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Techno-Economic Analysis of the Business Potential of Second-Life Batteries in Ostrobothnia, Finland

Sami Lieskoski *, Jessica Tuuf and Margareta Björklund-Sänkiaho

Faculty of Science and Engineering, Energy Technology, Åbo Akademi University, Rantakatu 2, 65100 Vaasa, Finland; jessica.tuuf@abo.fi (J.T.); margareta.bjorklund-sankiaho@abo.fi (M.B.-S.)
* Correspondence: sami.lieskoski@abo.fi

Abstract: In an effort to tackle climate change, various sectors, including the transport sector, are turning towards increased electrification. As a result, there has been a swift increase in the sales of electric vehicles (EVs) that use lithium-ion batteries (LIBs). When LIBs reach their end of life in EVs, it may still be possible to use them in other, less demanding applications, giving them a second life. This article describes a case study where the feasibility of a hypothetical business repurposing Tesla Model S/X batteries in the Ostrobothnia region, Finland, is investigated. A material-flow analysis is conducted to estimate the number of batteries becoming available for second-life applications from both the Ostrobothnia region and Finland up to 2035. The cost of repurposing batteries is evaluated for four different scenarios, with the batteries being processed either on the pack, module, or cell level. Three scenarios were found to be feasible, with repurposing costs of 27.2–38.3 EUR/kWh. The last scenario, in which all battery packs are disassembled at the cell level, was found not to be feasible due to the labor intensiveness of disassembly and testing at the cell level. This work gives indications of the potential for repurposing batteries in the Ostrobothnia region and Finland.

Keywords: second life; lithium-ion battery; electric vehicle; business model; material flow analysis; Levelized Cost of Storage

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1. Introduction

Several measures need to be taken to combat climate change and deal with the problems arising from increased greenhouse gas emissions. By turning from fossil fuels to renewable energy sources (RESs) (e.g., wind and solar power, and biomass), various sectors, such as the transport, energy, and industrial sectors, could contribute to more sustainable solutions. Since wind power and solar power are intermittent sources, meaning that the production of power is not regular nor adjustable, there is a growing need to balance power production with energy storage as the share of variable RES increases. Various types of energy storage technologies have been considered, including thermal energy storage, pumped hydro storage, and batteries. In addition to promoting enhanced RES utilization, another way to address the environmental challenges is to turn towards increased electrification. This development is already clearly seen in society today, with more sectors electrifying their specific processes. The transport sector is also heavily taking advantage of this, with battery-powered electric vehicles (EVs) as a result.

1.1. Literature Review

Lithium was introduced as a component in batteries in the late 1960s and has since been gaining enormous popularity as a cathode material [1]. Various types of cathode materials are used in EV batteries, including Lithium Nickel Manganese Cobalt Oxide (NMC), Lithium Nickel Cobalt Aluminum Oxide (NCA), Lithium Cobalt Oxide (LCO), Lithium Manganese Oxide (LMO), and Lithium Iron Phosphate (LFP) [2]. Hence, batteries are often categorized according to these. Different automobile producers have established their preferred material. For example, NMC technology has been the most successful system amongst EV manufacturers. When looking at the worldwide market share of battery chemistries in 2022, the dominant technology is NMC (60%), while LFP has a share slightly below 30%, and NCA has a share of about 8% [3]. Tesla has been a strong utilizer of the NCA chemistry in all their former EV models. However, in 2021, Tesla revealed that they intended to change the battery chemistry in their standard-range EVs to LFP [4]. Since Tesla is considered a leader in the EV sector, it might have significant implications for other EV manufacturers. For example, some non-Chinese EV manufacturers have indicated their intentions to start using LFP batteries, including Hyundai and Kia [5] as well as Ford [6]. A set of patents on LFP batteries expired during 2021–2022, which will allow original equipment manufacturers outside of China to start manufacturing their own LFP batteries [7]. However, as of 2022, of all the LFP batteries utilized in electric light-duty vehicles, the vehicles manufactured in China accounted for approximately 95% [3].

Lithium-ion batteries (LIBs) can consist of different compositions, but they can also be of many sizes and shapes. LIBs usually have the same arrangement, which is packs, modules, or cells (Figure 1). A LIB pack usually consists of several modules. The modules are arranged in series, with the pack providing the housing for the modules and the modules providing the housing for the cells. The pack and modules also contain additional components. The cells are arranged in series and parallel in the module [8]. The structure of the battery cells can be of diverse types, and the most used are cylindrical, prismatic, and pouch cells. A simplified schematic description of a lithium-ion battery pack, a Tesla Model S 85 kWh battery pack made of cylindrical cells, is shown in Figure 1.

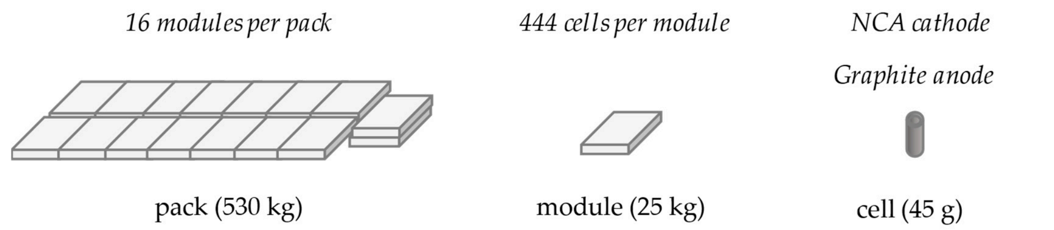

Figure 1. Schematics of a Tesla Model S 85 kWh battery pack (Panasonic) containing cylindrical-shaped cells. Modified from [9].

Environmental challenges are occasionally associated with the utilization of LIBs. Since some of the LIBs contain cobalt, nickel, or manganese, there is a risk of the pollution of water and landfills if they leach into the environment. For example, a study has shown that the mining process of metals is problematic since it contributes to environmental, geopolitical, and social challenges in Africa, which is the region where cobalt is usually found [10]. Also, many of the metals are not infinite, and in 2020, the European Union described some of the metals as critical raw materials, including cobalt, lithium, and natural graphite [11]. These facts promote further research into novel materials and technologies as well as replacing new battery production with alternatives, such as recycling and repurposing. Recycling is a process where the battery is broken down, and its raw materials are recovered. Nowadays, it is well recognized from an environmental perspective that rather than disposing of batteries in landfills, recycling old batteries is a better alternative [12]. However, from an economic perspective, the case for recycling is weaker. Cobalt is the only material worth recycling in LIBs, but there are attempts to shift away from cobalt by decreasing its share in the batteries or even completely removing it [13]. The potential decrease in cobalt content further reduces the economic feasibility of recycling. This decrease may make another future for batteries at the end of their first life, i.e., the concept of repurposing, more economically attractive [14]. Battery repurposing helps reduce the environmental load of batteries, as it extends the lifetime of batteries, and the manufacture of new battery storage systems is avoided. Repurposed batteries can also be referred to as second-life batteries (SLBs). Recyclers are hesitant to make large investments in recycling technology for different materials until there are strong price signals for the commodities used, especially as battery chemistries are changing [15]. Hence, the use of SLBs can delay the recycling of batteries, providing more time for battery recycling technology to improve and reduce costs [16,17].

When an EV battery has reached the end of its first life, which has been suggested to occur when 70–80% of the original capacity is left, there is a possibility to repurpose it and give it a second life in other applications. Figure 2 portrays the stages in the life of an EV battery and at what battery capacities these are expected to occur. It is still not clearly defined when the end of the battery's second life occurs. However, suggestions of 30% [13,18] or 50–60% [19] have been put forward. Several applications for SLBs have been proposed. These include, for example, stationary energy storage in microgrids [20], power peak-shaving applications [21], and grid energy arbitrage [22]. Common characteristics of these operations are lower power or specific energy requirements. Other potential non-stationary second-life operations can be micro-mobility applications such as e-scooters and industrial vehicles such as various electronics and forklifts [23].

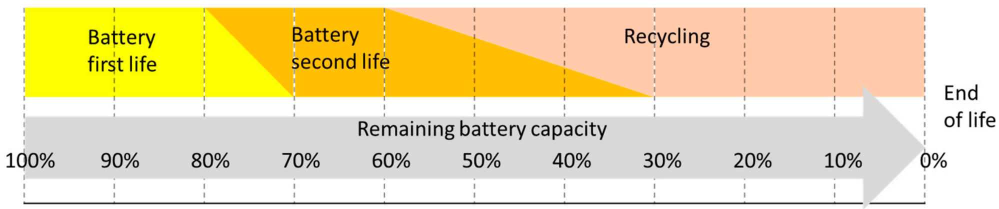

Figure 2. Schematics of the electric vehicle (EV) battery life range.

The degradation of LIBs is affected by the way they are used, so-called cyclic aging, and they also degrade over time regardless of their use, so-called calendar aging. The State of Charge (SOC) and the temperature impact calendar aging, and the rate of degradation is faster at higher levels of SOC or temperature, in that order [8]. Cycle aging is impacted by two other factors in addition to the previously mentioned ones: the Depth of Discharge (DOD) and the C-rate (discharge/charge rate). The capacity fade of batteries is higher at greater discharge depths and at higher discharge/charge rates [24].

Battery legislation and directives in both the European Union (EU) and Finland support actions to recycle and repurpose batteries. In the EU, Battery Directive 2006/66/EC was initiated to reduce the negative effects of batteries, accumulators, and waste batteries on the environment [25]. Several updates have been made, and a new EU regulation for batteries has been proposed by the European Parliament and the Council [26]. This regulatory framework focuses especially on LIBs and on promoting sustainable batteries. A suggestion is that the EV batteries should have a "digital battery passport" to facilitate the follow-up of the models and their use. In Finland, a national battery strategy for 2025 has been released [27]. This report predicts Finland to be a forerunner in building a sustainable battery value chain and in battery management and recycling, and six main visions were identified. For example, Finland should employ responsible batteries production and use procedures, and the Finnish battery cluster should be part of the international battery ecosystem. Altogether, these steps, together with other necessary actions, will make the whole battery value chain more sustainable, and it will comply with the Green Deal targets that have been set for Europe. It is worth remembering that there are currently no legislation or standards in the EU that are specific to the safety aspects of SLBs and their systems [28].

Several technical key parameters in a battery system need to be evaluated before a battery can be considered suitable for SLB applications. The State of Health (SOH), the DOD, and the cyclic lifetimes are examples of such parameters. To decide the SOH of a battery, experimental, model-based, and machine learning methods are generally applied [29]. The distinct types of batteries and chemistries will cause the SOH assessment to be different, and this might make the evaluation of SLBs problematic. In addition, when setting up a second-life Battery Energy Storage System (BESS), the optimal solution is that the batteries are of similar type, chemistry, capacity, and voltage level. Such a system will contribute to better performance, as well as a longer lifespan [30]. Montes and co-workers (2022) have defined several requirements that should be evaluated before SLB installation, e.g., capacity, maximum power, weight, volume, and energy management system [31].

To elucidate whether an SLB system is economically viable, a techno-economic analysis is usually performed by characterizing various parameters, such as the Net Present Value (NPV), return on investment, internal rate of return, and discounted payback period. From a business point of view, economic feasibility is crucial and needs to be addressed before commercialization. There is no standard for addressing the costs in an economic model of a BESS. However, the Levelized Cost of Storage (LCOS) is one methodology to use when calculating the profitability of an energy system. This method analyzes not only the storage system's costs but also the energy and service delivered to the system. For example, in an LCOS study, the costs of various types of batteries were compared to other forms of energy storage [32]. The results showed that, at that time in 2016, the LCOS of Li-ion batteries was between 0.23 and 0.37 EUR/kWh at 365 cycles per year. However, it was indicated that the prices of LIBs were to decrease shortly. In another study, it has been put forward that applying LCOS on BESS is not that straightforward since there might be variability in how to treat different parameters, which might make a comparison between different LCOS studies challenging [14]. Currently, there is an advanced online tool available to calculate the profitability of SLBs. The Battery Second-Use Repurposing Cost Calculator [33] (hereafter referred to as "B2U calculator"), developed by the National Renewable Energy Laboratory (NREL) in the US, provides a detailed economic model for calculating the costs of a facility that processes SLBs. For example, in a study, an LCOS model was refined by developing a probabilistic LCOS model that compared prior studies by Monte Carlo analysis and the harmonization of parameter values for second-life and new BESSs [14]. LCOS was analyzed for two different scenarios: a market scenario, where the used EV battery is bought off the market, and an owner scenario, where the repurposer owns the EV battery, and thus, there are no battery purchasing costs, only repurposing costs. The costs for the owner scenario were obtained from the B2U calculator, which the authors made amendments to. The results showed that while SLB BESSs have lower upfront costs than new BESSs, they had a higher LCOS compared to new BESSs.

In another case study, an activity-based costing model using 71 kWh capacity batteries from the EV model Audi e-tron quattro 50 (2019) for energy storage systems [34] was integrated into a cost–benefit analysis tool to assess the profitability of repurposing. The authors found that the repurposing of batteries is profitable with the process design and assumptions they used when the purchase price for the used EV batteries was 75 EUR/kWh (storage capacity) and the sales price was 500 EUR/kWh for the energy storage systems.

These studies indicate that there are numerous parameters involved in cost analyses but also that there are different methods available to evaluate the profitability of repurposing SLBs. In addition, case-specific parameters need to be considered to make the analysis as reliable as possible.

1.2. The Case Study

The Ostrobothnia region is in western Finland, with Vaasa as the main city. The region has a strong knowledge of energy technology, with around 160 different energy businesses operating. In addition, there are planned investments in the Vaasa region in energy technology infrastructure that will be worth EUR 1.2 billion by the end of the year 2025 [35]. An industrial zone, the GigaVaasa area, is being planned in the Ostrobothnia region. The zone contains plots with a combined area of about 300 ha that are being prepared for battery factories that could manufacture battery components on the gigawatt scale if established [36]. One cathode material plant [37] and two anode material plants are currently being planned in the area [38,39].

There is currently only a handful of companies with SLBs as their core business in Finland. These include Cactos [40] and Autocirc Battery Recycling Finland [41], which present as promising examples due to them bringing SLBs to the market. To explore the interests in and knowledge of SLBs amongst enterprises and companies in the Ostrobothnia region, a survey was carried out in 2023 [42]. A questionnaire was sent to various companies in the battery ecosystem in the region, and data were gathered. For example, several knowledge gaps were identified, including aspects of fire, safety, and warrants, as well as business opportunities. Furthermore, it was stated that a regulatory framework and a stable investment environment in the Finnish energy sector could help create a more attractive battery ecosystem. Hence, it is obvious that the SLBs in the region are at the beginning of their journey, and that there is much work to be done before retired EV batteries can be fully commercialized.

Today, there are many EV manufacturers and models. They have a wide variety of battery packs that have diverse structures and use different chemistries. It is thus natural that there will be a mix of different battery packs available in the future. This poses a challenge from a repurposing perspective because the repurposing process will differ for each type of battery pack. Hence, it is likely that a battery-repurposing business could opt to specialize in a specific single EV brand/model. By looking at the number of electric passenger cars in traffic in Finland in 2022, Tesla Motors had the largest share of cars in traffic (25.3%), with Volkswagen as the second largest manufacturer (14.6%) [43]. In the Ostrobothnia region, both Volkswagen and Tesla have shares of just under 20%. Hence, since Tesla batteries have a great share of the electric cars in traffic in Finland and Ostrobothnia, it was decided to conduct a case study for a business repurposing Tesla Model S and X batteries.

This study aims to investigate SLBs in circulation in Ostrobothnia and Finland up to 2035 using material flow analysis (MFA). This future prognosis sets the ground for the study of the business potential of SLBs in the Ostrobothnia region using the B2U calculator [33]. However, in this investigation, the B2U calculator is modified to better mimic the aim of the analysis. Here, it is assumed that the EV batteries arrive as packs and not as modules, which is considered in the original B2U calculator. To investigate whether SLBs might be economically beneficial from a business perspective in the Ostrobothnia region, four different scenarios were examined. In these scenarios, the battery packs are either disassembled at the module level, to cell level, or left intact as a battery pack. The goal of the study is to give insights into the prospects and business potential for SLBs in the region. Also, challenges and uncertainties identified in the study are discussed to shed light on the complexities involved in the techno-economic analysis of SLBs.

Hence, the main contributions of this work are: (a) a future prognosis of available EV batteries in Ostrobothnia and in Finland up to 2035; (b) a suggested modified calculation tool based on the B2U calculator [33] that takes into account actual costs in the region (such as labor costs, electricity prices, etc.); (c) four different scenarios to analyze the potential for a fictive facility to process and sell SLBs. The novelty of this work is that the costs of processing used EV batteries have been compared not only at the pack and module level but also at the cell level, using a modified version of the B2U calculator. To our knowledge, this has not been accomplished before.

2. Materials and Methods

This study examines the economic feasibility of repurposing second-life EV batteries in the Ostrobothnia region of Finland. A key factor when studying the economic feasibility of repurposing EV batteries is the volume of EV and the volumes of EV batteries available for repurposing. Hence, an MFA is conducted. MFA is a tool for accounting for the flow and stocks of materials in a defined physical system, defined by boundaries in space and time [44]. In this study, the material is a good: EV batteries. The inflow of new EV batteries was determined by forecasting the volume of EVs in the Ostrobothnia region and Finland up to 2030, and the outflow volume of used EV batteries available for repurposing up to 2035 was calculated using battery and EV lifespans. Due to the substantial number of EV manufacturers, EV models, battery models, and chemistries, a battery-repurposing business could likely opt to specialize in a single EV brand/model. Hence, it was decided in this case study to investigate the feasibility of a business repurposing Tesla Model S and

X batteries. This battery type was chosen because Tesla has been a frontrunner in the EV market globally and has had a large market share in the early years of the EV market. Also, in Finland, these Tesla models had a dominant market share of the EV market in the early years (albeit it was a small market). The economic feasibility of the battery-repurposing business is investigated using a modified version of NREL's B2U calculator.

2.1. MFA of EV Batteries

An MFA of EVs and their LIBs in Ostrobothnia and Finland was conducted to find out the number of batteries that will be available for second-life applications. Furthermore, to analyze the potential for a business focusing on a specific type of EV battery, an MFA was conducted for Tesla Model S and X batteries, which use the same type of battery packs that utilize 18,650-sized NCA cells. The battery pack consists of 16 modules, with each module containing 444 cells [9].

The forecast for EV deployment in Finland was made by assuming that the Finnish government's ambition of having 375,000 plug-in EVs on the road by 2030 is reached [45]. Historical data on the number of EVs in use in Finland and Ostrobothnia in the years 2012–2022 were obtained from Traficom, the Finnish Transport and Communications Agency [43]. The development of the EV stock was calculated by assuming the EV stock during 2023–2030 grows with a constant compound annual growth rate (CAGR) of 30.4% to reach the 2030 target.

The forecast for EV deployment in the Ostrobothnia region was calculated by assuming that the ratio of the share of EVs to the total amount of passenger cars continues to develop on a linear trajectory based on historical data on the ratio of EVs to total passenger cars in Ostrobothnia compared to Finland. The estimated number of total passenger cars in Finland for the years 2025 and 2030 was obtained from a forecast prepared by the VTT Technical Research Centre of Finland [46], and the passenger car stock was assumed to grow to these levels with constant CAGRs of 0.25% up to 2025 and 0.64% up to 2030. This estimated development of the passenger car stock was then used to evaluate the future EV share of total passenger cars in Ostrobothnia and Finland.

The characteristics of the EV batteries applied in the MFA are displayed in Table 1. The MFA was conducted using the same truncated normal distribution of EV LIB lifespan that Richa et al. [47] applied in their MFA of EV batteries in the US. The use of a lifespan distribution helps reflect that the lifespan of an EV battery would depend on the charging patterns and how it is used, which is different from user to user. A normal distribution results in most batteries having lifespans of 8–10 years, while fewer have shorter or longer lives than this. A lifespan of 8–10 years is in line with warranty terms for EV batteries from many manufacturers [47]. Based on analyses conducted in previous studies, it was estimated that 75% of EV batteries would be eligible for second-life applications at the end of their first life [48].

Table 1. The battery lifespan distribution applied in the material flow analysis (MFA) and the share of EV batteries assumed suitable for second-life applications.

Material Flow Analysis Assumptions					**Ref.**
EV battery lifetime (first life)	6 years	8 years	10 years	12 years	[47]
Share	10%	40%	40%	10%	
Share of EV batteries suitable for second life	75%				[48]

EV lifespan is another factor to account for in the MFA. Richa et al. [47] assumed a fixed 10-year lifespan for EVs and performed a sensitivity analysis using a 16-year lifespan. An MFA on EVs and batteries in the EU set the lifetime of EVs to 15 years [49] based on a previous European study on light-duty vehicles [50]. For the study conducted here, the authors decided to apply fixed 10- and 16-year EV lifespans, similarly to Richa et al. [47], to analyze the impact that different EV lifespans may have on the flow of EV batteries.

If the battery reached its end of life (EOL) before the EV, it was assumed that the battery would be replaced, but a maximum of one battery change is allowed during the lifetime of a vehicle. If the EV reaches its EOL while the battery still has not reached EOL, the battery is still assumed to be used in a second-life application rather than being reused in the same application. Batteries from plug-in hybrid EVs (PHEVs) were not considered in this study because it is thought that they will not be suitable for second-life applications [49].

An MFA was conducted to find out the possible flows of Tesla Model S and X batteries in Finland for the case study of a battery-repurposing business in the Ostrobothnia region. Historical data on the number of Tesla Model S and X EVs in use in Finland during the years 2015–2022 were obtained from Traficom [43]. The number of Tesla Model S and X batteries was estimated by assuming that these EV models' share of the Finnish EV market continues to decline during 2023–2030 at the same linear trajectory of the years 2015–2022. The same MFA assumptions of Table 1 were applied.

2.2. The Selling Price of SLBs and LCOS

The B2U calculator [33] was modified and used in this study to evaluate the costs associated with preparing an EV battery for a second-life application and the business potential for a battery-repurposing plant located in the Ostrobothnia region. The first step for utilizing this tool is to calculate the selling price of the SLBs sold by the battery-repurposing business. The selling price is calculated with the requirement that repurposed batteries should be cost-competitive with new batteries that are equally capable. Table 2 lists the parameters used in calculating the battery selling price and the LCOS.

Table 2. Parameters for calculating the battery selling price and the Levelized Cost of Storage (LCOS).

Parameter	Symbol	Units	Value	Reference
Used-product discount factor	K_U	N/A	0.75	[51]
Battery health factor	K_H	N/A	0.65	Calculated
Cost of new lithium-ion battery	C_N	EUR/kWh	133	[52]
Price of repurposed battery	P_{rp}	EUR/kWh	65.5	Calculated
Present value of throughput	PVT	EUR	N/A	N/A
Present value of throughput of used battery	PVT_U	EUR	137,605	Calculated
Present value of throughput of new battery	PVT_N	EUR	210,212	Calculated
Inflation rate	r_i	%	2	Assumed
Discount rate	r_d	%	8	Assumed
Year	i	N/A	N/A	N/A
Battery life in years	n	N/A	N/A	N/A
Cost of charging the batteries in a year	$C_{chargen}$	EUR/MWh	N/A	Calculated
Energy charged in a year	$E_{chargen}$	MWh	N/A	Calculated
Energy discharged in a year	$E_{dischargen}$	MWh	N/A	Calculated
Electricity price in a year	E_{costn}	EUR/MWh	Varies (115 in 2022)	[53]
Roundtrip efficiency of battery storage	η_{rt}	%	86	[54]
Battery self-discharge	η_{self}	%/day	0.1	[54]
Nominal energy capacity of the battery	$Cap_{Nom,E}$	MW	2	Assumed
Battery cycles in a year	Cyc_{year}	N/A	365	Assumed
Battery depth of discharge	DOD	%	60	Assumed
Battery cycling degradation	cyc_{deg}	%	0.018%	Estimated using data from [55]
Battery calendar degradation	T_{deg}	%	1.48	[54]
Battery calendar life	$life_{years}$	years	15	[54]
Capital expenditure	CAPEX	EUR	See Table 3	[56]
Operating expenditure	$OPEX_n$	EUR	See Table 3	[56]
Project lifetime	N	years	10	Assumed

The selling price (P_{rp}) of a repurposed battery is calculated using the cost of a new battery (C_N) by taking into consideration the health of the used battery (K_H) and a used-product discount factor (K_U), as shown in Equation (1) [51]. The used-product discount factor is the ratio of the price that a customer is willing to pay for a used product compared to what they are willing to pay for a new product with the same capabilities.

$$P_{rp} = K_U K_H C_N \quad (1)$$

The health factor (K_H) is calculated using Equation (2) by dividing the present value of throughput (PVT_U) of a used battery employed to a grid application after its first life in an EV by the present value of throughput of a new battery (PVT_N) that is employed to the same grid application throughout its entire life [51].

$$K_H = \frac{PVT_U}{PVT_N} \quad (2)$$

The present value of throughput (PVT) is used as a metric to compare the SOH of an SLB to that of a new battery. The PVT is calculated using Equation (3) [54].

$$PVT = \sum_{i=1}^{n} \frac{(1 + r_i)^{i-0.5}}{(1 + r_d)^{i-0.5}} C_{charge_n} \quad (3)$$

The cost of charging the batteries ($C_{chargen}$) is equal to the amount of energy charged in a year ($E_{chargen}$) multiplied by the price of electricity (E_{costn}) in the year n. The electricity price (E_{costn}) is assumed to increase at the rate of inflation (r_i). The energy charged ($E_{chargen}$) in a year is calculated using Equation (4) [54].

$$E_{charge_n} = \left(\frac{E_{discharge_n}}{\eta_{rt}}\right) + Cap_{nom,E} \times \eta_{self} \times 365 \quad (4)$$

The energy discharged in a year ($E_{dischargen}$) is calculated using Equation (5).

$$E_{discharge_n} = cyc_{year} \times DOD \times Cap_{nom,E} \times \eta_{rt} \times (1 - \eta_{self}) \times \left(1 - cyc_{deg}\right)^{n \times cyc_{deg}} \times \left(1 - T_{deg}\right)^{n} \quad (5)$$

The battery is assumed to be cycled at an SOC between 20 and 80%. The cycling degradation rate was calculated by linearizing the degradation rate of four 18,650-sized NCA cells using test data from the tests conducted by Preger et al. [55]. The data were downloaded from [57]. The cells had been cycled using an SOC in the range of 20–80% at a C-rate of 0.5 and maintained at a temperature of 25 °C. The calendar degradation (T_{deg}), the degradation of the battery per year, is evaluated using Equation (6) [54].

$$T_{deg} = -\frac{\ln(0.8)}{life_{years}} \quad (6)$$

The cyclic (cyc_{deg}) and calendar degradation (T_{deg}) rates were used for evaluating when a new LIB or SLB reached their end of life in the second-life application. The second-life application chosen is peak shaving, as it is one of the most promising applications for SLBs [58]. The batteries are cycled once a day. It is assumed that the EOL of both batteries is reached when their SOH drops to 60% and that the second life of the used battery begins at an SOH of 80%.

After the lifetimes of the new battery and the second-life EV battery are known, the health factor can be calculated using Equations (2) and (3). With the health factor (K_H) known, the selling price of the repurposed battery (P_{rp}) can be calculated using Equation (1).

The LCOS of the new LIB pack and the second-life EV battery packs in the peak-shaving application were calculated using Equation (7) [54].

$$LCOS = \frac{CAPEX + \sum_{n=1}^{N} \frac{OPEX_n + C_{charge_n}}{(1 + r_d)^n}}{\sum_{n=1}^{N} \frac{E_{discharge_n}}{(1 + r_d)^n}} \quad (7)$$

The size of the BESS was set to 1 MW, 2 MWh, so the BESS operates at a 0.5 C-rate. A BESS, especially a larger system, consists of several cost components except for the battery itself. These include various auxiliary components and installation costs. The CAPEX and OPEX costs for a 1 MW, 2 MWh BESS were obtained from [56], as shown in Table 3. However, it should be noted that these costs are for an NMC-type battery, not an NCA-type battery. The DC storage block cost is substituted with the cost of a new EV battery or the cost of an SLB.

Table 3. CAPEX and OPEX costs for a 1 MW, 2 MWh NMC lithium-ion battery energy storage system (BESS) [56].

Cost	Value	Unit
DC Storage Block	193	EUR/kWh
DC Storage Balance of System	40	EUR/kWh
Power Equipment	75	EUR/kW
Controls and Communication	35	EUR/kW
Systems Integration	56	EUR/kWh
Engineering, Procurement, and Construction	69	EUR/kWh
Project Development	82	EUR/kWh
Grid Integration	27	EUR/kW
Fixed O&M	3	EUR/kW-year

As the lifetimes of the new and the SLB packs are shorter than the project lifetime (N) of the BESS, the battery packs will need to be replaced during the BESS lifetime. Bloomberg New Energy Finance (BNEF) price estimates of new battery packs of 135 EUR/kWh in 2023, 101 EUR/kWh in 2026 [52], 56 EUR/kWh by 2030 [59], and 40 EUR/kWh by 2035 [60] were used to estimate the future replacement costs of the batteries. The BESS project was set to start in 2023 and end after 2032. The replacement cost for a certain year was obtained by the linear interpolation of the given cost data points for new battery packs while also accounting for the discount rate.

2.3. Battery Second-Life Repurposing

In this work, a case study is conducted on a hypothetical Tesla Model S and X battery-repurposing plant located in the Ostrobothnia region, which was sized to process 50 MWh (588 battery packs) based on the results obtained in Section 3.3. The B2U calculator [33] provides a detailed economic model for calculating the costs of a facility that processes SLBs. The model accounts for the labor costs of repurposing batteries for second-life use, electricity costs for testing the batteries, transportation costs, the testing and logistics equipment, insurance, warranty, general and administrative costs, research and development costs, etc. In the B2U calculator, the used EV batteries are received as modules, and these modules are processed and tested at the repurposing facility. Some of the significant modifications made to the B2U calculator in this study are listed below:

- The EV batteries are received as battery packs. The processing and testing of packs are included.
- Costs for the disassembly of packs to modules have been added. The processing and testing of modules are included.
- Costs for the disassembly of modules to cells have been included. The processing and testing of cells are included.

When the data are available, economic parameters for Ostrobothnia and Finland are used (e.g., labor costs, electricity price, rental price, tax rates). When economic parameters specific to Ostrobothnia or Finland cannot be found, the cost suggestions of NREL are used [51,58].

With the selling price for an SLB that had been obtained using the method described in Section 2.2 and Equation (2), the repurposing cost and the buying price for the used EV battery packs are evaluated using the B2U calculator, with the aim of achieving a NPV of 0 over 5 years.

The B2U calculator was used to evaluate the following four different scenarios, as shown in Figure 3:

- Scenario 1: The battery packs are not disassembled. Only the battery packs are processed and tested.
- Scenario 2: The battery packs are disassembled at the module level. Both the packs and modules are tested.
- Scenario 3: The battery packs are disassembled at the module level, but the modules with faulty cells are disassembled at cells. Packs, modules, and cells are tested.
- Scenario 4: All battery packs are disassembled at the cell level. Only the cells are tested. There is no testing of modules or packs.

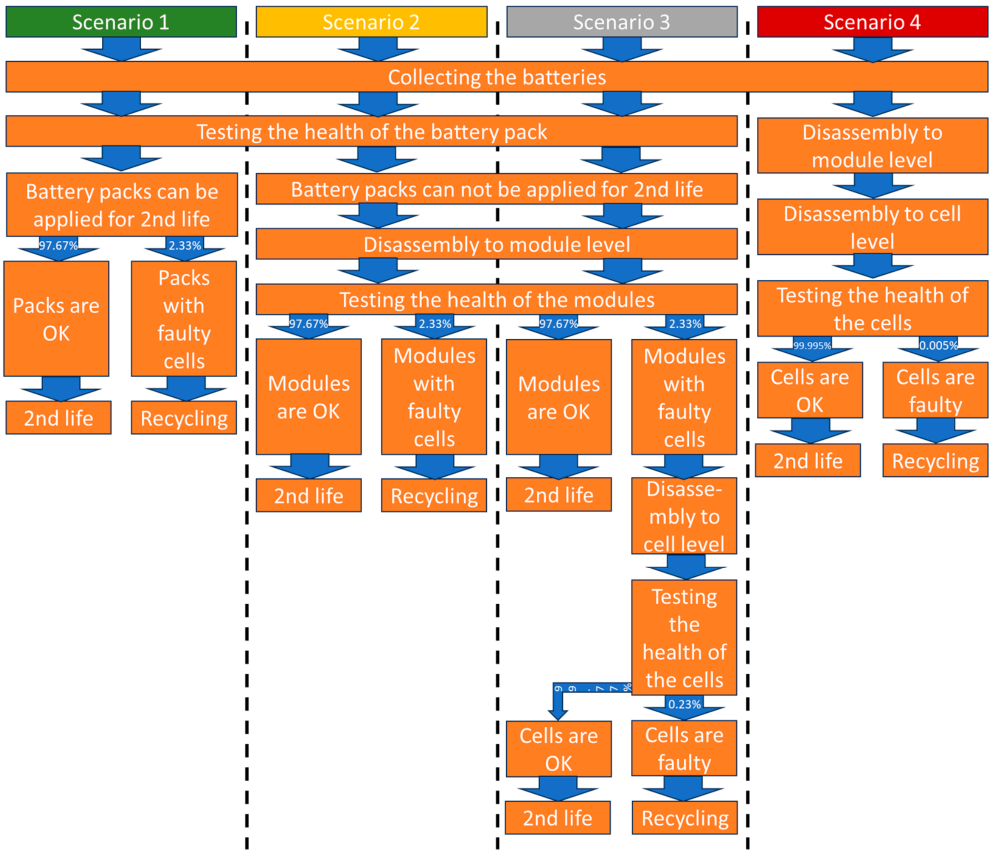

Figure 3. Chart of the four different analyzed scenarios.

In the scenarios, the cell fault rate and the number of packs with faulty cells are the same. The scenarios aim to compare the impact on repurposing costs and the buying price when the battery packs must be disassembled at the module level before reuse or even at the cell level.

The time required for processing and testing the battery packs, modules, and cells at the battery-repurposing facility is displayed in Table 4. With the processing times known, it is possible to evaluate the number of technicians required. These time estimates are based on information from [58,61] and our own estimations. A longer testing protocol was assumed for the testing of large battery pack, and shorter testing times were assumed for the module- and cell-level testing. The shorter protocol reflects a case when onboard diagnostics data are available and the use of an advanced electrochemical diagnostics model with an efficient characterization protocol. This shortens the testing time, as full cycles are not required to determine the SOH of the battery. The longer protocol reflects the absence of onboard diagnostics data from the EV and the use of a more traditional testing protocol using a lower C-rate of about C/3 [58]. The longer protocol was used to reflect that it takes longer to process a battery pack compared to a module, although the electrical testing time should be similar if onboard diagnostics data are available, as is assumed in the testing of modules. The electrical testing time does not have any impact on the number of batteries processed at the facility, as the amount of testing equipment is adjusted to meet the output requirements. Only one piece of testing equipment is required for testing the battery packs as relatively few battery packs (588) are processed at the facility.

Table 4. The processing and testing times for batteries at the battery-repurposing facility.

Battery Pack Processing Time	**Value**	**Unit**	**Ref. [58]**
Receiving Inspection and Handling	60	min	
Connection to and Initiation of Electrical Test Equipment	10	min	
Electrical Testing	460	min	
Time Spent Charging	260	min	
Average C-Rate for Charging	0.333333	C	
Disconnection from Electrical Test Equipment	5	min	
Final Inspection and Packaging	45	min	
Total Technician Handling Time	120	min	
Module Processing Time	**Value**	**Unit**	**Ref. [58]**
Receiving Inspection and Handling	10	min	
Connection to and Initiation of Electrical Test Equipment	10	min	
Electrical Testing	75	min	
Time Spent Charging	45	min	
Average C-Rate for Charging	1	C	
Disconnection from Electrical Test Equipment	5	min	
Final Inspection and Packaging	10	min	
Total Technician Handling Time	35	min	
Cell Processing Time	**Value**	**Unit**	**Ref.**
Receiving Inspection and Handling	1	min	Estimate
Connection to and Initiation of Electrical Test Equipment	0.1	min	[61]
Electrical Testing	75	min	Estimate
Time Spent Charging	45	min	Estimate
Average C-Rate for Charging	1	C	Estimate
Disconnection from Electrical Test Equipment	0.1	min	[61]
Final Inspection and Packaging	1	min	Estimate
Total Technician Handling Time	2.2	min	

Besides the time spent processing and testing the batteries, the disassembly time must be considered when the batteries are processed at the module or cell level. The time required for disassembling the battery packs at the module and cell level is listed in Table 5. The disassembly time for a Tesla Model S battery pack was calculated based on estimates provided in [62]. The estimated time to disassemble the Tesla Model S battery module was obtained from work in the project "Developing Battery 2nd-life Business in Ostrobothnia" [63], where a Tesla Model S battery module was partly disassembled at the cell level. As a result of this work, it was found that the disassembly of a Model S battery module is extremely time-consuming. The time estimate arrived at in this project, 2680 min, is much greater than the theoretical estimate of 20 min calculated based on information from Lander et al. [62]. The cells are difficult to remove as they are glued to the plastic chassis of the module. Care must be taken while disassembling so as not to damage the cells.

Table 5. Disassembly times for the Tesla Model S/X battery packs at module (based on [62]) and cell level [63].

Time to Disassemble Battery Pack into Modules	Value	Unit	Ref. [62]
Peel off glued plastic cover	5	min	
Unscrew top cover	5	min	
Unclamp top cover	5	min	
Empty coolant	5	min	
Disconnect wires	5	min	
Disconnect battery management system (BMS)	5	min	
Disconnect coolant hoses	5	min	
Unscrew modules from tray	79	min	
Total disassembly time	113	min	
Time to disassemble battery pack into modules	**Value**	**Unit**	**Ref. [63]**
Total disassembly time per module	2680	min	

With the battery processing, testing, and disassembly times established, the specifics of the battery-repurposing facility are then evaluated using the B2U calculator.

3. Results

3.1. Forecast of EVs in Finland and Ostrobothnia up to 2030

The forecasted amount of EVs in use in Finland and Ostrobothnia is shown in Figure 4. It was calculated that the Finnish EV stock would have to grow with a CAGR of about 30% from the 2022 amount of 44,889 EVs to reach 375,000 EVs in 2030.

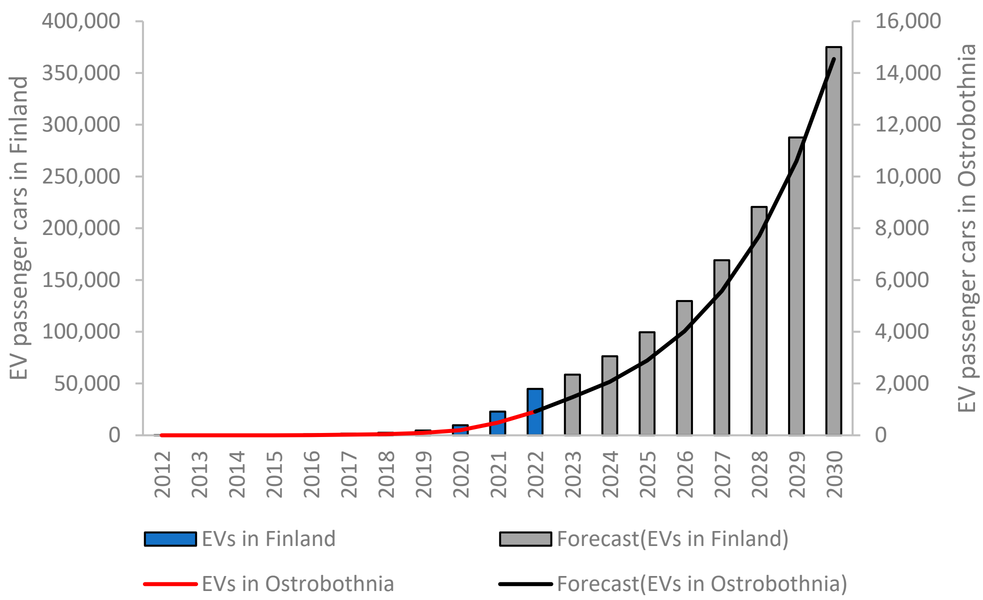

Figure 4. The forecasted total number of passenger EVs in use in Finland and Ostrobothnia up to 2030.

The Ostrobothnia region has been a slow adopter of EVs, with the region having a ratio of EVs to total passenger cars that is 43% smaller than the rest of Finland in 2022 (0.93% vs. 1.64%) [43]. Based on the linear trajectory forecast that was made, the Ostrobothnia region is expected to catch up to the rest of Finland in 2030, obtaining a ratio of EVs to total passenger cars about 10% larger than the rest of Finland (14.5% vs. 13.2%).

3.2. MFA of EV Batteries in Finland and Ostrobothnia up to 2035

Using the forecasts for EVs on the road in the Ostrobothnia region and Finland up to 2030 obtained in Section 3.1, MFAs for LIBs reaching their end of life up to 2035 were conducted. First, an MFA of EV batteries available for second-life applications was conducted for Finland. By observing Figure 5, it can be deduced that larger amounts of EV batteries will start to be available for second-life use in Finland after 2030 when an amount of about 10,000 EV batteries per year is reached in both cases. It is also possible to deduce that the EV lifespan will not have that big of an impact overall on the availability of SLBs in both Finland and Ostrobothnia. In the case of Finland, the shorter 10-year EV lifespan leads to roughly 34,000 EV batteries being available for second-life applications in 2035 compared to about 27,000 for a 16-year lifespan.

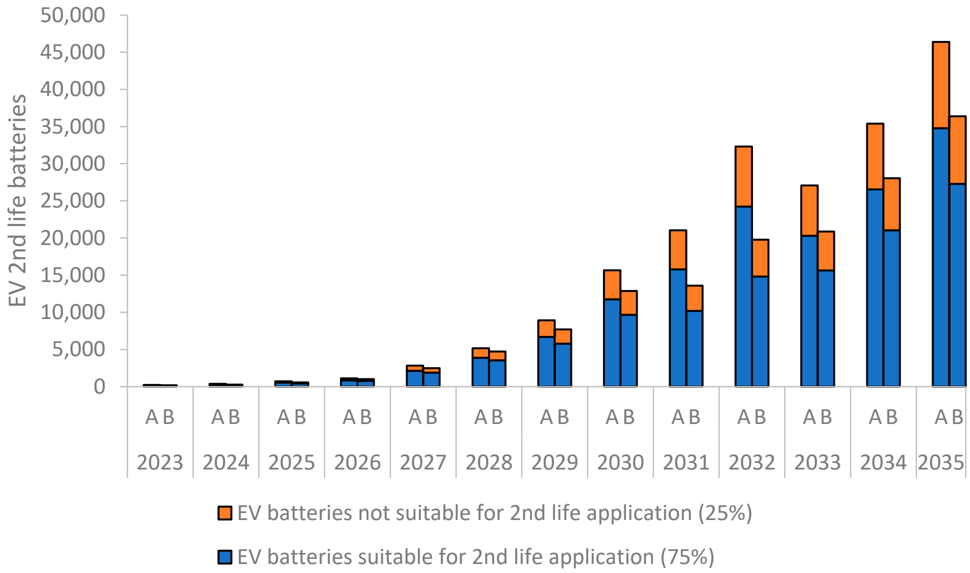

Figure 5. The estimated availability of second-life batteries in Finland. A—10-year EV lifespan; B—16-year EV lifespan.

The results of the MFA for the Ostrobothnia region using 10-year and 16-year EV lifespans are shown in Figure 6. It can be deduced that the number of EV batteries available for second-life applications from the region is not significant, reaching an amount of about 200 batteries annually in 2030 in both cases and 1000 batteries per year in 2035. Based on this, it can be concluded that there is no major business potential for sourcing SLBs only from the region, at least not in the near future. Thus, businesses interested in establishing an SLB business in the Ostrobothnia region should consider sourcing their batteries from a larger market, i.e., Finland.

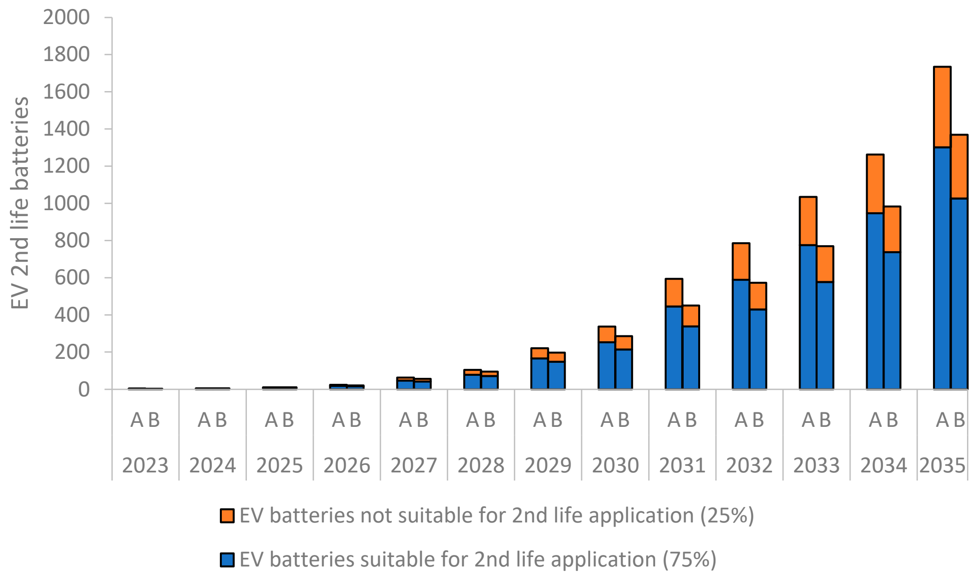

Figure 6. The estimated availability of Second-Life Batteries in Ostrobothnia. A—10-year EV lifespan; B—16-year EV lifespan.

3.3. MFA of Tesla Model S and X Batteries in Finland up to 2035

In 2022, the combined market share of Tesla's Model S and X in Finland was 6% [43], and the resulting forecast, which assumes the market share of the Tesla models follows the same linear trajectory, shows the market share declining to 3% in 2030. The results of the MFA for Tesla Model S and X batteries using 10-year and 16-year EV lifespans are shown in Figure 7.

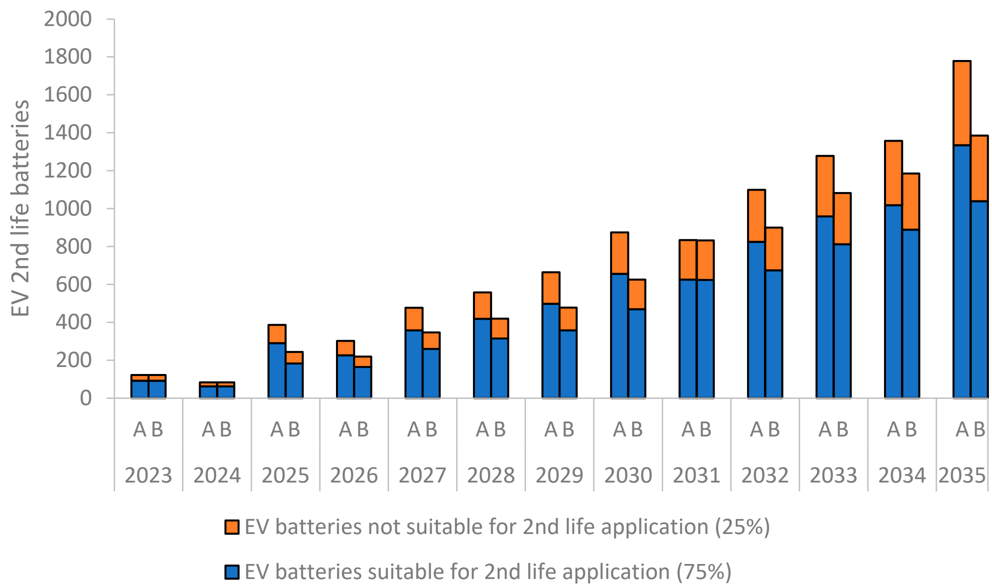

Figure 7. The estimated availability of second-life Tesla Model S and X batteries in Finland. A—10-year EV lifespan; B—16-year EV lifespan.

In both cases, an amount of 500+ Tesla Model S and X SLBs per year will be reached in the 2030s, and by 2035, over 1000 batteries will be available annually for second-life applications. It is assumed that all the battery packs are of the same type, that is, a Tesla Model S/X battery pack with a capacity of 85 kWh. Based on these results, the hypothetical SLB business was assumed to process 50 MWh, which corresponds to 588 of these Model S and X batteries annually. In reality, there are different versions of the battery packs for these models, with different capacities. Furthermore, Tesla has signaled plans to switch from the 18650 cylindrical cells currently used in the Model S and X batteries to 4680 larger cells, which will change the structure of the battery packs. This highlights the challenge for SLB businesses hoping to specialize in a specific battery pack for efficiency: battery packs are prone to change and development.

3.4. The Selling Price of a Repurposed Battery and the LCOS of a Second-Life BESS

To evaluate the selling price of a repurposed battery and the LCOS, the lifetime of the battery packs must be determined. Using the parameters listed in Section 2.2 and considering cyclic and calendar degradation, new LIBs were found to be able to perform 2267 cycles before reaching their EOL, corresponding to 1360 full equivalent cycles (FECs). The resulting lifetime of the new LIB is 6.2 years. The SLB could perform 1277 cycles or 766 FECs before reaching its EOL, giving it a lifetime of 3.5 years. With the lifetimes of the batteries known, the present value of throughput of used and new batteries was evaluated using Equation (3). These were then used to determine the health factor of the used battery using Equation (2). The health factor was found to be 65%. With the health factor known, the selling price of a repurposed battery can be determined using Equation (1) as well as the average cost of a new EV LIB pack, which was 151$/kWh or 133 EUR/kWh in 2022 [52]. The selling price of a repurposed battery was found to be 65.5 EUR/kWh.

The LCOS of the BESS applying new LIBs or SLBs in a peak-shaving application is determined while considering the lifetime of the battery packs. As the project lifetime of the BESS is 10 years, the BESS with new batteries will be required to replace the batteries once, and the BESS using SLBs will be required to replace them twice. The LCOS could then be evaluated using Equation (7) and the BESS cost data listed in Table 3.

As such, the LCOS shown in Table 6 was obtained for the peak-shaving BESS. The result shows that a system using SLBs would have about 12% lower LCOS compared to a system using new LIBs.

Table 6. Comparison of the LCOS for a peak-shaving BESS utilizing new LIBs vs. SLBs.

LCOS of 2 MWh, 1 MW Peak-Shaving BESS		
New LIBs	648	EUR/MWh
SLBs	568	EUR/MWh

3.5. Evaluation of the Tesla Model S and X Battery-Repurposing Business

General information on the Tesla Model S/X battery packs handled at the fictive repurposing facility are listed in Table 7. The resulting yield at the module level becomes 97.67% with an assumed cell fault rate of 0.001%. The yield becomes 99.995% if the faulty modules are disassembled at the cell level.

Table 7. Information on the Tesla Model S and X battery packs processed at the repurposing facility.

Parameter	Value	Unit
Pack Nameplate Energy	85	kWh
Percent Remaining Energy at Time of Repurposing	80	%
Approx Remaining Energy at Time of Repurposing	68	kWh
Number of Modules in Pack	16	pieces
Module Nameplate Energy	5.3	kWh
Approx Remaining Energy at Time of Repurposing	4.24	kWh
Number of Cells in Module	444	pieces
Cell Fault Rate	0.001	%
Yield (at module level)	97.67	%
Yield (at module + cell level)	99.995	%

The annual throughputs of the repurposing facility in the different scenarios evaluated are listed in Table 8. The battery packs, modules, and cells are processed at different stations: inspection stations, electrical test stations, and packing stations. When calculating the number of stations and testing equipment required, it is assumed that the facility operates 365 days per year, 24 h per day. Each technician is assumed to work 252 days per year, 8 h per day [58].

Table 8. Annual throughput of the facility in scenarios 1–4.

Annual Throughput of the Facility		Scenario
Packs per year throughput	588	(1) (2) (3) (4)
Packs per day throughput	1.6	(1) (2) (3) (4)
Modules per year throughput	9408	(2) (3) (4)
Modules per day throughput	25.8	(2) (3) (4)
Modules with faulty cells per year	219	(3) (4)
Faulty cells per year	219	(3) (4)
Cells per year throughput	97,236	(3)
Cells per day throughput	266.4	(3)
Cells per year that are OK	97,017	(3)
Cells per year throughput	4,177,152	(4)
Cells per day throughput	11,444	(4)
Cells per year that are OK	4,176,933	(4)

The main results obtained from the modified B2U calculator are compiled in Table 9. The repurposing costs seem reasonable for scenarios 1–3 as they are in the same range as those of [58]. However, in scenario 4, the buying price for the used battery pack is negative. Thus, it can be concluded that the disassembly of the Tesla Model S module at the cell level is not recommendable due to the high labor costs of the long disassembly process. Due to the long disassembly time, a large number of technicians would have to be added to disassemble all the modules and test the cells. The size of the facility would also increase significantly in this scenario to accommodate these personnel.

Table 9. The main economic results for the Tesla Model S and X battery-pack-repurposing facility in the different scenarios.

Scenario	(1)	(2)	(3)	(4)	
Battery Selling Price (EUR/kWh) *	65.5	65.5	65.5	65.5	
Battery Pack Buying Price (EUR/kWh—nameplate)	38.3	34.7	27.1	−328.4	
Effective Repurposing Cost (EUR/kWh—nameplate)	27.2	30.8	38.3	393.8	
Battery buying price (EUR)	3252	2949	2307	−27,909	per pack
Battery selling price (EUR)	5564	5564	5564	5564	per pack
		348	348	348	per module
			0.8	0.8	per cell
Annual revenue (EUR)	3,195,175	3,195,315	3,271,227	3,271,227	
Yield (at pack, module, module + cell, or cell level) (%)	97.67	97.67	99.995	99.995	

* The selling price stays fixed in this method, while the repurposing cost and buying price are variable.

The increasing share that the labor costs account for when more steps are added can be observed in the breakdown of the annual costs in the repurposing facility in the different scenarios, as shown in Figure 8.

The remarkably negative pack buying price obtained in scenario 4 means that the repurposing business would have to be paid that much to recover the costs of repurposing the battery. Because the module-to-cell disassembly time applied here is significantly longer compared to the literature value based on Lander et al. [62], sensitivity analyses were conducted for scenarios 3 and 4. The sensitivity analyses were conducted by varying the module-to-cell disassembly time between 20 and 2680 min and examining the effect this has on the repurposing cost and the pack buying price. The result of the sensitivity analysis for scenario 3 is shown in Figure 9. The repurposing cost varies between 31.8 and 38.3 EUR/kWh, and the pack buying price varies between 33.7 and 27.1 EUR/kWh. The lower end of the repurposing cost and the higher end of the pack buying price lie close to the pack buying price of scenario 2, where the pack buying price was 34.7 EUR/kWh, and the effective repurposing cost was 30.8 EUR/kWh. Thus, when the module-to-cell disassembly time is 20 min, there is no significant difference in the repurposing costs for scenarios 2 and 3.

The result of the sensitivity analysis for scenario 4 is shown in Figure 10. The repurposing cost varies between 128.6 and 393.8 EUR/kWh, while the pack buying price varies between −328.4 and −38.3 EUR/kWh. It can thus be deduced that the disassembly of all battery packs at the cell level remains unfeasible even when the module-to-cell disassembly time is short due to the added labor of disassembly at the cell level and the testing of the cells. However, this is assuming that the price obtained for the sale of the repurposed battery cells is the same as for battery packs or modules. It may be possible to obtain a higher price per kWh for the sales of repurposed battery cells, as smaller battery packs can be made of these, such as for e-scooters, which have a higher cost per kWh.

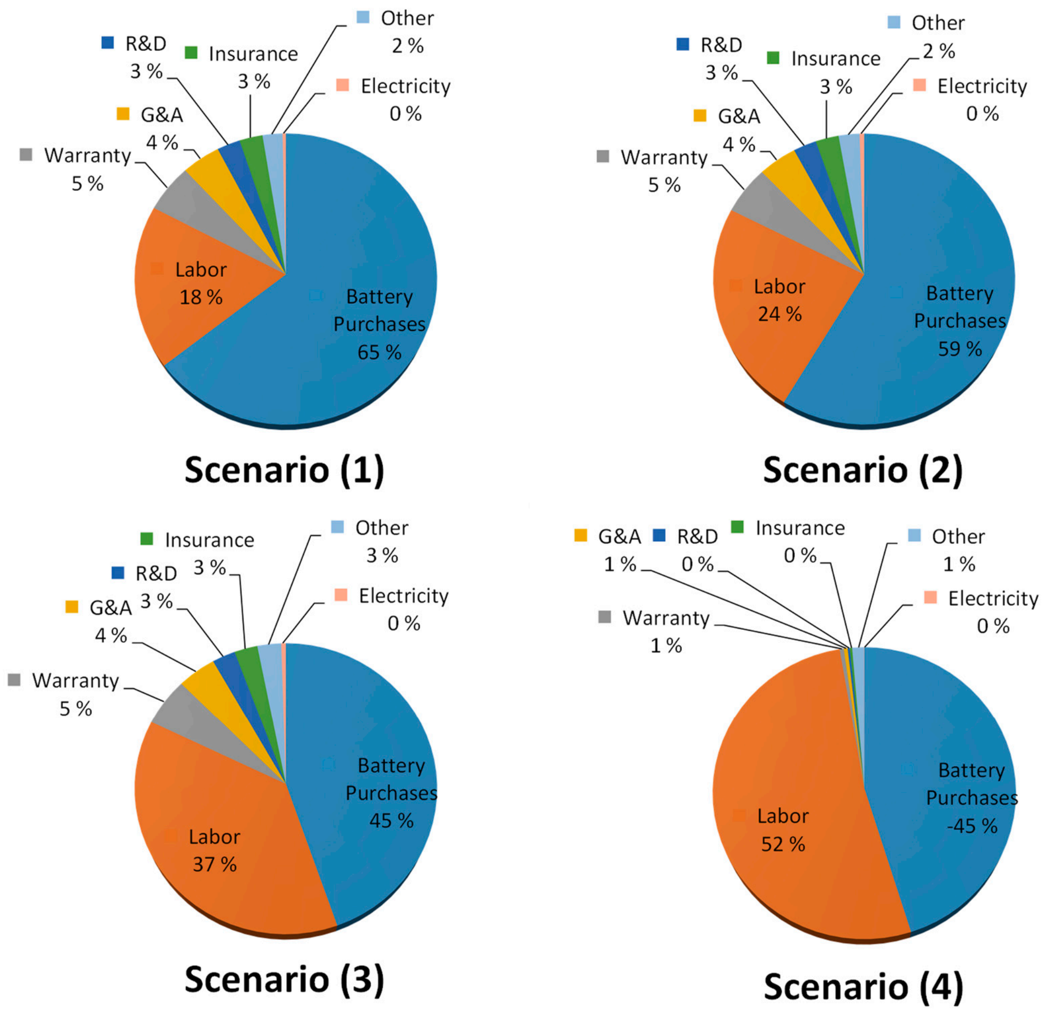

Figure 8. A breakdown of the annual costs of the repurposing facility in the different scenarios.

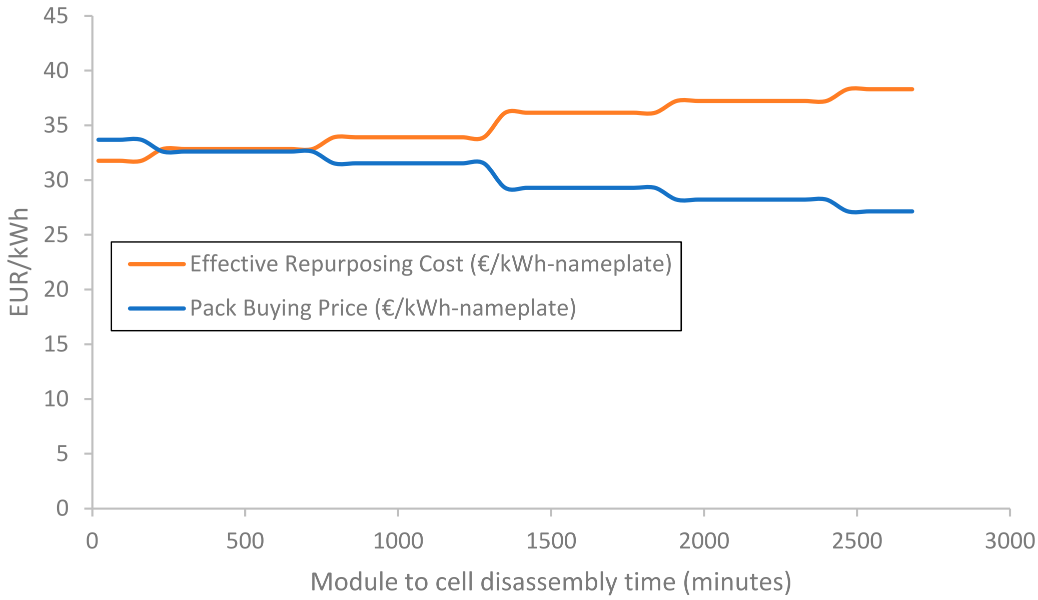

Figure 9. Sensitivity analysis for scenario 3. Module-to-cell disassembly times from 20 min to 2680 min.

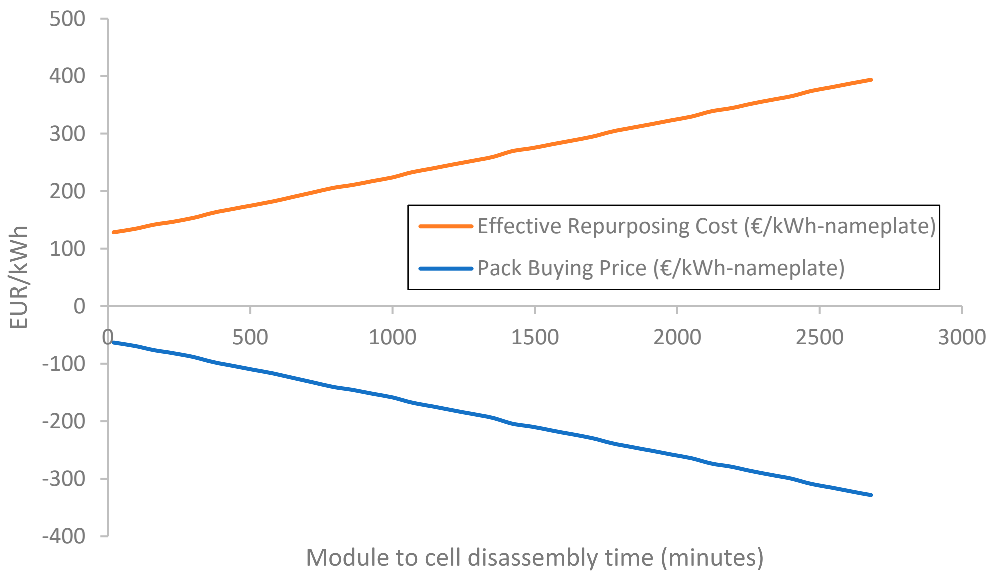

Figure 10. Sensitivity analysis for scenario 4. Module-to-cell disassembly times from 20 min to 2680 min.

4. Discussion

The purpose of this paper was to analyze the business potential for SLBs in the Ostrobothnia region through a case study of a hypothetical business repurposing Tesla Model S and X batteries. This section discusses the results of this study and focuses on the uncertainties and general challenges encountered when analyzing SLBs, given their complexity. Also, suggestions are given for improvements that could be made in future research.

The first step in assessing the potential of SLBs was to conduct an MFA for EVs and their LIBs from Ostrobothnia and Finland to assess how many batteries might be available for repurposing. The promising aspects of the results of Figure 4 are that the share of EVs compared to total passenger cars was expected to be 10% higher in Ostrobothnia than in the whole of Finland by 2030. However, the number of batteries becoming available from the region does not seem sufficient to have any major business potential.

It should be noted that in the MFA of EVs, a simplification has been made where it is assumed that all the EVs added each year are newly manufactured vehicles. However, in reality, this is not the case, as the EVs registered as being in use in a year also include used EVs that have been imported from abroad. Thus, assuming the imported EVs follow the same lifespan distribution, there may be a larger number of EV batteries becoming available for second-life applications earlier on than what the MFA shows, depending on the age of the imported EVs and their batteries. In the MFA, both 16-year and 10-year EV lifespans were studied. A 16-year lifespan was considered a more likely scenario, a 10-year lifespan seems unlikely in Finland as the average age of passenger cars in use was 12.5 years in 2022 [64], and the average scrapping age of passenger cars was 22.2 years in 2022 [65]. The lifespan of cars with internal combustion engines and EVs could turn out to be different. However, Kurdve et al. [66] stated that the average lifespan of EVs could be 8–24 years or longer.

PHEVs were not included in the MFA of EVs because it is predicted that they will not be suitable for second-life applications. Baars et al. [49] assumed that PHEV batteries will not be replaced during the lifetime of the vehicle because there is limited incentive to do so. In PHEVs, due to the hybrid function of the vehicle, the range is not as important a factor as in pure EVs. There is thus limited incentive to replace a battery in a PHEV due to a decrease in capacity, and it is assumed PHEV batteries end up going straight for recycling. It should be noted, however, that it is possible to reuse PHEV batteries. For instance, batteries from Volvo plug-in hybrids were given a second life in a 1 MW/250 kWh installation at Fortum's hydropower plant in Landafors, Sweden, where the battery storage offers fast frequency reserve regulation to the power markets [67].

The LCOS calculation gave an interesting result, as observed in Table 6: a system using SLBs would have an LCOS that is about 12% lower compared to a system using new LIBs. This contrasts with the results of Steckel et al., who found the LCOS of second-life BESS to be, on average, 11–32% higher than new BESS [14]. One explanation for the discrepancy, and a weakness in the calculation in this study, is that the labor cost of replacing the batteries in the BESS was not accounted for. As the SLBs required two replacements and the new batteries required only one replacement during the lifetime of the BESS, this could increase the LCOS of the BESS using SLBs. Another flaw is that the residual value of the batteries after the end of the BESS project was not accounted for. As the once-replaced new LIB had a longer lifetime left than the twice-replaced SLB, this could further tip the LCOS in favor of the BESS using new LIBs.

The LCOS and the health factor were only determined for the second-life application of peak shaving in this study. Further research could, in combination with a better battery degradation model and using hourly day-ahead electricity prices, evaluate the LCOS and health factor for different second-life applications in order to evaluate the most profitable second-life application for the batteries.

The battery-repurposing plant was found to be feasible in three of the scenarios analyzed with the modified B2U Calculator. When the used batteries are processed on the pack or module level, the initial costs invested in the SLB business could be recovered over 5 years. The repurposing costs start to increase significantly when the batteries are processed on the cell level. Due to the small number of faulty cells, the business could remain feasible in Scenario (3) when only the modules with faulty cells were disassembled at the cell level. However, Scenario (4), in which all the battery packs are disassembled at the cell level, is economically infeasible. The scenario leads to a substantial increase in the number of workers and space required. This leads to the scenario becoming infeasible, as the labor cost is the second largest cost category behind the purchasing costs of the used batteries.

Challenges or uncertainties identified in this study have been summarized in Table 10. The uncertainties have been divided into three categories: technical, market, and economic.

Table 10. List of challenges or uncertainties that were identified in this study.

Technical
Handling and processing time of batteries (disassembly and testing).
Not all tests were included.
Access to BMS data.
Battery SOH range and degradation uncertainty—when do the batteries end their first and second lives?
The ratio of batteries with faulty cells and used batteries that will be suitable for second-life applications.
Market
Forecast of EV and LIB availability.
The SLB market is still emerging and developing—potentially different markets for new LIBs and SLBs.
Potentially limited market potential for SLBs. The BESS market might be relatively minor compared to the EV market and quickly reach saturation.
Competing against the declining cost of new and more efficient LIBs which may favor recycling.
Economic
Battery pack buying price.
Battery pack selling price.
Costs (labor, facilities, equipment, etc.).
Discount rate.

The results of this study showed that after the cost of purchasing the batteries, labor costs make up the most significant cost factor of the repurposing business. However, the disassembly times and testing times are based on time estimates. The time estimate for the module-to-cell disassembly arrived at in this study differed vastly from time estimates in the literature, indicating significant uncertainty. The actual disassembly and testing times may differ significantly from the estimates used here, and they are subject to change as testing technologies are being developed. The processing time for testing the batteries may be significantly shorter if the repurposer has access to battery management system (BMS) data [58]. As EV LIBs are currently disassembled manually [62], manual disassembly was assumed in this study. In the future, however, automated disassembly may become a possibility, which could significantly decrease disassembly time and labor costs [9]. The impact of labor costs on the potential feasibility of businesses is significantly pronounced in regions with high labor costs, such as Finland, which ranks among the 10 countries with the highest labor costs in the EU [68]. Hence, it is likely that an automated solution would have a larger impact on the repurposing of SLBs in Finland compared to countries with lower labor costs.

In this study, the testing of the used batteries involves electrical testing to determine the SOH of the battery packs, modules, or cells. However, after the repurposed battery packs have been installed in a second-life application, additional functional and safety tests may be required [34], thus increasing the repurposing costs. When modules or cells are reassembled into new packs, the new packs would require testing. In this study, the costs for the reassembly of the modules or cells into packs were not included in the repurposing costs, nor the costs for the addition of new components and the possible replacements of the BMS, the energy management system, or the thermal management system.

The degradation behavior of SLBs has a strong impact on the lifetime of the batteries, which in turn has a strong impact on the market price of the SLBs. In this study, calendar and cyclic aging were accounted for. However, the calendar aging model was not specific to NCA-type batteries, and cyclic aging was linearized based on data from [55]. More advanced and accurate models for the degradation of the batteries could be used.

It was assumed that the batteries begin their second life at an SOH of 80% and end their second life at 60%, but it is uncertain whether these thresholds are accurate. Battery degradation during the first life of an EV battery is impacted by the charging/discharging pattern of the EV consumer and their driving style, the specifications of the battery, and climate [69]. Consumers have different preferences: some customers may consider a battery has reached its EOL when the range has dropped below a certain threshold due to degradation, but the range may be sufficient for another consumer. Hence, the EV could end up exchanging owners on the used car market until the battery has reached its EOL without a second life, assuming the vehicle did not reach its EOL before. Studies have found that an EV battery retired from first life at 60% SOH can still meet the daily travel needs of the majority of drivers [18,70]. However, at this SOH, the battery's performance may be limited by a rise in the internal resistance, and the risks of reaching the aging knee (which is when the aging of the battery rapidly accelerates) increase substantially.

In the forecast of future Model S and X battery availability, the same assumption was applied to these as to the forecast of EV batteries in general, i.e., that 75% of the batteries are suitable for second-life applications. However, the share of batteries suitable for second-life applications is likely to be higher for these batteries because they have a large capacity of 85 kWh. Assuming the same driving profile, the effects of cyclic degradation are smaller on batteries with large capacities. Hence, these batteries can be expected to retire from their first life in better shape and at a higher SOH and be suitable for second-life applications [71]. Thus, the share of Model S and X batteries available for second-life applications could be higher. On the other hand, the assumed cell fault rate of 0.001% used in this study for the batteries that arrive at the repurposing facility is rather optimistic.

In this study, the EV forecast was built on a target set by the Finnish government of 375,000 EVs on the road being met by 2030. A more accurate forecast could take into account EV and battery price developments and secondary economic factors, for example, taxes and incentives, electricity and fuel prices, and carbon pricing [66].

Even though the EV market is set to grow significantly, and there might be a sufficient supply of used EV batteries in Finland for a repurposing business to operate, it may be that the market for BESS is minor compared to the market for EV batteries. It has been predicted that the mobility market will grow much faster than the energy storage market [72]. The mobility market will account for around 91% of the global demand for LIBs of 4.7 TWh by 2030, with the remainder being split between BESS and consumer electronics [73]. A small market like Finland might quickly become saturated with BESSs. Repurposing circular business models might not be profitable in countries without the demand for energy storage [74]. Thus, the repurposing business would have to operate internationally to find a market elsewhere for the SLBs. Then, the export of the batteries would add to the transportation costs and hamper the economic feasibility of the business. Alternatively, if the supply of retired EV LIBs from the Finnish market was not sufficient, the batteries would have to be imported, which would also negatively impact the economic prospects. A study by Rallo et al. found a decentralized scenario, in which batteries are dismantled and prepared for a second life or recycling locally in Spain, to be more economically (and environmentally and socially) viable compared to a centralized scenario, in which batteries are handled in Germany [75]. The reason for this was the greater logistical costs for transportation in the centralized scenario and the fact that these costs occupy a large share of the total costs.

The price of new LIBs has been decreasing rather fast, and this can lower or erase any economic advantages that SLBs may have over new LIBs [76,77]. The cost of repurposing batteries must remain small enough to compete with new batteries. Furthermore, battery technology is evolving fast, with the capacity of batteries increasing by 3% per year [72]. This may prove unfavorable for SLBs. An SLB at 70–80% of its initial capacity would only have 50–60% of the capacity of a new battery after 10 years.

The new EU batteries regulation will require a certain level of recycled materials in new EV batteries in the 2030s [78], and obtaining that amount of recycled material may prove difficult if a significant share of used EV batteries ends up in second-life applications [79]. This may lead to recycling becoming favored over repurposing.

In terms of economic uncertainties, the most significant uncertainty comes from the price of the batteries, as the purchasing costs of the used batteries make up the largest share of the annual costs. There are also uncertainties around the other costs of the business, but mainly the labor costs, as these accounted for the most significant share after the battery purchasing costs. The discount rate assumptions used can also have a significant effect on the results of economic analyses.

As there are not yet many SLBs available and the market is still developing, there are uncertainties regarding what prices used batteries can be bought at and for what the SLBs can be sold. McKinsey predicted that in 2025, SLBs may be 30–70% less expensive compared to new LIBs [80]. Lehmusto and Santasalo-Aarnio considered the assumption made by Tsiropoulos et al. [81] that used EV battery packs can be sold to manufacturers at 50% of the cost of new ones to be somewhat optimistic. Lehmusto and Santasalo-Aarnio assumed in their study that the sales price of second-life LIBs could reach 50% of the price of new LIBs [82]. Therefore, the pack buying price will be lower than this to cover the repurposing costs of the used LIBs. Rallo et al. concluded, based on the results of some previous studies, that the cost of repurposed batteries should be lower than 50% of new ones [83]. A study by Mathews et al. reached the result that the costs of SLBs must be <60% of new batteries to be profitable [84]. The selling price (65.5EUR/kWh) arrived at in this study is about 49% of the average cost of new EV batteries (133 EUR/kWh [52]) and thus falls in line with the previously mentioned studies.

When looking at the current situation in the SLB market, the repurposed battery selling price of 65.5EUR/kWh arrived at in the study, and the range in scenarios 1–3 for the SLB pack for the resulting buying prices of the used Tesla Model S and X battery packs, 27.2 EUR/kWh–38.3 EUR/kWh, seem rather low. An investigation by the consulting firm Circular Energy Storage found the lowest price of a used battery pack on the market to be 71.5 EUR/kWh [85]. However, it was stated that the average cost for battery packs, of which there is a high volume on the market, such as Tesla battery packs, is higher than this. Based on this information, the calculated selling price and battery pack buying prices do not quite seem to correspond to reality. The reason for this might be that the market for SLBs is different from the market for new battery packs. The average small-scale customer does not have access to battery packs at the average cost of new battery packs and pays a much higher price than this.

5. Conclusions

An MFA of the EV stock and the number of LIBs reaching their EOL in Finland and the Ostrobothnia region was conducted to find out when a considerable number of retired EV batteries will be available for SLB businesses. Larger volumes (around 10,000 LIBs/year and 500 Model S/X batteries/year) will start to be available by 2030 in Finland. It was concluded that the number of batteries becoming available for second-life use from the Ostrobothnia region is too small to present any significant second-life business opportunities for companies, at least in the near future.

The LCOS calculations showed that SLBs applied in a peak-shaving BESS application have a 12% lower LCOS compared to new LIBs. This indicates that there may be a business case for using SLBs over new LIBs in BESSs and that there would be demand for repurposed batteries.

A techno-economic analysis was conducted using a modified version of NREL's B2U calculator in a case study of a hypothetical SLB business operating in the Ostrobothnia region, Finland. The results showed that the initial investment costs of the SLB business can be recovered over a 5-year period in scenarios when the used batteries are processed at the pack or module level. The repurposing costs increase significantly when the batteries are processed at the cell level. The business remained feasible in the scenario when only the modules with faulty cells were disassembled at the cell level. However, the scenario when all battery packs were disassembled at the cell level was not economically feasible. It would have required a large number of workers and additional space, and the labor cost is the second most significant cost after the purchasing costs of the used batteries. If automation is made technologically possible in the future, it could help bring down the costs of the labor-intensive process of repurposing used batteries for second-life applications. The repurposing costs of used batteries and the selling price of the SLB arrived at in this study seem to agree with the values found in the literature.

The results of this study gave an indication of the potential availability of EV LIBs for second-life applications from the Ostrobothnia region and Finland, and the costs of repurposing batteries in the region, as well as the differences in costs when processing batteries on the pack, module or cell level. This techno-economic analysis of the business potential of SLBs may prove useful for companies in the region that are interested in the SLB market.

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