aren't the problem either. A complete EV battery pack is a complex assembly of many parts, and it's equally possible that a sensor has failed or a fastener has come loose to cause the error. Your authorised provider may identify a simple fix to get you back on the road again.



***Figure 13: An authorised technician uses an industrial hoist to help inspect the high-voltage underfloor battery in an electric vehicle. Do not try this at home!***

## **Battery Refurbishment**

Some EV batteries may be refurbished to restore their “near new” performance, but this is a complicated and hazardous process that requires extensive training in battery disassembly/reassembly, as well as in using the specialised diagnostic equipment that is used for identification, matching and balancing of cells.

Refurbishment is an emerging offer in the global EV market via specialist third party providers, as the quantity of used EV batteries grows to a volume substantial enough to make this business model viable. However at the time of writing, no commercial EV battery refurbishers were established yet in New Zealand.

Some refurbishers work via a wholesale relationship with manufacturers (to salvage and refurbish batteries that dealers cannot repair), and these wholesale refurbishers also benefit from being authorised by the manufacturer to work with their batteries. Motorists would typically obtain one of these wholesale refurbished EV batteries via an enquiry through their dealer/importer.

Whereas other refurbishers provide retail products directly to EV motorists, they may not have an authorisation from the manufacturer. For example, one Australian company (Hybrid Battery Rebuild) sells refurbished batteries for a claimed quarter the cost of a dealer replacement battery, and also provides a one year unlimited mileage warranty. While this is a legitimate alternative option in the market, motorists should carefully consider whether they want to obtain EV batteries from a provider who is not authorised by the manufacturer.

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Overall, it is still very early days in the battery refurbishment segment, so it remains to be seen what form the battery refurbishment industry will take in the future in New Zealand.

## Battery Replacement

EV batteries may be readily replaced by an authorised provider, as all EV brands in New Zealand have indicated that they have inventory and facilities available to provide this service.

Full replacement with a factory-direct new battery is clearly the most-expensive option, but battery prices are continuing to fall due to economies of scale in the rapidly-growing global EV market. Furthermore, as battery technology continues to improve, it is possible that the replacement battery will have better performance than the original battery, making it worthwhile. Finally, a total battery replacement should also renew the battery warranty coverage to provide further peace of mind.

Battery replacement costs are set by the global vs. local markets, and thus are continually varying and do not necessarily correlate between markets. At the time of writing, some estimates for total battery replacement cost from within the global marketplace were:

- Tesla Model S: NZ\$35,000 for 85kWh (US\$25,000)
- Nissan Leaf: NZ\$7,700 plus fitting for 24kWh (US\$5,500)
- BMW i3: NZ\$22,400 for 22kWh (US\$16,000)
- Outlander PHEV: NZ\$10,000 plus fitting for 12kWh (US\$7,000)

Note these prices are not necessarily reflective of current prices in New Zealand, given that these are continually evolving and in some cases for certain brands have not been fully disclosed as of yet. Furthermore, these prices are certainly not a good indicator of how battery costs will have fallen further through economies of scale in the New Zealand and global markets in 5-8 years' time.

Note that the net replacement cost is also heavily-influenced by the residual value of the battery, as determined by the emerging markets for repurposed or recycled batteries (see sections below). In the future the dealer price for a replacement battery may include some form of credit on this basis.

In the next section, we present a case study for the Total Cost of Ownership (TCO) of an EV versus a petrol vehicle, including the cost of one complete EV battery replacement.

Partial replacement with a new battery module is more complicated. One of the most important things is to ensure that all battery modules retain their balance, and so authorised providers will ensure that the replacement module is a good match with the existing modules, and will also typically perform a module equalisation process before an EV goes back out on the road. Partial module replacement is therefore only permitted when a battery pack has a modular construction, when suitable replacement module(s) are available and, of course, only when authorised by the manufacturer.

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## Battery Repurposing

An EV battery that is no-longer suitable for automotive use may still provide significant value in other markets, such as stationary energy storage for renewables. This “2<sup>nd</sup>-life” can provide a way to extract more lifetime value from each battery such that the upfront cost to motorists is reduced.

The 2<sup>nd</sup>-life batteries are an emerging market opportunity being explored by automotive manufacturers in partnership with electric utilities, as well as specialist third parties. Some of the challenges include:

- Competing with new batteries that are built-for-purpose in the other application (Figure 14). While used EV batteries may cost less, they may also have inferior performance.
- Being able to reliably diagnose the residual performance and projected life of used EV batteries, and characterize these in terms of the requirements of the 2<sup>nd</sup>-life application.
- Adapting the shape and construction of the EV batteries to the requirements of the 2<sup>nd</sup>-life application. EV batteries are typically housed inside a vehicle via unique mounting points, and with unique interfaces to electrical systems, cooling systems etc. The 2<sup>nd</sup>-life application may require an alternative form of enclosure, but with equivalent interfaces to match.
- Being able to source and aggregate enough used EV batteries that are suitable for the 2<sup>nd</sup>-life application, such that it becomes economically viable and economies of scale are achieved.



**Figure 14: Tesla battery packs – the Model S (left) versus the Powerwall (right). The Model S battery can potentially find a 2<sup>nd</sup>-life in other applications, but would it provide a superior value proposition compared to other batteries built-for-purpose?**

A good example of an 2<sup>nd</sup>-life battery programme is provided by BMW, who have recently demonstrated two new innovations in Germany based on the EV batteries from the BMW i3. In June 2016, BMW unveiled a home energy storage solution (Figure 15) that is designed to incorporate 2<sup>nd</sup>-

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life batteries from BMW i products as these 2<sup>nd</sup>-life units become increasingly available in the market. Then in September 2016, BMW announced a 2.8MWh grid-scale energy storage facility in Hamburg, Germany (Figure 16) powered by 2<sup>nd</sup>-life batteries from more than 100 EVs and developed in partnership with Bosch and the European electric utility company Vattenfall.



**Figure 15: The BMW home energy storage system powered by 2<sup>nd</sup>-life BMW i batteries**



**Figure 16: The grid-scale 2<sup>nd</sup>-life energy storage system developed by BMW, Bosch and Vattenfall**

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With these commercial pilot 2<sup>nd</sup>-life battery programmes now well underway, it's simply a matter of watching the space as the industry assesses the long-term opportunity for repurposed batteries.

## Battery Recycling

The raw materials in a used EV battery are quite valuable and, given the size and thus the worth of a typical EV battery in terms of material value, they are excellent candidates for large-scale recycling programmes. However this too is an emerging market opportunity that depends on the age and number of EVs in the fleet, and thus the growing supply of waste EV batteries with a view to economies of scale.

Members of the Motor Industry Association (MIA) of New Zealand (representing the vast majority of New Zealand automotive brands) comply with a code of practice that states:

*“MIA members will have suitable systems in place to monitor the use, capture, return, re-furbish/re-use or recycle/dispose of traction batteries from EV/PHEV/HEVs. The systems will include recovery mechanisms capable of maximising the value from re-use of finite resources with the aim of no traction batteries ending up in landfills.”* (Motor Industry Association, 2014)

The current EV battery recycling plans of New Zealand EV brands include warehouse storage until recycling facilities are in place in New Zealand; and shipping to specialist offshore recycling facilities. Many are also investigating repurposing options (as mentioned in the previous section). As the local New Zealand EV market continues to grow, and as the current crop of EV batteries begin to require replacement (e.g. from 2020 onwards), it is likely that a significant local market opportunity will emerge in New Zealand for the recycling and/or repurposing of used EV batteries.

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## Part 4: The Overall Cost of EV Battery Degradation – A Case Study

The cost of battery degradation can be an important factor in the overall Total Cost of Ownership (TCO) for electric versus petrol vehicles. However, the specific impacts on TCO will clearly vary for different makes and models, as well as between motorists' differing personal circumstances.

Since the New Zealand EV market is still in its early stages, it is further difficult to make any clear conclusions about how significant battery degradation costs may be in terms of local prices for local products. In many cases, the local cost data is not yet available (since the EVs are only just entering the local market and thus their batteries are still 5-8+ years from replacement), or the current costs are expected to change drastically as the local market matures. Fortunately, some guidance can be obtained by substituting data from global markets (as appropriate) that are more mature and thus more indicative of the trends.

This section presents a case study for the Total Cost of Ownership (TCO) of an EV versus a petrol vehicle in New Zealand, including the cost of one complete EV battery replacement. This example focuses on the Nissan Leaf (which is the most popular EV on New Zealand roads, most often as a used-import), and compares it to the Nissan Pulsar hatch (petrol). However, the battery replacement costs for this analysis are derived from the US market which is far more mature and thus more indicative given that more than 100,000 Nissan Leafs have been sold into that market since 2010.

Otherwise the input data and results are based on local market data as provided by EECA's *Vehicle Total Cost of Ownership Tool*. Specific assumptions were made to simulate the plausible New Zealand scenario of a used-import EV that requires a complete battery replacement during its working life in the New Zealand market, as follows:

- Used petrol vs. EVs with an initial age of three years and final age of 10 years are compared using market values derived from the EECA TCO tool database
- The seven years of operation at 14,600km of annual travel per vehicle (40km per day average) equates to approximate 100,000km during the period of ownership.
- One complete battery replacement is included for the Nissan Leaf, whereas no engine replacement or refurbishment is included for the Nissan Pulsar.
- Otherwise the default model inputs for fuel/electricity costs, maintenance, etc. are used.
- For simplicity, the taxation aspects of the TCO tool (applicable to business customers) have been excluded to provide an example for the general public.

**Table 3: A case study for the total cost of ownership of a used-import Nissan Leaf relative to a comparable used petrol vehicle.**

<b>COST OF OWNERSHIP COMPARISON</b>	<b>NISSAN LEAF</b>	<b>NISSAN PULSAR</b>
<b>Purchase price (used at three years)</b>	<b>\$19,504</b>	<b>\$14,716</b>
Finance/interest costs	\$6,002	\$4,558
Running cost – fuel/electricity	\$2,126	\$11,756
Running cost – scheduled maintenance	\$2,676	\$5,233
<b>Battery replacement (estimate)</b>	<b>\$8,200</b>	<b>n/a</b>
<b>Subtotal</b>	<b>\$38,508</b>	<b>\$36,263</b>
Residual value (at 10 years)	\$9,595	\$6,925
<b>TCO over seven years (net of residual)</b>	<b>\$28,913</b>	<b>\$29,338</b>

The results show that, even with the complete battery replacement included, the EV is still competitive in terms of overall total cost of ownership. While these results should not be extrapolated to the New Zealand market as a whole, they do suggest that battery degradation costs should not be viewed as a deal breaker within this overall context.

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