sustainability

MDPI

Article

Recoverability Analysis of Critical Materials from Electric Vehicle Lithium-Ion Batteries through a Dynamic Fleet-Based Approach for Japan

Fernando Enzo Kenta Sato [1,2] and Toshihiko Nakata [2,*]

1 Cyclical Resource Promotion Division, Honda Motor Co., Ltd., Wako 351-0114, Japan; kenta_b_sato@hm.honda.co.jp
2 Department of Management Science and Technology, Graduate School of Engineering, Tohoku University, Sendai 980-8577, Japan
* Correspondence: nakata@tohoku.ac.jp

Received: 5 December 2019; Accepted: 20 December 2019; Published: 23 December 2019

Abstract: This study aims to propose a model to forecast the volume of critical materials that can be recovered from lithium-ion batteries (LiB) through the recycling of end of life electric vehicles (EV). To achieve an environmentally sustainable society, the wide-scale adoption of EV seems to be necessary. Here, the dependency of the vehicle on its batteries has an essential role. The efficient recycling of LiB to minimize its raw material supply risk but also the economic impact of its production process is going to be essential. Initially, this study forecasted the vehicle fleet, sales, and end of life vehicles based on system dynamics modeling considering data of scrapping rates of vehicles by year of life. Then, the volumes of the critical materials supplied for LiB production and recovered from recycling were identified, considering variations in the size/type of batteries. Finally, current limitations to achieve closed-loop production in Japan were identified. The results indicate that the amount of scrapped electric vehicle batteries (EVB) will increase by 55 times from 2018 to 2050, and that 34% of lithium (Li), 50% of cobalt (Co), 28% of nickel (Ni), and 52% of manganese (Mn) required for the production of new LiB could be supplied by recovered EVB in 2035.

Keywords: lithium ion batteries; recycling; reusing; critical materials; forecasting; dynamic modeling

1. Introduction

Several environmental goals, such as sustainable development goals [1] and the Paris agreement [2], have been globally settled in the last decade to achieve a more sustainable society. In this sense, the advancement of electrification of vehicles seems to be inevitable, considering that, currently, the transportation area accounts for 25% of the total energy consumption [3] and carbon dioxide (CO_2) emissions [4,5] of the word. Japan has the third-highest representative vehicle market when worldwide production and the sales volume of vehicles are considered [6,7], but it is also one of the countries that is leading the development of new electrical technologies in the transportation area, including the development of hybrid electric vehicles and fuel cell vehicles.

Internal combustion engine vehicles depend on fossil fuels; however, electric vehicles, including hybrid electric vehicles (HV), plug-in hybrid electric vehicles (PHEV), battery electric vehicles (BEV), and fuel cell vehicles (FCV) depend partially or totally on electricity. Currently, electric vehicles (EVs) account for 32.9% of vehicle sales in Japan [8], and a rapid increase in their share is expected in the upcoming years. Here, the size and weight of electric vehicle batteries (EVB) vary depending on the electrification level, the driving range of the vehicle, and its technology. Most of those vehicles use lithium-ion batteries (LiB) to store the energy needed for traction due to their higher energy density and extended lifespans compared with other available technologies. Additionally, considering the use of LiB in consumer electronics and grid energy storage, the increment of the dependency of the transportation sector but also of society on those technologies in the middle and long term seems to be inevitable.

The sustainable production of LiBs in the upstream part of the supply chain is indispensable; however, adequate collection, treatment, recycling, and reuse of those batteries in the downstream stage is also necessary. Firstly, the electrical, fire-explosion, and chemical hazard potential of LiBs must be considered [9]. Secondly, the high carbon intensity of the cell's production and the significant potential of its cascade use to minimize its life cycle environmental impact must be taken into account [10,11]. Third, it must be considered that valuable and critical materials such as Cobalt and Nickel can be recovered with an adequate recycling process [12]. Moreover, collected LiB can be reused in second life stationary applications for the storage of solar or wind power, peak shaving, EV charging, electricity trading, backup, and so on [13], significantly reducing their production cost. Finally, the high processing and transportation costs of scrapped LiB, approximately 10 to 15 thousand yen per unit of battery for HV in Japan [14], need to be reduced. This is a critical factor when the total weight of future scrapped EVB is considered. In this sense, directives by governments have been settled to promote the efficient collection and recycling of batteries [15].

The current recycling flow of the vehicles, including the EV, consists firstly in the removal of their batteries, fluids, tires, and airbags as a preventive measure. Subsequently specific automotive parts are selected and extracted to be resold as second-hand spare parts. At this stage of the procedure, other parts are also separated to be recycled as alternative raw materials. The remaining dismantled vehicles are pressed and sent to shredding companies, where metals are primarily separated magnetically. Finally, the automobile shredder residues that are composed primarily of plastics, foam, and textiles are obtained as remainders.

The criticality of the different materials could vary depending on the country and the time when the material is supplied. There is also a strong dependence on the risk factors considered in its calculation. However, when criticality related to the production of the LiBs is analyzed, lithium (Li), nickel (Ni), cobalt (Co), and manganese (Mn) are usually highlighted as the representative elements [16–18]. Many studies have analyzed the importance of reusing and recycling the spent LiB [13,19–21]; however, those approaches do not include in assessment limitations of the EVB and EV market itself, excluding in the analysis the real potential of them when proposed concepts are put into practice. For this, two variables have proposed as indispensable for analysis: the recovery volume and the time of the batteries. Few studies have proposed dynamic approaches to forecasting; however, one of the critical factors in the modeling, which is the return/scrap timing of the EV and batteries, is modeled considering the lifespan of the vehicle as a constant by a single point estimation [22–24], or a truncated lifespan distribution is used [25,26]. Moreover, the changes in battery technology over time, which impact directly on their material composition, are also not considered. Additionally, to the author's knowledge, previous studies have been centered on Europe or North America, and no studies have analyzed the Japanese market. Evaluation of the mentioned country is essential considering that as the third-largest economy in the world [27], Japan has one of the biggest vehicle markets, and its technological contribution to the electrification of vehicles is indispensable. Moreover, worldwide-scale automakers and battery makers lead the local automotive industry and are pioneers in the development of electric vehicles.

This study aims to propose a model to forecast the number of critical materials that can be recovered from LiB through recycling end of life EV and analyzing the potential of a closed-loop supply in Japan. The presented model forecast the volume of end of life vehicles base on the scrapping rate by year of life, calculated considering past data of the Japanese vehicle market. Possible changes in the material composition of the recovered and supplied batteries are calculated based on open data of different LiB specifications collected between 2010 and 2035. In addition, material value comparisons are also carried out. System dynamics modeling is utilized for this purpose.

2. Methodology

2.1. Analysis of Vehicle Sales, Fleet Size, and Scrapping

Figure 1 shows the concept of our forecasting model, where the entire vehicle market is analyzed, dividing the vehicle market into three parts: sales, fleet/aging, and scrapping. Different powertrains (ICEV, HV, PHEV, BEV) sold depending on the type of vehicle (mini passenger cars, mini trucks, standard passenger cars, small passenger cars, standard trucks, small trucks and large buses, and small buses) are considered.

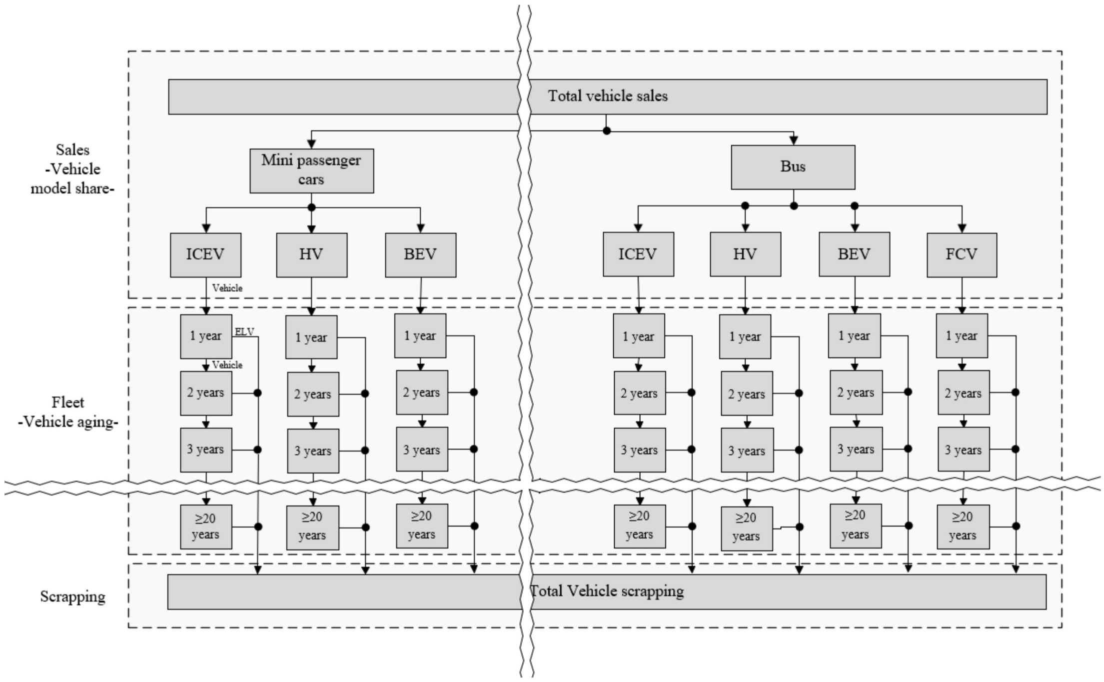


Figure 1. Concept of the dynamic forecasting model.

The total number of vehicles in a region (fleet size) is updated annually, considering the number of vehicles sold and scrapped in a year, as indicated in Equation (1). Here, the term "vehicle scrapping" includes end of life vehicles (ELV) that are dismantled but also the ones that spent their second lives in foreign countries.

$$VSa_{t+1} = V_{t+1} - V_t + VSc_{t+1} \tag{1}$$

V_t: Number of vehicles at the end of year t in the fleet [units];
V_{t+1}: Number of vehicles at the end of the year t+1 in the fleet [units];
VSa_{t+1}: Number of vehicles sold during the year t+1 [units];
VSc_{t+1}: Number of vehicles scrapped during the year t+1 [units].

The above flow was separately analyzed considering the type and power train of the vehicles using Equations (2)–(5):

$$V_t = \sum_i \sum_p \sum_l V_{i,p,l,t} \tag{2}$$

$$V_{t+1} = \sum_i \sum_p \sum_l V_{i,p,l,t+1} \tag{3}$$

$$VSc_{t+1} = \sum_i \sum_p \sum_l VSc_{i,p,l,t+1} \tag{4}$$

$$VSa_{t+1} = \sum_{i}\sum_{p} VSa_{i,p,t+1} \quad (5)$$

$V_{i,p,l,t}$: Number of vehicles of type i, power train p, and year of life l at the end of year t in the fleet [units];
$V_{i,p,l,t+1}$: Number of vehicles of type i, power train p, and year of life l at the end of the year t+1 in the fleet [units];
$VSc_{i,p,l,t+1}$: Number of vehicles scrapped of type i, power train p, and year of life l during year t+1 [units];
$VSa_{i,p,t+1}$: Number of vehicles sold of type i and power train p during year t+1 [units].

The number of vehicles (fleet size) was forecast considering previous studies by Dargay et al. [28,29], who proposed the use of an s-shaped function to represent the relation between the vehicle ownership per capita and the GDP growth of a country, as indicated in Equation (6). Results of the model proposed by the above author allow comparisons over time but also amongst countries through the analysis of a single econometric specification.

$$VO_{t+1} = \gamma \times \theta \times e^{\alpha \times e^{\beta\ GDP}} + (1-\theta) \times VO_t \quad (6)$$

VO_{t+1}: Vehicle ownership at the end of year t+1 [units per 1000 people];
VO_t: Vehicle ownership at the end of year t [units per 1000 people];
γ: Saturation level of the number of vehicles [units per 1000 people];
α: Alpha parameter related to the shape of the function;
β: Beta parameter beta related to the shape of the function;
θ: Speed of the effect between the variables ($0 < \theta < 1$).

Moreover, the number of vehicles reaching their end of life during a year depends on the number of vehicles available in the market and the probability of them being scrapped depending on the type, power train, and year of life, as indicated in Equation (7):

$$VSc_{i,p,l,t+1} = \sum_{i}\sum_{p}\sum_{l} V_{i,p,l,t} \times Psc_{i,p,l,t+1} \quad (7)$$

$Psc_{i,p,l,t+1}$: Probability of a vehicle of type i, powertrain p, and year of life l being scrapped during year t+1.

Finally, the total sales of vehicles per year can be divided by type and powertrain, considering future share predictions using Equation (8):

$$VSa_{i,p,t+1} = VSa_{t+1} \times \sum_{p}\sum_{l} Ss_{i,t+1} \times Ss_{p\in i,t+1} \quad (8)$$

$Ss_{i,t+1}$: Share of vehicles sold of type i during year t+1;
$Ss_{p\in i,t+1}$: Sale share of vehicles with powertrain p in the market of vehicle type i during year t+1.

2.2. Analysis of the Possible Critical Material Supply from LiB Recovered from End of Life EVs

Firstly, it is worth clarifying that two types of EVB are available: nickel–metal-hybrid batteries (NiMH) and LiB. However, analyses of recovered and supplied critical materials have focused only on the second one, considering that NiMH are still used in some HV but LiB are more attractive for PHEV and BEV due to their much higher energy density, longer cycle life, lightweight, and ability to provide deep discharges [12]. Supplied and recovered amounts of critical metals (Ni, Co, Mn, Li) used in the production of LiB with the ability to be recovered from scrapped vehicles are forecasted.

The amount of LiB supplied to the automotive industry is calculated through Equation (9):

$$SLiB_t = \sum_i \sum_p VSa_{i,p,t} \times LibV_{i,p,t} \times VLiB_{i,p,l} \quad (9)$$

$SLib_t$: Amount of supplied LiB during year t [kwh];
$LiBV_{i,p,t}$: Size of LiB of a vehicle of type i and power train p in year t [kwh/unit];
$VLiB_{i,p,t}$: Rate of vehicles of type i and power train p in the year t that use LiB for traction.

Moreover, the material supplied for the production of the LiB depends on the technology of the battery, as indicated in Equation (10):

$$SMat_{m,t} = \sum_i \sum_p VSa_{t,\ \ i,p} \times LiBV_{i,p,t} \times VLiB_{i,p,t} \times WMat_{m,i,p,t} \quad (10)$$

$SMat_{m,t}$: Amount of supplied material m for the production of LiB during year t [kg];
$WMat_{m,i,p,t}$: Weight of material m of a LiB from a vehicle of type i and power train p in year t [kg/kwh].

The size of the LiB recovered from scrapped varies depending on the type, power train, and year of life of the vehicle, as indicated in Equation (11):

$$RLib_t = \sum_l \sum_i \sum_p VSc_{i,p,l,t} \times LiBV_{i,p,l,t} \times VLiB_{i,p,l,t} \quad (11)$$

$RLib_t$: Amount of recovered LiB during year t [kwh];
$LiBV_{i,p,l,t}$: Size of LiB of a vehicle of type i, power train p, and year of life l in year t [kwh/unit];
$VLiB_{i,p,l,t}$: Rate of vehicles of type i, power train p, and year of life l in year t that use LiB for traction.

The material recovered from the scrapped LiB depends on the material composition of its cells, which varies through the evolution of its technologies, as indicated in Equation (12):

$$RMat_{m,t} = \sum_l \sum_i \sum_p VSc_{i,p,l,t} \times LiBV_{i,p,l,t} \times VLiB_{i,p,l,t} \times WMat_{m,i,p,l,t} \quad (12)$$

$RMat_{m,t}$: Amount of recovered material m from the LiBs during year t [kg];
$WMat_{m,i,p,l,t}$: Weight of material m of a LiB from a vehicle of type i, power train p, and year of life l in year t [kg/kwh].

3. Analysis of the Japanese Vehicle Market

Figure 2 shows the analysis flow of this approach. To assess the effect of the LiB recovery through the methodology proposed above, the main characteristics of the Japanese vehicle market and manufacturing were analyzed and listed below in order for use as input data for our model. It is worth mentioning that some of the input data are based on the Japanese fiscal year (April to March).

(a) Vehicle fleet size: Figure 3a shows the forecast of the Japanese Gross Domestic Product (GDP) presented by the Organisation for Economic Co-operation and Development [30], which was used in Equation (6) to calculate the growth of vehicle ownership shown in Figure 3b. Figure 3c indicates the population growth forecast of the country estimated by the world bank [31]. Finally, Figure 3d) shows an estimation of the size of the future Japanese vehicle fleet. Moreover, the initial (2017) composition of the Japanese vehicle fleet by type and powertrain was estimated based on reports from the Next Generation Vehicle Promotion Center [32] and Automobile Inspection and Registration Information Association [33].

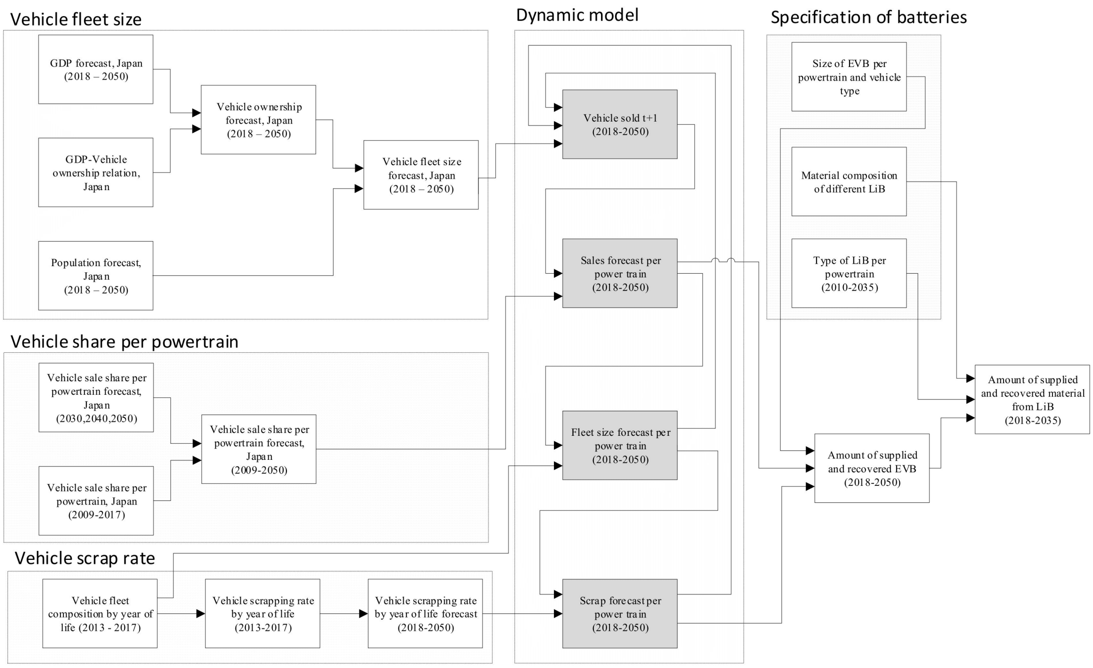


Figure 2. Analysis flow of the model.

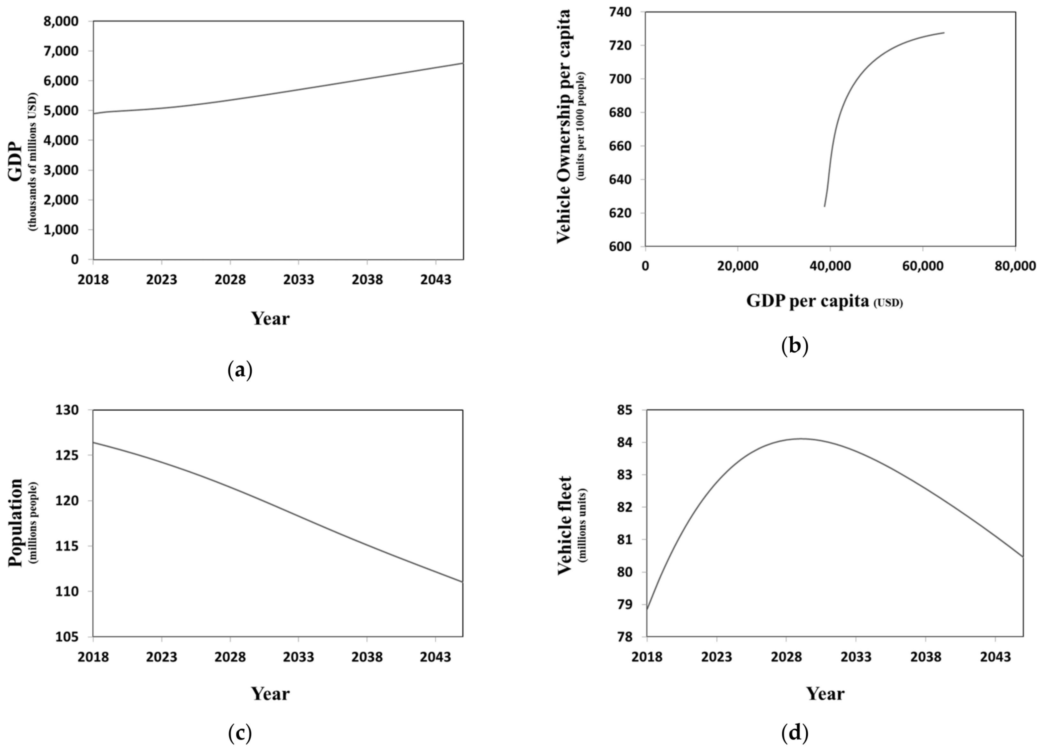
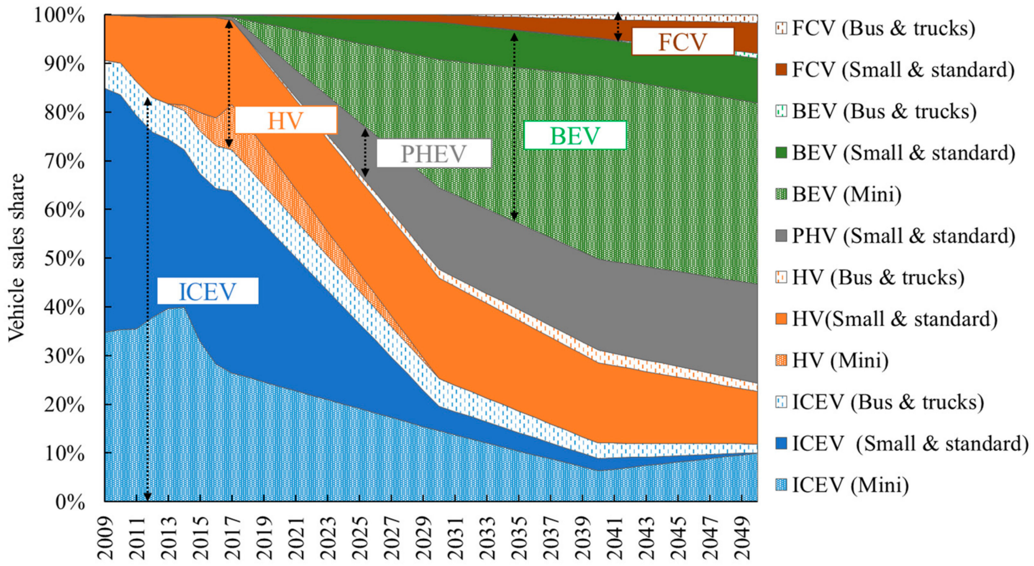


Figure 3. Forecast of the Japanese GDP, population, vehicle ownership, and vehicle fleet: (**a**) GDP; (**b**) vehicle ownership; (**c**) population; (**d**) vehicle fleet.

(b) Sale share of vehicles: Figure 4 shows the share of future vehicle sales in Japan by type and power train estimated considering data from the Ministry of the Environment [34], the Japan Automotive Manufacturers Association [35], and the Next Generation Vehicle Promotion Center [36]. Moreover, it is worth mentioning that the share from 2009 to 2017 represents historical records of the market [35–37].



Mini: mini passenger cars, mini trucks.
Small and standard: standard passenger cars, small passenger cars.
Bus and trucks: small trucks, standard trucks, small buses, large buses.

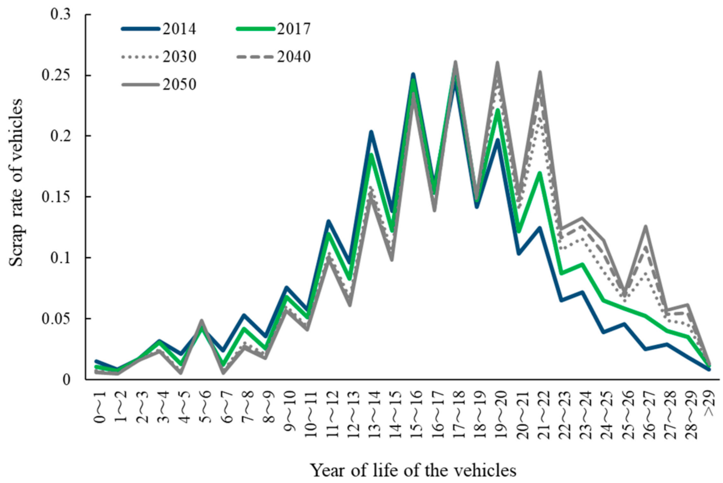
Figure 4. Share prediction of the vehicle sales for the Japanese market.

(c) Probability of vehicles being scrapped: Vehicle scrapping rates were calculated as the percentage of vehicles that are scrapped annually per year of life based on reports from the Automobile Inspection and Registration Information Association [33]. Here, average data of standard/small passenger cars and trucks were utilized, and the scrapping rate from 2018 to 2050 was estimated by linear least-squares regression. Figure 5 shows the historical and forecasted data of the vehicle scrapping rate considered in this model. It is worth clarifying that the scrapping rate of passenger cars varies sharply every two years due to the impact of the automobile inspection requirement of the Japanese government. On the other hand, this effect is not observed for trucks and buses considering that, for those types of vehicles, the above requirement must be annually fulfilled. Additionally, the scrap rate is flatter due to the longer life expectancy of them.

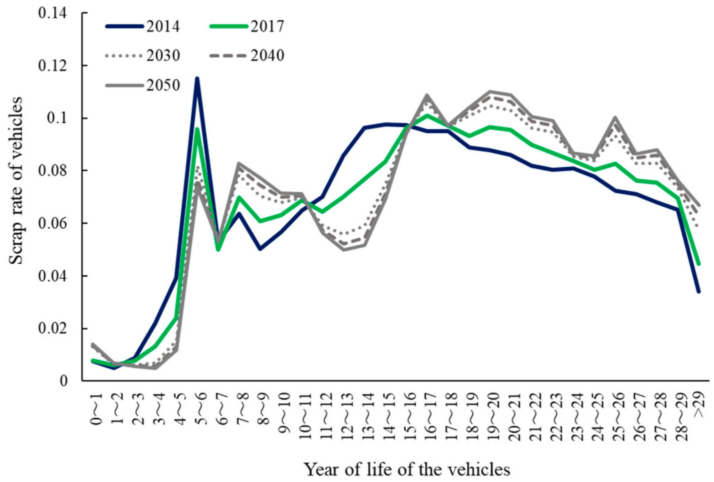
(d) Size of LiB: The size of the LiB varies widely depending on the type, power train, and specifications of the vehicle. In this study, the capacities of the batteries of mini passenger cars and mini trucks, and standard/small passenger cars were considered to be 2 kWh for HV, 9 kWh for PHEV, and 28 kWh for BEV [38]. Moreover, batteries for standard/small trucks and large/small buses were considered to be 3.9 kWh for HV [39] and 304 kWh for BEV [40].

(e) Battery technologies: The material compositions of the batteries were modified considering the core LiB technology used in electric vehicles. Here, a time frame from 2010 to 2035 was settled including underdeveloped battery technologies. Figure 6 shows the evolutive scenario adopted in this study. Firstly, LiB technologies representative of those used in previous years were estimated based on the Nissan motor corporation [41] and the New Energy and Industrial Technology Development Organization [42]. Then, possible new technologies of batteries for the following years were forecasted considering reports from the International Energy Agency [18], Argus Media Ltd. [43], and Lebedeva et al. [44]. Moreover, Table 1 shows the material compositions of those technologies where the next generation LiB are expected to have low cobalt content and high energy density.

(f) Cost of the materials and batteries: Table 2 shows the prices of the materials used for the production of the cathodes. Here, the data from the report of the International Energy Agency [18] were considered.



(**a**)



(**b**)

Figure 5. Scrapping rate forecast of the Japanese vehicles: (**a**) passenger cars; (**b**) trucks and buses.

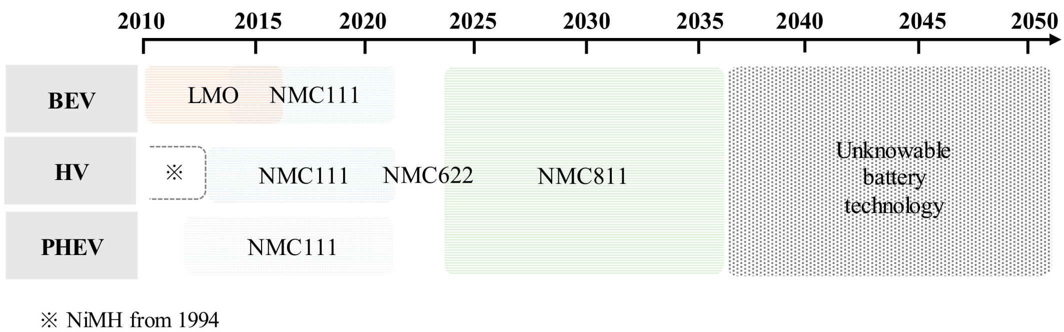


Figure 6. Changes in the electric vehicle batteries (EVB) technologies by year. BEV, battery electric vehicles; HV, hybrid electric vehicles; PHEV, plug-in hybrid electric vehicles.

Table 1. Cathode active material composition of lithium-ion battery technology.

	[kg/kwh]							
	LMO	**Ref.**	**NMC 111**	**Ref.**	**NMC 622**	**Ref.**	**NMC 811**	**Ref.**
Li	0.10	[45–47]	0.15	[18]	0.13	[18]	0.11	[18]
Co	0.00		0.4		0.19		0.09	
Ni	0.00		0.4		0.61		0.75	
Mn	1.56		0.37		0.2		0.09	

LMO, Lithium ion manganese oxide; NMC, Lithium nickel manganese cobalt oxide

Table 2. Prices of critical raw materials.

	Price of Raw Materials	
	$ per kg	**Ref.**
Lithium Carbonate	8.00	[18]
Cobalt	30.00	[18]
Nickel	9.00	[18]
Manganese	2.00	[18]

4. Results and Discussion

The proposed forecasting model was simulated through System dynamics and the software Vensim PLP x32 [48]. System dynamics is a computer modeling method that considers different variables in order to numerically simulate nonlinear behavior over time and it applies to problems arising in complex social, ecological or economic systems. Stocks, flows, and converters are used allowing the researcher clarifies the relation between the different variables considered in the model and predicts the change of state of elements and flows along a time scale.

4.1. Forecast of Vehicle Fleet Size, Sales, and Scrapping

Figure 7a shows the forecast for vehicle sales by power train in the market. Here, it can be observed that the total sales of vehicles will decrease moderately in the following years due to changes in the Japanese vehicle fleet size. However, sales of electric vehicles will increase considerably and are expected to reach a peak in 2040 with 4.17 million units sold per year. This value represents 2.2 times the EV sales of 2018 considering that drastic changes in the HV demand are not expected. However, if sales of BEV are analyzed separately, it can be observed that the related sales will reach 1.94 million units in the same period, an increase of 11.6 times from the sales of 2018.

Figure 7b shows the forecast of the Japanese vehicle market size. Here, it is possible to observe that even though increases in the GDP per capita and vehicle ownership are expected, the Japanese vehicle fleet could reach a peak in 2029 with 84.1 million units of vehicles in the market due to the possible decrease of the population. Moreover, compared to sales, where the domination of electric vehicles in the following years can be observed, the vehicle fleet itself will still be dominated by ICEV until 2032.

Figure 7c shows the forecast for the number of vehicles scrapped in the market. Here, it can be observed that the number of ELV will vary slightly in the following years. Moreover, ICEV will dominate the ELV market until 2038, reaching 2.58 million units scrapped per year compared to the 2.45 million units of EV. Moreover, even though a substantial quantity of HV will reach their end of life in the coming years, the amount of BEV and PHEV expected to be collected until 2025 is likely to be minimal, being less than 2% of the total ELV generated in a year.

Finally, it is worth mentioning that the grey parts on the left side of each figure indicate historical records of vehicle sales [35–37], fleet [49], and scrapping [50], which are compatible with the values forecasted in this model.

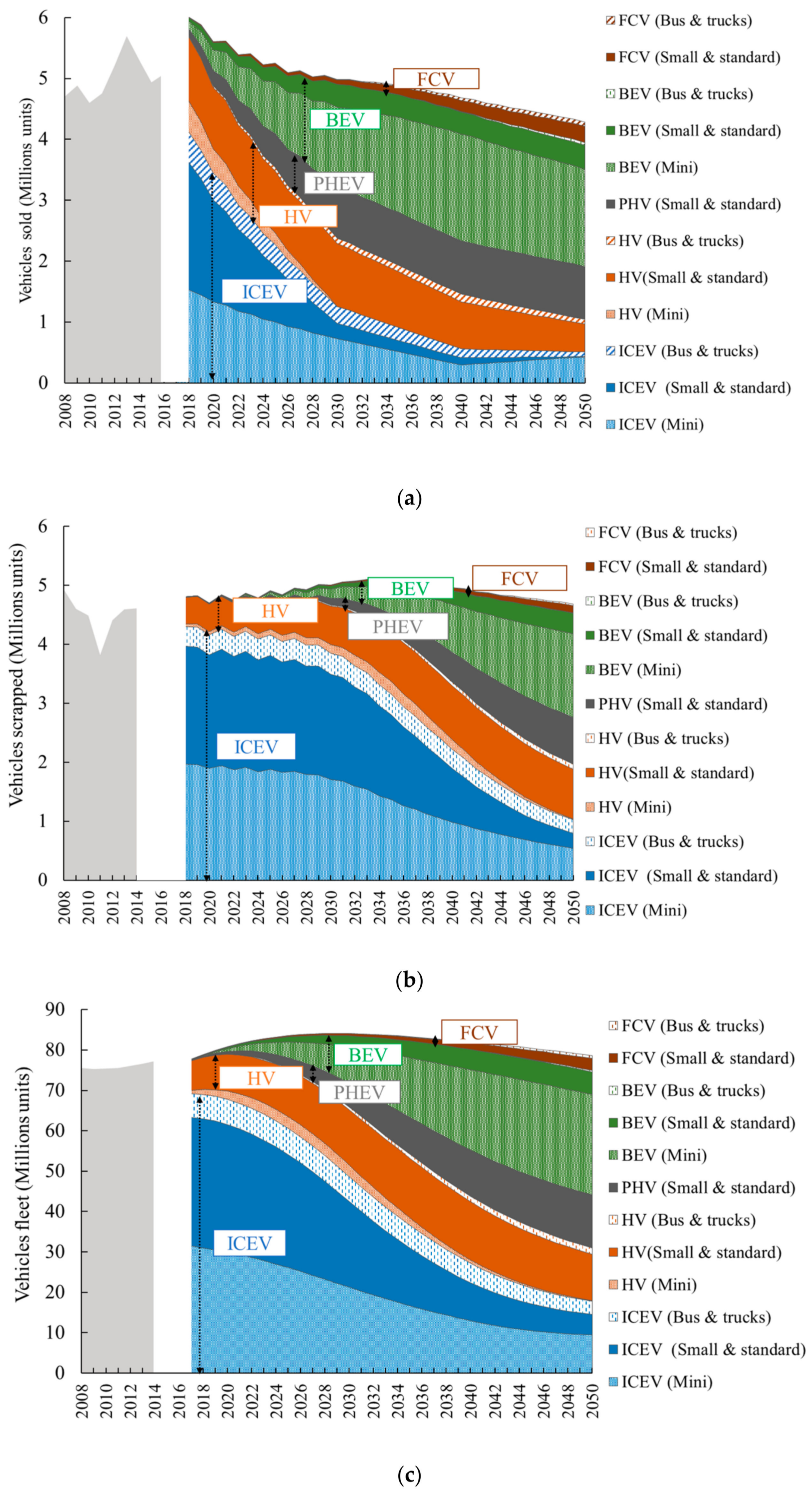


Figure 7. Forecast of the Japanese vehicle market by vehicle type and power train: (**a**) sales; (**b**) fleet; (**c**) scrapping.

4.2. Forecast of EVB Supply and Recovery

Figure 8a shows the forecast of the EVB supply simulated by this model. Here, it can be noted that even though, in term of vehicles sales, HV play an essential role, the demand of EVB for BEV is going to dominate the market considering their higher energy capacity. EVB demand is going to increase rapidly in the following years; however, it is expected to reach maturity near 2030, with its growth rate considerably decreasing after that. It is expected that the supply of EVB will reach 78 GWh per year in 2050, increasing 8.4 times from 2018 but 1.37 times from 2030. Moreover, electric buses and trucks will importantly affect the demand for future EVB.

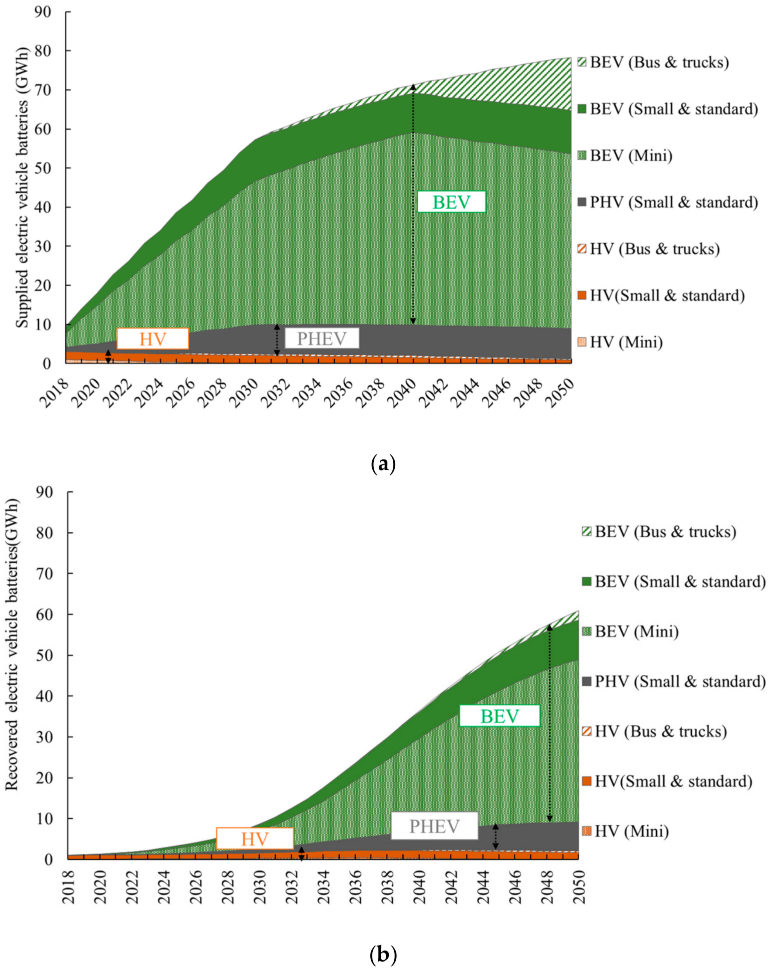


Figure 8. Forecast of EVB supply and recovery for the Japanese vehicle market: (**a**) EVB supply for the automotive industry; (**b**) EVB recovery from ELV.

Figure 8b shows the forecast for the number of EVB that can be recovered from the ELV. The quantity of EVB for recycling and reuse is expected to be dominated by batteries from HV in the first years, but after this period, batteries recovered from BEV will represent the majority of the returning volume, drastically increasing the size of the entire market from that time onward. The recovered number of recovered EBV will reach 61 GWh in 2050, representing an increment of 55 times compared to 2018.

Figure 9 shows the forecast of the relationship in terms of energy capacity between the total EVB supplied for new vehicles and that expected to be recovered from ELV. It can be noted that, in 2025, the recoverability will be still less than 10% of the supply, but also, rapid growth of those values can be expected in the following years, reaching 31% in 2035. Moreover, a complete closed loop can be expected in 2050 if only the energy capacity of batteries is considered.

4.3. Forecast of the Critical Material Supply and Recovery for LiB

This section includes the analysis of different LiB technologies from 2010 to 2035 considering the composition of their critical materials.

Figure 10a1,a2 show the forecasts of supplied and recovered LiB in terms of energy capacity by technologies. It can be observed that the LiB supplied until 2035 is going to be recovered gradually, and the mode of the returning flow is going to be nearly 2044. The grey section of the chart illustratively indicates the possible supplied and recovered volumes of unknowable battery technology.

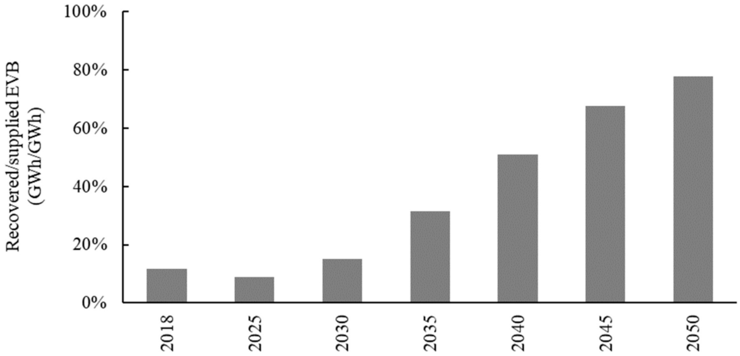


Figure 9. Percentual relation between the supplied and recovered EVB.

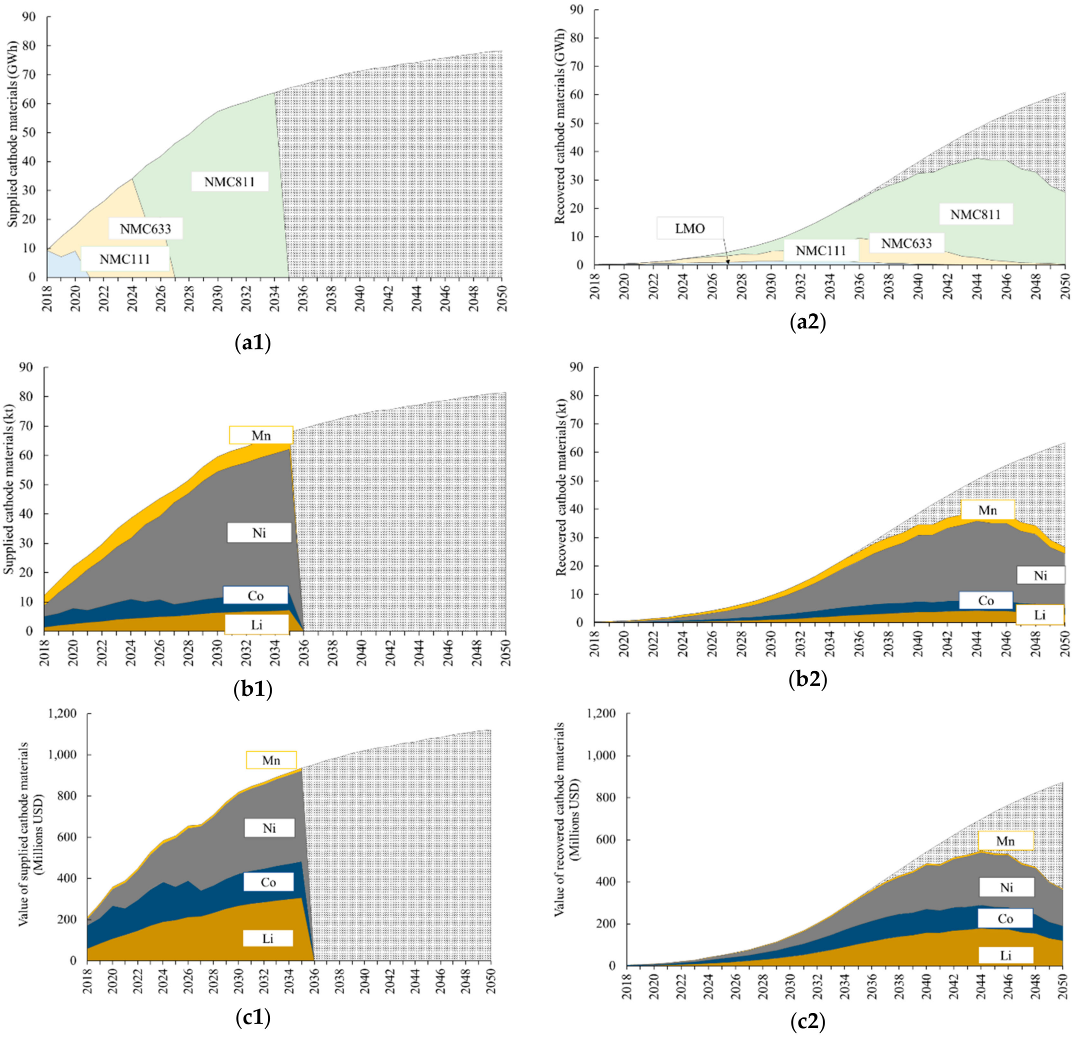


Figure 10. Forecast of LiB and critical materials supplied and recovered: (**a1**) supplied LiB; (**a2**) recovered LiB; (**b1**) weight of supplied materials; (**b2**) weight of recovered materials; (**c1**) value of supplied materials; (**c2**) value of recovered materials.

Figure 10b1,b2 show the weight of each critical material supplied for LiB production and recovered from the market. Here, it is possible to observe that the demand for Ni is going to increase concisely in the following years, as it is the most representative critical material required for LiB production.

However, even though the production of LiB is predicted to increase, the demand for Mn, Co, and Li is not predicted to change. Similarly, the most representative critical material, in terms of recovered mass, is also Ni, and 15.7 tons are expected to be returned from ELV in 2035. Moreover, the supplied and recovered weights of Mn, Co, and Li seem to be similar. This can be explained by the expected increment in the Ni concentration in LiB, which increases the energy content of the batteries in exchange for stability [12].

Figure 11 indicates that 34% of the lithium, 50% of the cobalt, 28% of the nickel, and 52% of manganese required for the production of new LiB could be supplied by batteries derived from end of life vehicles in 2035. Compared to Figure 9, where the possible closed loop is analyzed in terms of energy capacity, and the recovered batteries represent 31% of the volume supplied, here, the assessment of the recovery material also considers the material weights. It can be observed that, when changes in the battery technologies are taken into consideration, the results are different, highlighting the importance of analyzing the potential of a closed loop, including its material composition.

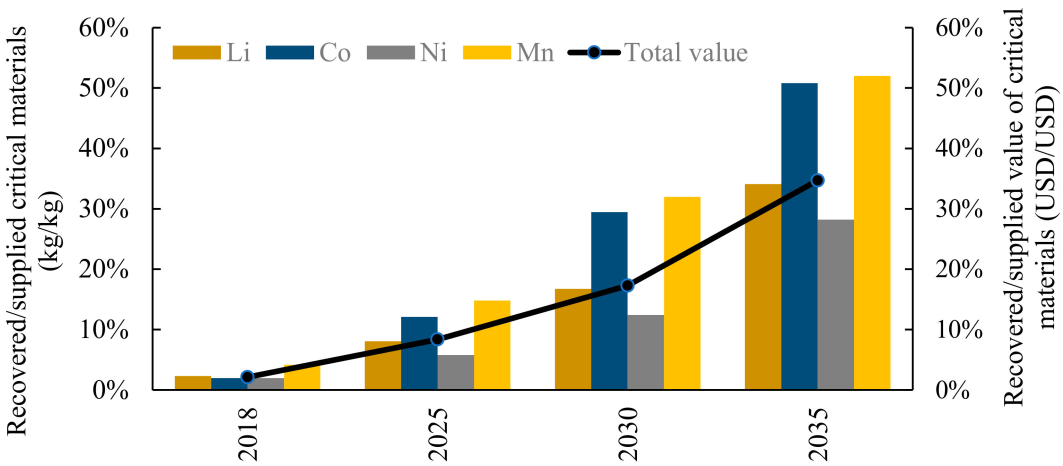


Figure 11. Percentage relations between the weights and values of supplied and recovered critical materials.

4.4. Economic Analysis of the Recovered Materials

Figure 10c1,c2 show the value of each critical material supplied for production and recovery from LiB. Compared to the analysis based on material weights, here, it is possible to observe that the values of Co and Li supplied and recovered are as important as those of Ni. However, it is seen that the value of the Mn is considerably lower. The total value of critical material required in Japan for the vehicle production of LiB is predicted to reach 936 million US dollars in 2035, where 325 million dollars of materials from ELV could be recovered. The secondary axis of Figure 11 shows the above relation, where 35% of the value of critical materials could be supplied locally by scrapped LiB in Japan, considerably reducing the dependency of those materials from foreign countries.

4.5. Main Assumptions and Limitations

In order to recover the forecasted quantity of critical materials from scrapped LiB, the following obstacles must be overcome.

Firstly, battery recycling facilities in Japan are pyrometallurgical [51,52], recovering the Co and Ni as molten metal alloys and the Li and Mn as slag [53]. A shift to hydrometallurgical technologies must be carried out in order to obtain high-grade materials that can be used in the production of new batteries. The recycling efficiencies of the analyzed materials in those facilities are close to 100% [54].

Secondly, the exportation of used vehicles in Japan represents approximately 28% of the total ELV [50]. Here, the demand for used HV is notorious, where, in 2017, approximately 84% of them were sent overseas to spend their second lives [55]. In the case of BEV, this value exceeded 96% [55], having an important effect on the current LiB collection volumes. The exportation of end of life EV is centered in underdeveloped Asian countries; however, in the middle and long term, a natural decrease in those values can be expected jointly with the saturation of electric vehicles in the market.

Thirdly, the results of recovered LiB proposed in this approach could be used for recycling as well as reusing purposes. However, the reuse of LiB could delay the return time of the spent batteries. In this sense, future studies could be carried out to elevate the accuracy of forecasting by assuming alternative scenarios.

Fourth, this study proposed a model to forecast the Japanese vehicle market based on open data. Different approximations in the inventory analysis for the Japanese vehicle market were used in order to conduct the simulation. Moreover, external analysis methods, such as the forecasting of the Japanese population, GDP, and vehicle sales share were considered. Changes in those values could guide us to different results; however, the proposed forecasting model and main conclusions would not change.

Finally, the price of the critical metals varies constantly and unpredictably depending on changes in the global market. This study considered constant prices for the calculation of the values of the supplied and recovered critical materials. In this sense, the analysis methodology proposed in this approach can be easily adjusted to updated values.

4.6. Implications and Utilization in the Practice

The results presented in this study give a whole picture of the ELV market but also give perspectives of the scrapped EVB that can possibly be recovered from them. The proposed forecasting model can be applied by automakers and related companies for the proposal and verification of the economic feasibility of different battery reuse and recycling business strategies, clarifying the quantity and variety of "resources" available for its production process in the short, middle, and long term.

Even though the supplied of critical materials for LiB production will considerably increase due to the diffusion of EV in the immediate years, the quantity of returning batteries of BEV and PHEV is predicted to be minimal until 2025. In this sense, new business and development of LiB reuse and recycling technologies should be centered, in the short term, on HV batteries, considering the total returning volume of them.

Dismantlers and material recycling companies will be able to define optimal plans for the adaptation of their facilities, knowing the time and quantity of EV and LiB returning from the market. Moreover, the development of new recycling technologies should be centered on the recovery of Ni if the total available mass of material is prioritized but focused on Ni, Co, and Li when the material value is put in front. On the other hand, an efficient reverse logistics network for spent batteries could be planned considering the forecasting values of this research.

This study also demonstrated that more than 50% ELV will be ICEV until 2038. In this sense, the development of new technologies and new reuse and recycling projects should not play second fiddle considering its room for improvement [56,57].

Due to the lifetime of EV, the recovered LiB will not be a significant source of material for the production of new ones in the short term; however, when a longer time horizon is considered, and the principal limitation clarified in this study overcome, the recovered batteries will play an essential role in the automotive industry and a feasible total closed-loop for EVB.

Finally, it is worth mentioning that the proposed model can easily be adapted to other countries as well as for different products such as electrical household appliances that need to be recycled after their use, as was proposed by the approach of Baldé et al. [58].

Even though a few entities and consultants have forecasted the supply or recovery volume of critical material for EVB [43,59,60], details of the models implemented for the analysis are neither open nor available for utilization. In the same way, the accuracy and premises considered in the forecasting are unknown. In this sense, the proposed model can be adopted and modified depending on the necessity, allowing possible changes in premises to be reflected.

5. Conclusions

This study proposed a model to forecast the number of LiB and critical materials that can be recovered from the recycling of ELV. System dynamic concepts and open data were used to simulate the Japanese vehicle market. Compared with previous studies, this approach forecasts the number of end of life vehicles based on the scrapping rate by year of life, which was calculated considering past data of the Japanese vehicle market. The main conclusions of this approach, where vehicle fleet and sales were additionally analyzed, are listed below.

More than 50% of the ELV will be ICEV until 2038. In this sense, the development of new technologies and new reuse and recycling projects should not play second fiddle.

The amount of scrapped EVB will increase by 55 times from 2018, reaching 61 GWh recovered per year in 2050. Moreover, the recovered EVB are expected to be predominated by batteries from HV in the first five years, clarifying the need to center reuse and recycling projects in them in the short term.

Closed-loop EVB production can be expected in 2050 if only the energy capacity of batteries is considered. However, changes in battery technologies play an essential role, and the volume of critical material supplied for production that is possible to recover from ELV varies widely depending on the material composition of the LiB. The results indicate that 34% of the lithium, 50% of the cobalt, 28% of the nickel, and 52% of manganese required for the production of new LiB could be supplied by batteries derived from end of life vehicles in 2035.

The development of new recycling technologies should be centered in the recovery of Ni if the total available mass of material is prioritized but should be focused on Ni, Co, and Li when the material value is put in front.

The total value of critical material required in Japan for EV LiB production is predicted to reach 936 million US dollars in 2035, where 325 million dollars could be recovered by the recovery of materials from ELVs, considerably reducing the dependency of those materials from foreign countries

Considering that the quantity of returning BEV and PHEV batteries is predicted to be minimal until 2025, the new business and development of LiB reuse and recycling technologies should be centered, in the short term, on HV batteries.

The exportation of used EV has a substantial impact on the current LiB processing/recycling market. Moreover, local LiB recycling facilities should shift to hydrometallurgical process in order to achieve a closed loop of batteries.

Finally, the forecasting model proposed in this study could be adjusted to different situations and market premises considering that open data are used for the calculation, and the methodology used has been explained in detail.

Author Contributions: Conceptualization, F.E.K.S.; methodology, F.E.K.S.; software, Vensim PLP x32; formal analysis, F.E.K.S.; investigation, F.E.K.S.; writing—review and editing, F.E.K.S. and T.N.; supervision, T.N. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. United Nations. Sustainable Development Goals. 2015. Available online: https://www.undp.org/content/dam/undp/library/corporate/brochure/SDGs_Booklet_Web_En.pdf (accessed on 24 September 2019).
2. United Nations. Historic Paris Agreement on Climate Change: 195 Nations Set Path to Keep Temperature Rise Well Below 2 Degrees Celsius. Announcement 13 December 2015. Available online: https://unfccc.int/news/finale-cop21 (accessed on 30 September 2018).
3. U.S. Energy Information Administration. International Energy Outlook 2016. DOE/EIA-0484(2016). Available online: https://www.eia.gov/outlooks/ieo/pdf/0484(2016).pdf (accessed on 30 September 2018).
4. International Energy Agency. Transport Energy and CO2: Moving Towards Sustainability. 2009. Available online: https://doi.org/10.1787/9789264073173-en (accessed on 22 December 2019).

5. Intergovernmental Panel on Climate Chang. Climate change 2014, Mitigation of Climate Change, Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Available online: https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_chapter8.pdf (accessed on 8 August 2019).
6. International Organization of Motor Vehicle Manufacturers. 2018 Production Statistics. Available online: http://www.oica.net/category/production-statistics/2018-statistics/ (accessed on 26 October 2019).
7. International Organization of Motor Vehicle Manufacturers. Registrations or Sales of New Vehicles—All Types. 2018. Available online: http://www.oica.net/wp-content/uploads/total_sales_2018.pdf (accessed on 26 October 2019).
8. Next Generation Vehicle Promotion Center. Strategy for Diffusing the Next Generation Vehicles in Japan. 2018. Available online: http://www.cev-pc.or.jp/event/pdf/xev_in_japan_eng.pdf (accessed on 15 May 2019).
9. Diekmann, J.; Grützke, M.; Loellhoeffel, T.; Petermann, M.; Rothermel, S.; Winter, M.; Nowak, S.; Kwade, A. Potential Dangers During the Handling of Lithium-Ion Batteries. In *Recycling of Lithium-Ion Batteries*; Kwade, A., Diekmann, J., Eds.; Springer: Cham, Switzerland, 2018. [CrossRef]
10. Ellingsen, L.A.W.; Majeau-Bettez, G.E.; Singh, B.; Srivastava, A.K.; Valøen, L.O.; Strømman, A.H. Life Cycle Assessment of a Lithium-Ion Battery Vehicle Pack. *J. Ind. Ecol.* **2013**, *18*, 113–124. [CrossRef]
11. Ahmadi, L.; Young, S.B.; Fowler, M.; Fraser, R.A.; Achachlouei, M.A. A cascaded life cycle: Reuse of electric vehicle lithium-ion battery packs in energy storage systems. *Int. J. Life Cycle Assess.* **2017**, *22*, 111. [CrossRef]
12. Olivetti, E.A.; Ceder, G.; Gaustad, G.G.; Fu, X. Lithium-ion battery supply chain considerations: Analysis of potential bottlenecks in critical metals. *Joule* **2017**, *1*, 229–243. [CrossRef]
13. Olsson, L.; Fallahi, S.; Schnurr, M.; Diener, D.; Van Loon, P. Circular business models for extended EV battery life. *Batteries* **2018**, *4*, 57. [CrossRef]
14. Honda Motor Co. Advanced Recycling of Lithium Ion Batteries. 2017. Available online: https://www.env.go.jp/policy/kenkyu/special/houkoku/data_h28/pdf/3K152013.pdf (accessed on 24 June 2019).
15. European Union. Directive 2006/66/EC of the European parliament and of the council of 6 September 2006 on batteries and accumulators and waste batteries and accumulators and repealing Directive 91/157/EEC. *Off. J. Eur. Communities* **2006**, *266*, 1–14.
16. Helbig, C.; Bradshaw, A.M.; Wietschel, L.; Thorenz, A.; Tuma, A. Supply risks associated with lithium-ion battery materials. *J. Clean. Prod.* **2018**, *172*, 274–286. [CrossRef]
17. Song, J.; Yan, W.; Cao, H.; Song, Q.; Ding, H.; Lv, Z.; Zhang, Y.; Sun, Z. Material flow analysis on critical raw materials of lithium-ion batteries in China. *J. Clean. Prod.* **2019**, *215*, 570–581. [CrossRef]
18. International Energy Agency. Global EV Outlook. 2018. Towards Cross-Model Electrification. Available online: https://webstore.iea.org/global-ev-outlook-2018 (accessed on 26 October 2019).
19. Zheng, X.; Zhu, Z.; Lin, X.; Zhang, Y.; He, Y.; Cao, H.; Sun, Z. A Mini-Review on Metal Recycling from Spent Lithium Ion Batteries. *Engineering* **2018**, *4*, 361–370. [CrossRef]
20. Gaines, L. The future of automotive lithium-ion battery recycling: Charting a sustainable course. *Sustain. Mater. Technol.* **2014**, *1*, 2–7. [CrossRef]
21. Winslow, K.M.; Laux, S.J.; Townsend, T.G. A review on the growing concern and potential management strategies of waste lithium-ion batteries. *Resour. Conserv. Recycl.* **2018**, *129*, 263–277. [CrossRef]
22. Pehlken, A.; Albach, S.; Vogt, T. Is there a resource constraint related to lithium ion batteries in cars? *Int. J. Life Cycle Assess.* **2017**, *22*, 40. [CrossRef]
23. Ziemann, S.; Müller, D.B.; Schebek, L.; Weil, M. Modeling the potential impact of lithium recycling from EV batteries on lithium demand: A dynamic MFA approach. *Resour. Conserv. Recycl.* **2018**, *133*, 76–85. [CrossRef]
24. Link, A.N.; O'Connor, A.C.; Scott, T.J. *Battery Technology for Electric Vehicles: Public Science and Private Innovation*, 1st ed.; Routledge: London, UK, 2015; ISBN 10:9781138811102.
25. Bobba, S.; Mathieux, F.; Blengini, G.A. How will second-use of batteries affect stocks and flows in the EU? A model for traction Li-ion batteries. *Resour. Conserv. Recycl.* **2019**, *145*, 279–291. [CrossRef]
26. Richa, K.; Babbitt, C.W.; Gaustad, G.; Wang, X. A future perspective on lithium-ion battery waste flows from electric vehicles. *Resour. Conserv. Recycl.* **2014**, *83*, 63–76. [CrossRef]
27. World Bank. Gross Domestic Product. 2018. Available online: https://databank.worldbank.org/data/download/GDP.pdf (accessed on 30 September 2019).

28. Dargay, J.; Gately, D. Income effect on car and vehicle ownership, worldwide 1960–2015. *Transp. Res. Part A* **1999**, *33*, 101–138. [CrossRef]
29. Dargay, J.; Gately, D.; Sommer, M. Vehicle Ownership and Income Growth, Worldwide: 1960–2030. *Energy J.* **2007**, *28*, 143–170. [CrossRef]
30. Organisation for Economic Co-operation and Development. *GDP Long-Term Forecast (Indicator)*. 2018. Available online: https://data.oecd.org/gdp/gdp-long-term-forecast.htm (accessed on 21 May 2019). [CrossRef]
31. The World Bank. Population Estimates and Projections. 2019. Available online: https://datacatalog.worldbank.org/dataset/population-estimates-and-projections (accessed on 21 May 2019).
32. Next Generation Vehicle Promotion Center. Available online: http://www.cev-pc.or.jp/tokei/hanbai.html (accessed on 21 May 2019).
33. Automobile Inspection & Registration Information Association. Tendency of the Vehicle Ownership in Our Country. Available online: https://www.airia.or.jp/publish/statistics/trend.html (accessed on 21 May 2019).
34. Ministry of the Environment Government of Japan. Strategy for Diffusion of Environmental Vehicles. 2010. Available online: https://www.env.go.jp/air/report/h22-02/06_chpt3.pdf (accessed on 21 May 2019).
35. Japan Automotive Manufacturers Association. Active Matrix Database System. Available online: http://jamaserv.jama.or.jp/newdb/eng/index.html (accessed on 24 October 2019).
36. Next Generation Vehicle Promotion Center. Investigation and Statistics, Statistics of EV and Other Sales. Available online: http://www.cev-pc.or.jp/tokei/hanbai3.html (accessed on 21 May 2019).
37. Next Generation Vehicle Promotion Center. Survey Report on the Spread of Clean Energy Vehicles. March 2017. Available online: http://www.cev-pc.or.jp/chosa/pdf/H28_chosa_1_honpen.pdf (accessed on 24 October 2019).
38. Dunn, J.B.; Gaines, L.; Barnes, M.; Sullivan, J.; Wang, M. *Material and Energy Flows in the Materials Production, Assembly, and end-of-Life Stages of the Automotive Lithium-Ion Battery Life Cycle*; ANL/ESD/12-3; Argonee National Laboratory: Argonne, IL, USA, 2012. Available online: https://greet.es.anl.gov/publication-lib-lca (accessed on 22 May 2019).
39. Isuzu Motors Limited. Presentation Regarding Erga Transit Buses. 2012. Available online: https://www.isuzu.co.jp/press/2012/8_9bus.html (accessed on 17 August 2019).
40. Gao, Z.; Lin, Z.; LaClair, T.J.; Liu, C.; Li, J.M.; Birky, A.K.; Ward, J. Battery capacity and recharging needs for electric buses in city transit service. *Energy* **2017**, *122*, 588–600. [CrossRef]
41. Nissan Motor Corporation. High Capacity Lithium-ion Battery in a Lightweight, Compact Design. Available online: https://www.nissan-global.com/EN/TECHNOLOGY/OVERVIEW/li_ion_ev.html (accessed on 18 August 2019).
42. New Energy and Industrial Technology Development Organization. Development of Lithium Ion Battery Application Practical Application Technology Development Project. March 2019. Available online: https://www.nedo.go.jp/content/100880493.pdf (accessed on 4 November 2019).
43. Argus Media Ltd. The Outlook for Battery Materials and the Rechargeable Battery Sector—Evs in the Driving Set? JOGMEC Forum, Tokyo. 2019. Available online: http://mric.jogmec.go.jp/wp-content/uploads/2019/01/mrseminar2018_07_01.pdf (accessed on 18 August 2019).
44. Lebedeva, N.; Di Persio, F.; Boon-Brett, L. *Lithium Ion Battery Value Chain and Related Opportunities for Europe*; JRC105010; European Commission: Petten, The Netherlands, 2016. Available online: https://ec.europa.eu/jrc/sites/jrcsh/files/jrc105010_161214_li-ion_battery_value_chain_jrc105010.pdf (accessed on 27 October 2019).
45. Macquarie Research. Commodities Comment, the 2017 Battery Metal Story Might Well be Cobalt. 2017. Available online: https://www.metalicity.com.au/sites/metalicity.com.au/files/files/MacquarieCommoditiesComment%20Feb%202017.pdf (accessed on 27 October 2019).
46. Argonne National Laboratory. Greet Life Cycle Model. 2018. Available online: https://greet.es.anl.gov (accessed on 28 October 2018).
47. Dai, Q.; Kelly, J.C.; Dunn, J.; Benavides, P.T.; Argonne National Laboratory. Update of Bill-of-Materials and Cathode Materials Production for Lithium-ion Batteries in the GREET Model. October 2018. Available online: https://greet.es.anl.gov/files/update_bom_cm (accessed on 27 October 2019).
48. Vensim PLP x32. Computer Software. 2019. Available online: https://vensim.com (accessed on 22 December 2019).

49. Japan Automotive Manufacturers Association. Motor Vehicle Statistics of Japan. 2015. Available online: http://www.jama-english.jp/publications/MVS2015.pdf (accessed on 24 October 2019).
50. Ministry of Environment, Government of Japan. Industrial Structure Council, Industrial Technology Environmental Working Group, Waste/Recycling Subcommittee, Automobile Recycling Working Group. Central Environment Council, Recycling Social Committee, Automobile Recycling Technical Committee, Joint Meeting. Report on Evaluation and Examination of the Implementation Status of the Automobile Recycling System. September 2015. Available online: https://www.env.go.jp/council/03recycle/y033-43/mat03_2.pdf (accessed on 30 September 2018).
51. Elibama. European Li-ion Battery Advanced Manufacturing for Electric Vehicles. Li-ion Batteries Recycling. Available online: https://elibama.files.wordpress.com/2014/10/v-d-batteries-recycling1.pdf (accessed on 5 September 2019).
52. Mayyas, A.; Steward, D.; Mann, M. The case for recycling: Overview and challenges in the material supply chain for automotive li-ion batteries. *Sustain. Mater. Technol.* **2018**, *17*, e00087. [CrossRef]
53. Cusenza, M.A.; Bobba, S.; Ardente, F.; Cellura, M.; Di Persio, F. Energy and environmental assessment of a traction lithium-ion battery pack for plug-in hybrid electric vehicles. *Jounal Clean. Prod.* **2019**, *215*, 634–649. [CrossRef]
54. Tytgat, J. The Recycling Efficiency of Li-ion EV batteries according to the European Commission Regulation, and the relation with the End-of-Life Vehicles Directive recycling rate. *World Electr. Veh. J.* **2013**, *6*, 1039–1047. [CrossRef]
55. Japan Automobile Recycling Promotion Center. Vehicle Recycling Data Book. 2017. Available online: https://www.jarc.or.jp/renewal/wp-content/uploads/2017/07/DataBook_2017.pdf (accessed on 22 May 2019).
56. Sato, F.E.K.; Furubayashi, T.; Nakata, T. Energy and CO_2 benefit assessment of reused vehicle parts through a material flow approach. *Int. J. Automot. Eng.* **2018**, *9*, 91–98. [CrossRef]
57. Sato, F.E.K.; Furubayashi, T.; Nakata, T. Application of energy and CO_2 reduction assessments for end-of-life vehicles recycling in Japan. *Appl. Energy* **2019**, *237*, 779–794. [CrossRef]
58. Baldé, C.P.; Forti, V.; Gray, V.; Kuehr, R.; Stegmann, P. *The Global E-waste Monitor–2017, Quantities, Flows, and Resources*; United Nations University, International Telecommunication Union, and International Solid Waste Association: Bonn, Germany; Geneva, Switzerland; Vienna, Austria, 2017; ISBN 978-92-808-9053-2.
59. The Center for European Policy Studies. *Prospects for Electric Vehicle Batteries in a Circular Economy*; Research report No 2018/05; European Commission: Brussels, Belgium, 2018. Available online: https://circulareconomy.europa.eu/platform/sites/default/files/circular_economy_impacts_batteries_for_evs.pdf (accessed on 22 December 2019).
60. Avicenne Energy. The rechargeable battery market and main trends 2016–2025. In Proceedings of the 33rd Annual International Battery Seminar & Exhibit, Fort Lauderdale, FL, USA, 20 March 2017.