Tampereen yliopisto

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SECOND-LIFE USE OF ELECTRIC VEHICLE BATTERIES

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ABSTRACT

Tiia Uotila: Second-life Use of Electric Vehicle Batteries
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The demand for electric and hybrid vehicles has increased in the recent years, which has increased the production of lithium ion batteries. Batteries are typically discarded from electric vehicles even though they still have most of their capacity left. As a result, a high number of batteries ends up as a waste although they might still be used in other applications. The environmental consciousness has also increased the demand for renewable energy production, such as wind and solar energy. However, the renewable production suffers from fluctuation in output power. Using second-life batteries as electrical energy storages in renewable energy systems is one possible solution to both addressed problems.

This bachelor's thesis is a literature review considering the second-life use of electric vehicle batteries. The thesis shortly describes the first life of batteries, the aging of batteries and their repurposing process. Then applications of second-life batteries in wind and solar energy systems are addressed. Challenges in implementing second-life batteries and benefits from the use of second-life batteries are addressed.

The conclusion of the thesis is that second-life batteries can be used in both wind and solar energy applications. Several projects of using second-life batteries as electrical energy storages have already been executed. The challenges in implementing second-life batteries include their different chemistries and state of health. The use of second-life batteries provides huge opportunities for both the environment and economy.

Keywords: battery, electric vehicle, second-life, electrical energy storage, renewable energy

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1. INTRODUCTION

The demand for electric and hybrid electric vehicles has increased in recent years. The main reasons for this demand are the concerns about the environmental impact of CO_2 emissions from internal combustion engine powered vehicles, improvements in battery technologies and the continuous rise in gasoline prices.

The high upfront cost of electric batteries is one major factor in slowing down the adoption of electric vehicles. Many manufacturers design their battery system end of life to be achieved after the batteries reach 80 % state of health (SoH) which also creates an issue of many still usable batteries being discarded [1]. Approximately 95 % of all lithium-ion batteries end up in a landfill [2], even though a metal recycling company PF metals has stated that approximately 95% of the landfilled batteries could be reused or recycled [3].

Meanwhile, the increasing concern about the environment has also created a need to reduce the reliance on fossil fuels and grow the renewable energy production, such as wind and solar energy. However, due the nature of their resources, wind and solar energy suffer from fluctuation in the output power. This negatively affects the stability and reliability of the grid. [4] The most promising solution for this problem has been electrical energy storages (EES), which again have the downside of the cost of the batteries [5]. Being able to use the discarded batteries in battery storage systems could reduce the costs of both electric vehicles and energy systems requiring battery storages and lengthen the time the batteries can be utilized.

This thesis is a literature research examining the second-life -use of electric vehicle batteries in stationary applications. Second chapter describes the first life of batteries in electric vehicles, while presenting several reasons on why their SoH decreases and their repurposing process. The different applications of the second-life batteries are addressed, and some real-life examples are introduced in third chapter. Fourth chapter addresses the challenges and limitations of using second-life batteries, and fifth chapter analyses the benefits from environmental and economic perspective. Finally, conclusions are drawn in chapter 6.

2. FROM FIRST TO SECOND-LIFE USE

The demand for electric vehicles is increasing. The electric vehicle market reached 1.6 million sales in 2018 and close to 20 million vehicles are expected to be sold by 2025 [6]. This chapter addresses the first life of electric vehicle batteries, their ageing and the process of repurposing them for second-life use.

The different types of vehicles that use electric motors and batteries are electric vehicles (EV), hybrid electric vehicles (HEV) and plug-in hybrid vehicles (PHEV). EVs only use an electric motor which is exclusively powered by a battery. HEVs and PHEVs combine an electric motor with an internal combustion engine. Both EV and PHEV batteries are charged by external sources. [7] The EV battery systems are usually stored within modules and there are many modules distributed in a single vehicle. For example, Nissan Leaf has 48 modules with the combined weight of approximately 250 kg. [3]

The two most common battery chemistry types used in electric vehicles are lithium-ion (Li-ion) and nickel metal-hydride (NiMH) [5]. NiMH batteries are the most common type used in hybrid electric vehicles. However, they are less suitable for full electrification as Li-ion has twice the volumetric and gravimetric energy density, meaning NiMH battery requires about twice the space and weight of a Li-ion battery [7]. This thesis focuses on Li-ion chemistries.

2.1 Battery ageing

Over time the electrolyte/electrode interface is affected by a formation of solid electrolyte interphase (SEI), which causes the electrodes to degrade. This is the main cause of battery ageing resulting in increased impedance and loss of capacity. [8] Battery ageing can be divided into two terms, calendar ageing and cycle ageing [9]. Calendar ageing is the battery degradation during storage whether the battery is in use or not. Cycle ageing happens during battery charging and recharging. [8]

One major factor affecting both calendar and cycle ageing is temperature, as high temperatures accelerate electrode degradation [10][11]. For calendar ageing another important factor is state of charge (SoC) during battery storage. Higher SoC results in more capacity fade. [11] An important variable for cycle ageing is ΔSoC, which is the variation of SoC during charging and recharging cycles. High ΔSoC increases the development of SEI causing electrodes to degrade. [10]

The most used parameter to evaluate ageing is SoH, which is presented as follows [12]

$$SoH = \frac{nominal\ capacity\ at\ present\ time}{nominal\ capacity\ at\ initial}. \tag{1}$$

The determination of battery SoH is discussed more profoundly in chapter 4.

2.2 Repurposing process

As the batteries come to the end of their first life, they are removed from the vehicle and can be sent to a remanufacture plant. There the batteries are first visually inspected and ones that are damaged will be sent to recycling as they are unsafe to use. Then they undergo testing to determine their voltage, capacitance and SoH. [1][13]

The batteries can be repurposed in different ways. They can be directly reused, which means taking the battery as it is and adding adaptations for its second-life application. [13] These can be stationary applications such as grid frequency regulation or peak shaving [7], or the batteries can be used in vehicles with lower load requirements. Another way is to dismantle the battery into modules or cells and pack them up again. EV cells can be reused in smaller devices like laptops. [13] This thesis focuses on stationary applications which are addressed in the next chapter.

3. SECOND-LIFE BATTERY APPLICATIONS

In the recent years there has been several projects of using second-life electric vehicle batteries in stationary applications. Many EV manufacturers, such as Nissan, Renault, BMW and Daimler, have started to invest in second-life battery applications. The first ever second-life battery storage system was implemented in the micro grid of the University of San Diego in 2012 [14].

Europe’s first battery storage system was implemented in a smart grid application of the electric utility Vattenfall in Hamburg in 2014. The system used 8 BMW i3 battery packs from vehicles. Two battery packs were connected in series to be able to supply the operating voltage of 600 V to an inverter, resulting in four strings in parallel that can be independently controlled. Air ventilation and a heater were used to keep the temperature between 10 and 35°C in the isolated container. [14]

A subsidiary of Daimler, Mercedes-Benz Energy, has used second-life batteries in three energy storage units located in German Elverlingsen, Lunen and Hannover. The latest unit in Elverlingsen was built in 2016 on the site of a former coal power plant and uses 1920 battery modules. The unit in Lunen comprises 1000 and the unit in Hannover 3000 battery modules. All three units combined can offer almost 40 MWh of energy. The batteries used are from Mercedes smart electric vehicles. Daimler claims the storage system in Elverlingsen can react to grid instability in milliseconds. This is efficient as the maximum reaction time to ensure grid stability is 30 s. The storage systems also offset periods of peak demand and provide an emergency power supply. [15]

French company Renault has announced they plan to install the largest second-life energy storage in Europe. Renault claims the energy storage will facilitate the integration of renewable energy sources and stabilize the grid. The modular system will be located at multiple sites across France and Germany. First parts of the system will be built at Douai and Cléon in France and in North Rhine-Westphalia of Germany a former coal plant will be turned into an energy storage. The system will reuse over 2000 batteries from electric vehicles and provide 70 MW of power and 60 MWh of energy. [16]

Second-life batteries can be used in renewable energy applications. The next subchapters address the use of battery storages in wind and solar power systems and presents examples of projects using second-life batteries.

3.1 Wind power

Wind power is generated using a wind turbine and a generator. It suffers from two problems which make integrating to a grid difficult. First, wind is an intermittent source of energy, which means a single wind turbine will always not be rotating and supplying power constantly. Second, it is hard to predict when wind will happen and whether wind turbines will be supplying power or not. [17]

Battery storage systems are a viable solution to manage the intermittence and unpredictability of wind power output. Swedish energy company Vattenfall has executed several projects of applying second-life battery storages to wind farms in Europe. A battery storage system with the combined capacity of over 33 MWh was applied at an onshore wind farm in Wales. Up to 1000 Li-ion batteries with the capacity of 33 kWh were used. [18] In Netherlands a 3 MW battery storage system was integrated on a 90 MW wind farm located in central Netherlands [19]. Both battery storage systems used BMW i3 electric car batteries.

Wind farms combined with battery storage are especially useful on island systems, as wind potential is high and can result in discarded wind energy. Island of Crete in Greece has many wind farms and ongoing wind farm projects. A study [20] estimated that using second-life batteries as a wind farm energy storage could recover over 26 % of the lost power.

3.2 Solar power

Electricity can be generated from sunlight using photovoltaic cells. The challenge with photovoltaic energy production is the power output fluctuating during a year, especially in countries with noticeably changing seasons. In summers power output is higher but consumption can be low leading into over-voltage problems. During winters the opposite happens as output is lower and consumption is higher due to electricity used in heating. [21]

Combining solar cells with an energy storage can extend the time which the system can supply power and make solar systems that are connected to grid more reliable electricity sources. Since the output of solar cell is direct current, the cell can be used to charge a battery storage system without a need for a converter. [17]

In 2018 a second-life battery storage system was installed at a football stadium in Amsterdam. It stores energy from the 4200 photovoltaic cells located at the stadium’s roof. The system uses Li-ion batteries from Nissan Leaf electric cars with the combined power capacity of 3 MWh. [21][22]

Batteries can also be utilized in systems which are not grid connected. A light source by Nissan combines light emitting-diodes with a solar panel and a second-life battery from Nissan Leaf electric car. The solar panel's output during day charges the battery to provide light for night-time. The light can be used in areas without electric infrastructure. [23] Another example of smaller battery storages combined with solar panels are home power backup systems. In 2016 BMW announced its second-life batteries from i3 EVs will be used as home power backup. The system comprises of a controller and a 22 or 33 kWh battery pack, and it is possible for the owner to add more battery packs. According to BMW one backup battery could provide energy for the house for about one day. [24]

4. IMPLEMENTING SECOND-LIFE BATTERIES

Second-life batteries are optimised to be used in EVs. That is why their parameters differ from those designed specifically for battery storage systems. Table 1 demonstrates the differences in first and second-life applications of batteries used in stationary application project. [14]

Table 1: comparison of batteries' first and second-life use [14]

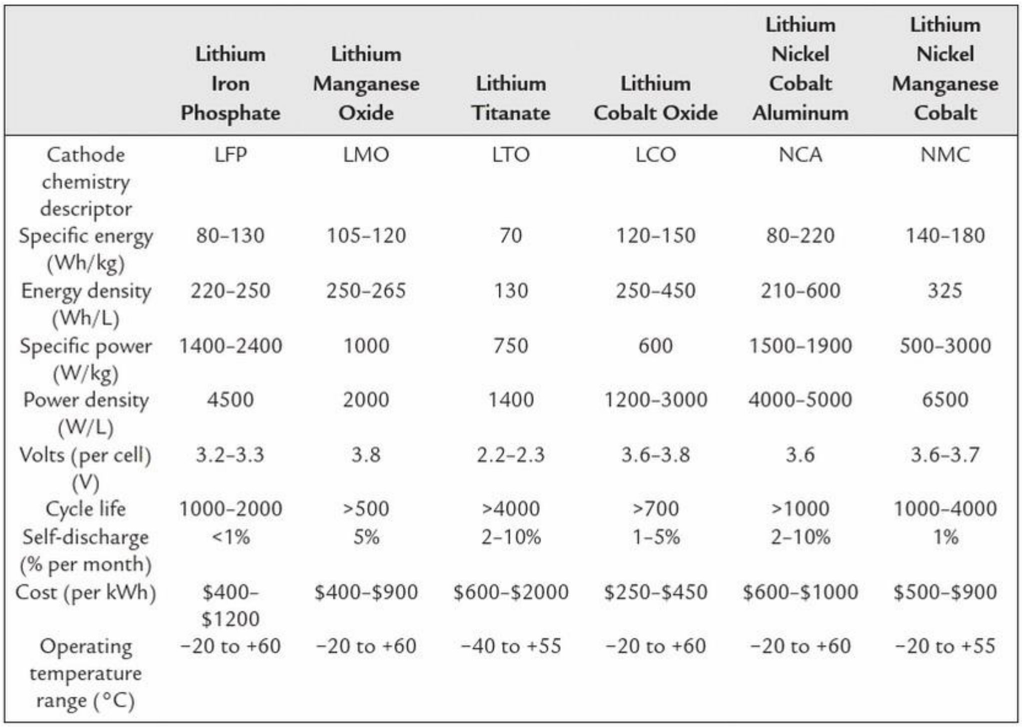
	1st life in EV	**2nd life in stationary application**
Nominal voltage level	~ 400 V	~ 800 V – 1000 V
Operating hours for 10a	~ 16 800 h (on)	max. 87 600 h (on)
Ambient temperatures	- 40 – 60 °C (in operation)	10 – 35 °C (in operation)
C-rates	continuous 2 – 3 C peak > 5 C	continuous < 0.5 C peak 0.5 – 2 C
Thermal management concept	active (air or liquid)	passive (active air or liquid only for specific use cases with critical temperatures)
Vibrations	typical for vehicles in motion	none
SoH (capacity being of life)	100 %	70 – 90 %

Another major issue is the differences in batteries' chemistries and state of health. The next subchapters cover the differences in battery chemistries, how their SoH can be estimated and how the different batteries can be integrated in the same system.

4.1 Li-ion battery differences

As formerly mentioned, there are different battery types, such as Li-ion and NiMH. However not even all Li-ion batteries have the same chemistry. There is variation in the cathode, anode and electrolyte materials. Some common cathode materials and their features are listed in table 2.

Table 2: Li-ion chemistries [1]



	Lithium Iron Phosphate	Lithium Manganese Oxide	Lithium Titanate	Lithium Cobalt Oxide	Lithium Nickel Cobalt Aluminum	Lithium Nickel Manganese Cobalt
Cathode chemistry descriptor	LFP	LMO	LTO	LCO	NCA	NMC
Specific energy (Wh/kg)	80–130	105–120	70	120–150	80–220	140–180
Energy density (Wh/L)	220–250	250–265	130	250–450	210–600	325
Specific power (W/kg)	1400–2400	1000	750	600	1500–1900	500–3000
Power density (W/L)	4500	2000	1400	1200–3000	4000–5000	6500
Volts (per cell) (V)	3.2–3.3	3.8	2.2–2.3	3.6–3.8	3.6	3.6–3.7
Cycle life	1000–2000	>500	>4000	>700	>1000	1000–4000
Self-discharge (% per month)	<1%	5%	2–10%	1–5%	2–10%	1%
Cost (per kWh)	$400–$1200	$400–$900	$600–$2000	$250–$450	$600–$1000	$500–$900
Operating temperature range (°C)	−20 to +60	−20 to +60	−40 to +55	−20 to +60	−20 to +60	−20 to +55

As can be seen from table 2, there are notable differences in different cathode materials. Manufacturers can also combine different chemistries to get the benefits of different materials into one cell design. Anodes are made from one material or mixture of two, usually graphite, or soft or hard carbons. Other materials such as lithium-ion titanite are possible as well. [1]

The electrolyte is usually a HC-based mixture that includes multiple additives that affect the attributes of the cell. The additives of certain batteries are not publicly known as they are an important part of intellectual property of the cell makers. [1] The electrolyte might include alkyl carbonates, such as dimethyl and diethyl, and lithium salts [25]. Different electrolytes differ in the formation of SEI layer, thermal stability of the cell, ionic conductivity and viscosity. Regarding safety, some are also more flammable than others. [26]

In addition to different chemistries, different Li-ion cell types and sizes exist as well. Three most common cell types are cylindrical, prismatic and pouch cells. Cylindrical cells are small, which means more cells are required for a battery. [1] With more cells, there is also more potential failure, as the cells are series connected and when one of them fails the whole battery pack fails [4]. The cylindrical cells also have higher initial impedance, which means they generate more heat. Most EV manufacturers use larger prismatic or pouch type cells, except for one major manufacturer, Tesla. For example, Tesla uses over 7000 cylindrical cells in their Model S EV batteries while Nissan uses only 192 pouch cells in their Leaf EV batteries. [1]

4.2 Estimating state of health

For battery storage systems to work well the batteries used need to be similarly aged. This maximises efficiency, minimizes non-uniform aging processes in the system and allows for a broad operative SoC range for charging and discharging the system. The identification of batteries with similar SoH can be challenging. [14]

One way to estimate the SoH is to analyse their first life in EV. Conditions such as the EV mileage, geographical climate and user driver profile need to be considered. For example, in one of the battery storage systems which was introduced in chapter 3, the 8 batteries used were used in central European climates and mileages below 50 000 km. [14]

In a study [4], SoH of battery cells was estimated using Electrochemical Impedance Spectroscopy (EIS) measurement. The battery cells were subjected to a 5 mV AC voltage and its AC current response was measured with the EIS device and used to calculate increase in internal impedance. The measuring was performed in 50 mHz to 10 kHz frequency range. Figure 1 illustrates the SoH estimated using EIS measurement as a function of actual measured SoH. The solid line represents zero difference between the estimated and measured SoH. The highest error obtained was 4.1 % and the average error 2.7%. According to the study, this method is fast and quite reliable way of SoH estimation.

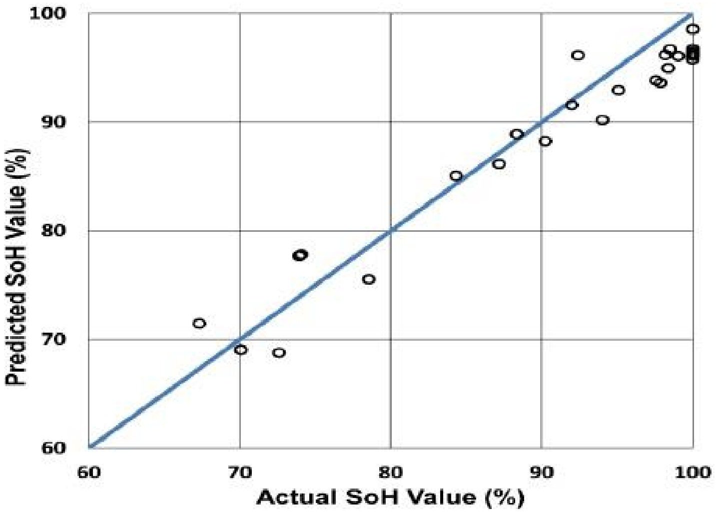


Figure 1: estimated and measured SoH [4]

4.3 Integrating to grid

There are two different ways of using second-life batteries in stationary applications. First, to group batteries with similar attributes, such as SoH, chemistry type and size, together. In the battery systems introduced in chapter 3 the batteries were all taken from the EVs of the same model. Second way is to use different batteries but reconfigure them by using a power electronics converter. [5]

A study [4] presents an example of the second scenario system. In the system battery cells have been assembled in two types of modules. The first type has one module which can be used to provide 0.7 kW of power and the second type has two modules which can provide 3 kW. The three modules have been integrated to the grid using a multiport converter and a three-phase inverter.

5. SECOND-LIFE BATTERY BENEFITS

Evaluating the benefits of second-life battery benefits is challenging as most published studies on the subject are fairly small and many are based on mathematical models rather than data from real life systems [27]. This chapter addresses the possible benefits of second-life battery applications from environmental and economical perspectives.

Approximately 95 % of all Li-ion batteries end up on a landfill [2]. At this moment most of Li-ion battery waste is from portable electronic devices, but the amount of used batteries from electric vehicles will increase in the future [28]. When Li-ion batteries are disposed on a landfill, toxic chemicals used in cathode materials, such as lithium, cobalt and nickel, can leach into solution. These chemicals can then end up in nature and drinking water. Another hazard that Li-ion batteries possess is that they can easily catch fire or explode in landfill conditions. For those reasons Li-ion batteries should be reused or recycled instead. [29]

Because of the increasing demand for batteries for electronics, ESSs and EVs, lithium demand is increasing as well. It is estimated that the global demand for lithium in 2015 was approximately 160 kilo tonnes per annum and was projected to increase to 500 kilo tonnes per annum by 2025. Another metal with increasing demand is cobalt, which is used in some Li-ion battery cathode chemistries. As a result of the demand the prices of the metals are expected to rise. In addition, 50 % of cobalt is produced in the Democratic Republic of Congo. There are concerns of environmental issues and human rights abuses from the region. [3]

A study conducted in 2019 [30] analysed the use of new and second-life batteries in two wind farms with capacities of 800 MW and 5 MW. The study compared the profits of the wind farm owners and showed that the use of second-life batteries in the studied wind farms was not economically worthwhile. Although second-life batteries might become more profitable in the future if wind energy prices decrease faster than battery prices. As lithium and cobalt prices are rising due to demand, it is possible second-life batteries compared to new batteries become more economical option in the future.

A factor limiting the use of second-life batteries is that there is more demand for batteries in battery storage applications than there are available used batteries. According to the law in Europe the vendor of a battery is responsible of taking back the battery and reusing or recycling it, but the owner of the battery is not obligated to send the battery back. [27]

It is possible for electric vehicle owner to profit from selling the battery for second-life use. A study [31] used mathematical models to estimate profits in a scenario where EV owner also participates to vehicle-to-grid, which means using battery still located in EV as an energy storage when the EV is plugged in to grid. According to the study the owner could save up to 19.56 % of the initial battery cost.

6. CONCLUSION

This thesis addressed the second-life use of electric vehicle batteries. It described the first life of the battery in an electric vehicle, its ageing and repurposing process. Stationary second-life applications were presented in general and relating to wind and solar energy production. Challenges of implementing second-life batteries and possible benefits of second-life use were addressed as well.

The main cause of battery aging is the formation of solid interphase layer resulting in increased impedance and loss of capacity. Important factors consider battery aging are state of charge during battery storage and variation of state of charge during charging and recharging cycles. Electric vehicle batteries are removed from vehicles when they reach 80 % state of health and are usually repurposed for stationary second-life applications by dismantling them into modules and packing them up again.

There has been several projects and studies of second-life electric vehicle batteries used in battery storage applications. Many electric vehicle manufacturers have invested in their own second-life battery projects. Battery storage systems can be used to stabilize grid, offset periods of peak demand and provide emergency backup power. Battery storages are effective combined to solar and wind power systems as those suffer from fluctuation of output power. Second-life battery storage systems have been implemented in both wind farms and solar power systems. Second-life batteries have also been utilized in small off-grid systems that are charged with solar panels.

One of the most important limitations in implementing second-life batteries are the differences in lithium ion batteries. Battery manufacturers use different chemistries and types and sizes of battery cells. These causes the batteries to have different attributes. Batteries also differ in state of health at the end of their first life, and the used batteries should be similarly aged to maximize the efficiency of the system. There are different methods for estimating the state of heath, such as evaluating their first life or using Electrochemical Impedance Spectroscopy measurement. Battery storage systems can either use batteries with similar chemistries and state of health or reconfigure different batteries by using a power electronics converter.

It is possible to achieve benefits with the second-life use of batteries. Lithium ion batteries ending up on a landfill is dangerous to the environment, as they can leach toxic chemicals, catch fire or explode. The increasing demand of lithium and cobalt can make second-life batteries a more economic as well as environmentally friendly option compared to new batteries. From the perspective of renewable energy source owners the use of second-life batteries has not shown to be profitable but the situation might change in the future. Electric vehicle owners can make profit from giving up their used battery for second-life use. More studies should be conducted to further explore the benefits.

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