Scenarios for end-of-life (EOL) electric vehicle batteries in China

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Abstract

Purpose – The paper concludes with showing that in the most optimistic scenario, end-of-life (EOL) batteries will account for 86% of energy storage for wind and 36% for solar PV in 2040.

Design/methodology/approach – With the growing demand for electric vehicles (EVs), the stock of discarded batteries will increase dramatically if no action is taken for their reuse or recycling. One potential avenue is to reuse them as energy storage systems (ESS) to mitigate the intermittent generation of renewable energy such as solar PV and wind. In a sense, the reliability for solar PV and wind energy can increase if energy storage systems become economically more attractive, making solar and wind systems more attractive through economies of scale.

Findings – The paper concludes with showing that in the most optimistic scenario, EOL batteries will account for 86% of energy storage for wind and 36% for solar PV in 2040.

Originality/value – The projection of scenarios can contribute to the information of policies, standards and identification of environmental promotion and promotion related to efficient management for EOL batteries.

Keywords End-of-life batteries, Energy storage systems, Electric vehicles, System dynamics

Paper type Research paper

1. Introduction

Major global problems such as energy security and climate change are changing global energy drivers, which used to be based only on technical and economic criteria, and now also include sustainability strategies (Barros, Coira, De la Cruz López, & del Caño Gochi, 2015). Two possible mitigating solutions to the problems described above are cleaner transportation technologies and renewable energy (Lund, Andersen, Østergaard, Mathiesen, & Connolly, 2012).

In the transportation sector, electric vehicles (EVs) are seen as one of the most promising solutions (Casals, Barbero, & Corchero, 2019); in the energy sector, technologies such as wind power, photovoltaics, among others (Benvenutti, Ribeiro, & Uriona-Maldonado, 2017). It is important to highlight that EVs alone are not the solution to the problem but their integration with renewable energies.

Moreover, in order to increase their integration rate, renewable energy sources may require a few energy storage systems (ESS) to ensure their stability and reliability (Casals, García, & Cremades, 2017). Batteries are one of the energy storage technologies used to provide some of the expected electricity grid services (Rastler, 2010).

In addition, most of the commercialized electric vehicles utilize lithium-ion batteries (LIB). These batteries reach their end-of-life (EOL) when their capacity is reduced by 20%; in other words, when their capacity reaches 80% of their original capacity, i.e., state of health (SOH)

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(Ahmadi, Yip, Fowler, Young, & Fraser, 2014). Thus, EV batteries should be recycled while they still have 80% of their original capacity (Casals, García, & Cremades, 2017).

In consequence, using batteries in ESS applications can offer low-priced batteries for stationary applications while, at the same time, selling those batteries may deliver some revenue back to car manufacturers. In addition, these additional revenues can revert to lower EV sales prices, making EVs more competitive in the automobile industry (Jiao & Evans, 2016).

Furthermore, the demand for batteries is expected to grow rapidly over the next years, making this market increasingly strategic at the global level. Batteries can be quite helpful when power supply fluctuates, offering flexibility by capturing solar and wind energy when abundant and dispatch when needed (European-Commission, 2019).

However, there are a few challenges related to the development of EOL battery management systems and policies for EVs, such as lack of data reference (such as amount or volume of disabled batteries), battery types, technology availability and demand for recycled or remanufactured products (Ai, Zheng, & Chen, 2019).

In this context, this article aims to estimate the volume of EOL batteries and the potential additional storage capacity for the installed wind and solar PV capacity in China. To achieve such goal, we present herein a system dynamics model that tracks EV and battery stocks up to 2040, allowing us to deliver future pathway scenarios for the most promising EOL methods.

1.1 End-of-life batteries

Batteries are defined as one or more electrochemical cells that convert stored chemical energy into electrical energy; they are considered a common energy source for many applications that go beyond EVs, such as industry or domestic application (Zeng, Li, & Ren, 2012).

One of their main characteristics is aging, caused by the gradual decomposition of the electrolyte at a given temperature over the lifespan (Ahmadi, Yip, Fowler, Young, & Fraser, 2014). Such aging is also affected by battery capacity and degradation rate, which varies according to the different types of EVs and the technology used; battery aging is in constant change due to extended battery's lifespan, consumers' usage pattern, reduction of charging frequency, driving behavior and general conditions of the road (Ai, Zheng, & Chen, 2019).

For EVs, battery degradation occurs when there is still about 80% of its SOH at the end of its useful life (Ahmadi, Yip, Fowler, Young, & Fraser, 2014). While battery manufacturers aim at increasing the lifecycle up to 15 years, currently such lifespan is about 8–10 years (Ai, Zheng, & Chen, 2019).

There are three EOL options for batteries that might mitigate some of the environmental impacts and allow reuse practices instead of immediate disposal: remanufacturing, recycling and reuse (DeRousseau, Gully, Taylor, Apelian, & Wang, 2017).

Battery second use strategies, i.e. removing an EV battery when it has reached its useful life (Viswanathan & Kintner-Meyer, 2011), can be used as energy storage systems (ESS), thus providing greater stability and reliability to the grid and increasing the integration rate of renewable energy (Casals, Martinez-Laserna, García, & Nieto, 2016). In order to use batteries as ESS, they can be used directly (Richa, Babbitt, & Gaustad, 2017), tested, remanufactured/reconditioned and utilized as stationary (Shokrzadeh & Bibeau, 2012). Several companies have pilot projects using batteries as ESS in solar panels and wind farms, residential and public energy as a backup, load leveling and among other secondary level applications (Jiao & Evans, 2016).

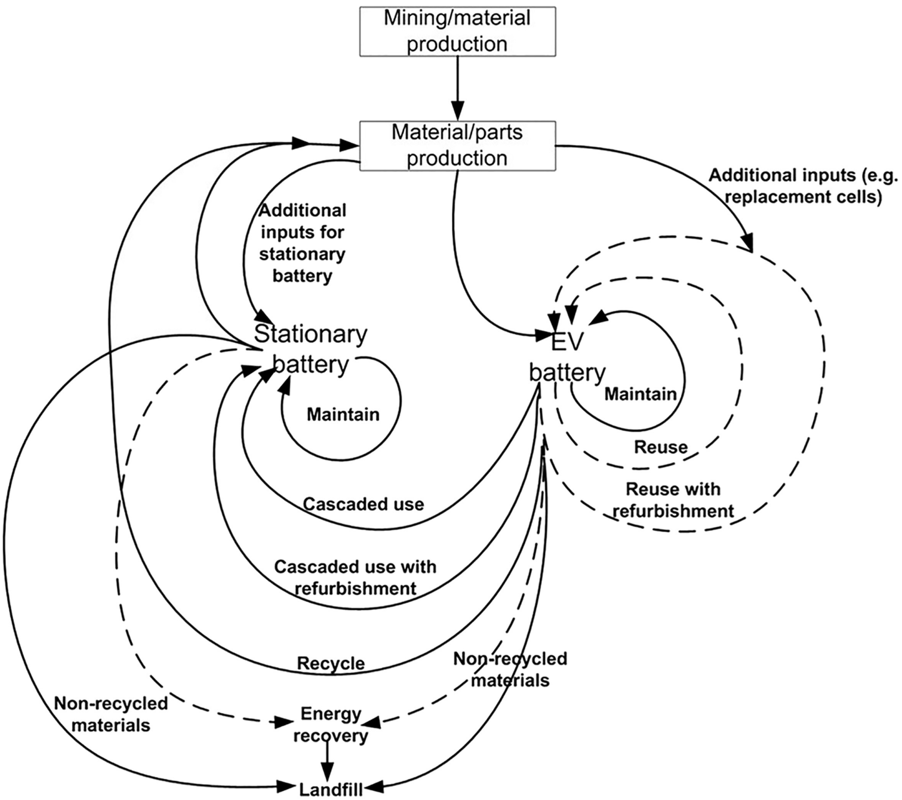
Furthermore, the possibility of reusing batteries in new business models is crucial for the development of a new "post-vehicle" market for obsolete batteries and also a way of reducing the price of EVs (Jiao & Evans, 2016).

Recycling is a potential strategy to increase the supply and mitigate price fluctuations of critical lithium battery materials (Mayyas, Steward, & Mann, 2019); to that end, it is essential to maintain a metal closed-cycle (Hamuyuni & Tesfaye, 2019) that commonly combines two steps: mechanical or direct recycling. The second stage can be pyrometallurgical (heat treatment) or hydrometallurgical (Heelan *et al.*, 2016; Mayyas, Steward, & Mann, 2019; Winslow, Laux, & Townsend, 2018).

In order to better understand the flows and hierarchies of batteries, Richa, Babbitt, & Gaustad (2017) have elaborated a theoretical hierarchy for EOL battery management (Figure 1). To this end, they used principles of the circular economy, which aims to eliminate waste, recycling materials and products within the system to obtain resource and energy efficiency, as well as profitability.

The transition to a circular supply chain may open unexplored opportunities for each stakeholder along the supply chain. In addition, the management of EOL batteries can help prevent shortages of rare materials to meet future demand for EVs (Salim, Stewart, Sahin, & Dudley, 2019a).

Before considering recycling or even landfill disposal, the batteries' second-life use should be thought out. This occurs because besides having a capacity between 70 and 80% of SOH (Olsson, Fallahi, Schnurr, Diener, & van Loon, 2018), which is expected to get lost during recycling, batteries use a large amount of relatively expensive materials and some have significant impacts on the environment (DeRousseau, Gully, Taylor, Apelian, & Wang, 2017).



Source(s): Adapted from Richa, Babbitt, and Gaustad (2017)

Figure 1.
Theoretical battery management hierarchy

EOL battery management – including secondary automotive battery applications, standards for battery waste management, and environmental requirements in battery design – is crucial to reduce the volume of critical raw materials needed for the manufacture of batteries and to avoid the risk of shortages (IEA, 2019).

1.2 The current state of EV diffusion and EOL battery policies in China

China is the world leader in electric vehicle fleet size (IEA, 2019), and therefore one of the few countries in the world that is already concerned about the impacts caused by short- and long-term battery disposal.

In this context, China has approximately a current fleet of 3.3 million units of EVs (considering battery electric and plug-in hybrid vehicles), leading the EV stock ranking in terms of absolute numbers, with an EV market share of 4.9% (IEA, 2020). The main motivations for the promotion of EVs are environmental issues, public health, energy security and production/innovation (Consoni, Oliveira, Barassa, Martínez, Marques, & Bermúdez, 2018). The projection of market penetration of EVs is quite uncertain since it is still an emerging technology and highly affected by evolving government policies (Hsieh, Pan, & Green, 2020).

According to Hsieh, Pan, & Green (2020), it is believed that the increase in the importance of LIBs – largely driven by the demand for EVs in China – will present several challenges worldwide as there is already a shortage of global supply of critical elements necessary for their manufacture, especially cobalt, lithium and possibly nickel, in addition to potential health and environmental risks caused by the inappropriate disposal of EOL batteries.

New regulation in China now holds EV makers responsible for the recovery of batteries, requiring them to set up recycling channels and service outlets where old batteries can be collected, stored and transferred to recycling companies. By the end of February 2019, 393 carmakers, 44 scrap car dismantling enterprises, 37 enterprises engaged in cascade utilization and 42 recycling enterprises had already joined the new traceability platform to track both the origin and owners of disposed batteries (Pagliaro & Meneguzzo, 2019).

Furthermore, since 2017 a new legislation forbids the import of electronic waste into China, including batteries, which is (1) leading China-based companies, which formerly supplied lithium carbonate, cobalt and nickel sulfates obtained from batteries derived from large consumer electronics companies, to establish new recycling plants "overseas" (in South Korea, for example) and (2) making foreign EV battery makers to open recycling plants in China (Pagliaro & Meneguzzo, 2019).

Industrial LIB recycling companies in China include Taisen Recycling, Zhejiang Huayou Cobalt, Brunp, Jinqiao Group, Jiangxi Ganfeng Lithium and GEM. The latter company, for example, operates in China with 13 automated plants for the disassembly of batteries and for recycling, where cathode and precursor materials are manufactured; the annual production capacity of cobalt, nickel and cathode materials exceeds 50,000 tons (Pagliaro & Meneguzzo, 2019).

The country presents a few policies that address the management of EV battery recycling. The city of Shenzhen has developed a pilot program that took place from 2018 to 2020. The program consisted of a deposit-refund system for batteries. By means of this strategy, the government charges retailers the initial fee of 20 RMB per kilowatt-hour for each and every EV sold. Similarly, in 2014, the "Interim Measures for the Management of Industry Standard, Announcement of the Comprehensive Utilization of New Energy Vehicle Used Power Battery" in Shanghai regulated a government grant of 1000 RMB per EV battery collected for EV manufacturers. In 2018, the "Application of Financial Support Policies for New Energy Vehicles" in Hefei stated that EV battery manufacturers, who are involved with used battery collection systems and EV batteries recycling, will be granted a subsidy of 10 RMB per kilowatt-hour (Daseon, 2020; Li, Mu, Du, Cao, & Zhao, 2020; NDRC, 2018).

2. The model

System dynamics (SD) is a theoretical approach used to understand and model the behavior of complex and nonlinear systems over time (Sterman, 2000). As the system dynamics' approach takes into account feedback process and feedback delays to represent and understand the dynamic behavior in the long run (Sterman, 2000), we chose to adopt such approach in the present research. In addition, the system dynamics approach is useful to design and assess the effects of policy on a complex system characterized by uncertainty in the long-term (Forrester, 1961).

System dynamics enables the assessment of different aspects involving strategies and policies, and it is well-suited to explore such aspects for many years (Benvenutti, Uriona-Maldonado, & Campos, 2019).

Moreover, it is a strong tool to understand mobility systems (Egilmez & Tatari, 2012), thus being able to assist in the understanding of EOL battery systems. Its use was verified in the work of Chen, Chen, Wang, & Hu (2015), in which the authors investigated the policies of EOL vehicles in China by making use of a combination of policies including government subsidies, taxes, and refund systems; subsequently, the effects of this combination were examined.

The same DS methodology was used in the work by Farel, Yannou, Ghaffari, & Leroy (2013) to assess the cost-benefit analysis of glass recycling in EOL vehicles in France. The use of DS enabled the demonstration of system variables with different levels of detail, which provided easy-to-understand graphical schemes to demonstrate the relationship among variables and, finally, becoming the main step in the construction of a quantitative model associated with mathematical methods.

Therefore, the studies mentioned herein reaffirm the importance of using DS associated with the management of EOL products, such as EV batteries, as it is a complex system that often involves sophisticated interactions and multiple feedbacks between different economic, regulatory, lifestyle and social factors (Alamerew & Brissaud, 2018).

2.1 Model structure and equations

The causal loop diagram is shown in Figure 2. There are three feedback loops that establish the system's behavior. The R1 loop links adopters to adoption of internal influences and it is known as "word-of-mouth" due to the interrelationship between members of the social system, forming a positive reinforcement loop. In other words, as the number of adopters grows, the likelihood of members of the social system (potential market) to meet an adopter increases, exposing the innovation to a large number of potential customers. As the number of adopters increases, two balance loops become dominant. Loop B1 demonstrates the effect of market saturation on the adoption of internal influences as the number of potential adopters decrease. B2 also produces a similar effect, which also reduces the adoption of outside influences as the number of potential adopters decrease.

A SD model has been built to integrate stocks and flows of EV sales to develop EOL battery strategies; subsequently, to create EOL battery management processes in China. For such simulation, some parameters and assumptions were used. The time horizon for this study was 35 years (2005-2040). The first sector is shown in Figure 3, which illustrates the electric vehicle diffusion sector.

In our model, the EV adoption flow (A_f) was based on the Bass diffusion model (Bass, 1969), presented in (1), which considers a potential market (m), the growth of adopters (A), associated with potential adopters (PA). The parameters p and q are calibrated based on historical data.

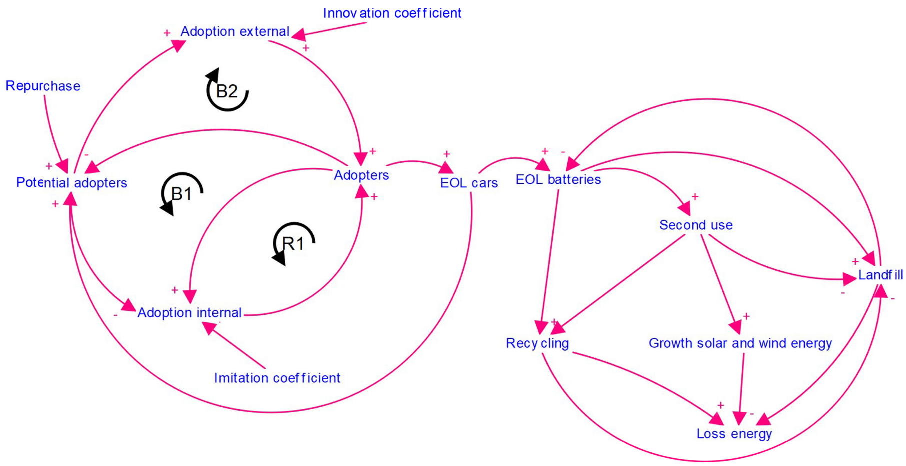


Figure 2.
Causal loop diagram

$$A_f(t) = (PA \cdot q) + \left(A \cdot PA \cdot \frac{q}{m}\right) \tag{1}$$

For PA Eqs (2) and (3), in addition to the influence arising from m through the growth flow (G), we also considered a repurchase flow (R), calculated by using a defined rate (R_r), which considers that a current adopter may become a PA in the future, and A_f, which feeds the stock of A.

$$PA = PA(t_n - 1) + \int_{t_{n-1}}^{t_n} [R + G(t) - A_f(t)]\mathrm{d}t \tag{2}$$

$$R = O_c(t) \cdot R_r \tag{3}$$

A is calculated considering A_f. However, we also considered an outflow, represented by the number of disposed cars (O_c), according to Eqn (4). To calculate O_c, we considered the use of Little's law alongside with delay.

$$A = A(t_n - 1) + \int_{t_{n-1}}^{t_n} [A_f(t) - O_c(t)]\mathrm{d}t \tag{4}$$

The behavior of m is controlled by means of a rate (F_r), in this case of growth (G_m), which is calibrated based on a historical data (Eqs (5) and (6)).

$$m\ (t) = m(t_n - 1) + \int_{t_n - 1}^{t_n} G_m(t)dt \tag{5}$$

$$G_m = m \cdot F_r \tag{6}$$

Finally, we have the stock of EOL vehicles (E_c), which represents the accumulation of EVs that exit the system due to their degradation, according to Eqn (7).

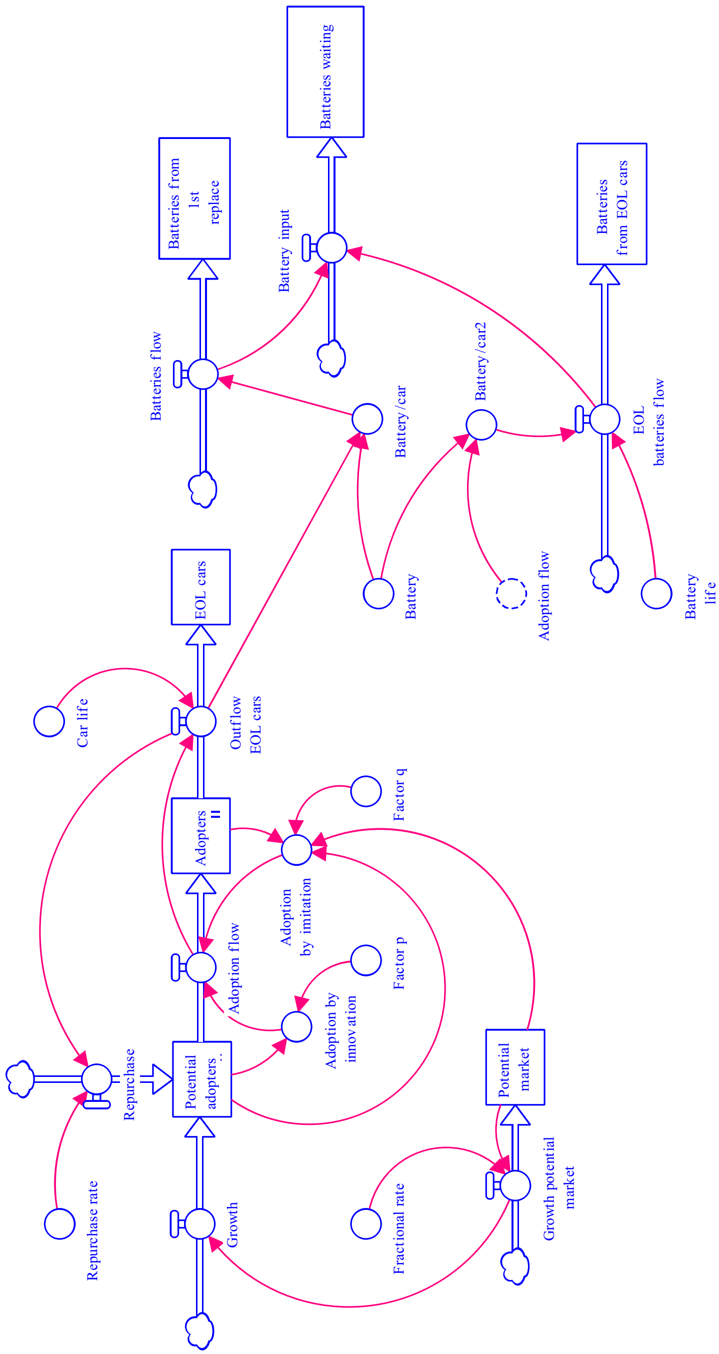


Figure 3.
Electric vehicle
diffusion model

$$E_c = E_c(t_n - 1) + \int_{t_n - 1}^{t_n} O_c(t)dt \quad (7)$$

For vehicle lifespan, we used the data provided by Yu, Chen & Yang (2019), who identified an average of 25 years of use for vehicles. Thus, it is possible to understand that after the first 25 years, the customer will need one more extra battery until the end of its life. Besides, battery degradation occurs after it reaches about 80% of its initial capacity (Shokrzadeh & Bibeau, 2016), an average between 8 to 10 years of use (Ai, Zheng, & Chen, 2019). It is also considered in the model that, after the use of the vehicle, the user returns it to the system to repurchase a new vehicle, for such a rate of 95% is assumed.

The second sector of the model corresponds to EOL batteries. EOL batteries accumulate over time, and they come from the first substitution while the vehicle is in use, and the second substitution when the vehicle itself has reached the EOL. Afterward, they are fractioned and forwarded to different forms of handling: recycling (Figure 4), landfill (Figure 5) and stationary batteries. For the modeling of EOL batteries, we considered that each vehicle unit contains a battery unit, which has a weight of approximately 250 kg (Ai, Zheng, & Chen, 2019; Idjis & da Costa, 2016).

The battery recycling stock (R_s) is calculated according to Eqn (8). In order to simplify the process, we consider that batteries, given a defined recycling rate (R_r), are sent for recycling through a flow (O_r).

$$R_s\,(t) = R_s\,(t_n - 1) + \int_{t_n - 1}^{t_n} O_r(t)dt \quad (8)$$

The O_r is the product of the used batteries (B_u) by R_r. However, it adds the difference of batteries that leave the sector of batteries collected for the second use, which after being used for some years can be recycled. The equation is presented in (9).

$$O_r = B_u \cdot R_r + (\text{dif} \cdot (\text{Transfer DS}_k + \text{Tranfer IS}_k)), \quad 1 \geq k \geq 5 \quad (9)$$

The same observed in the recycling sector occurred in the landfill sector, which represents the accumulation of batteries in a stock (L_s) defined from a landfill rate (L_r). In this case, integrating the landfill flow (O_l). They differ only by adding the variable of stationary batteries (S_r) that presents the batteries from the second use, according to (10) and (11).

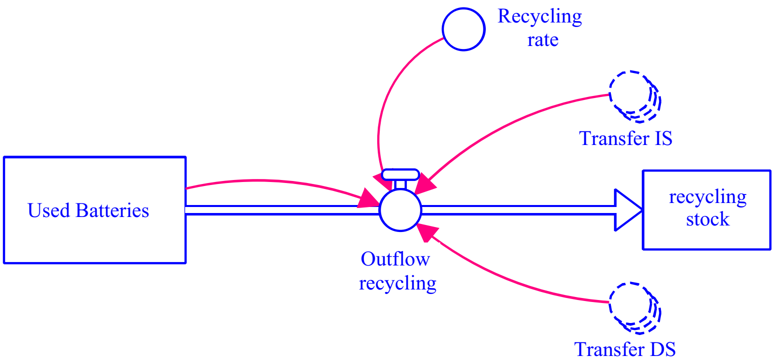


Figure 4.
Battery recycling sector

$$L_s(t) = L_s(t_n - 1) + \int_{t_n-1}^{t_n} O_l(t)dt \quad (10)$$

$$O_l = B_u + L_r + (S_r \cdot (\text{Transfer DS}_k + \text{Transfer IS}_k)),\ 1 \geq k \geq 5 \quad (11)$$

Stationary batteries, on the other hand, follow the paths shown in Figure 6.

The batteries can be reused directly (DS) or go through a remanufacturing process, which is known as an indirect strategy (IS). In both cases, they age along their chain, which directly affects the specific power. For modeling, we used the array (see Sterman, 2000) composed by five cohorts divided by year of battery use; every two years, up to ten years. The DS stock (2 years) is adding the value of the previous period plus the difference between the battery output of the system (transfer DS) as in (12). For all other cohorts, the stock is calculated by adding the stock of the period prior to the difference between the transfer rate of the previous cohort (r_{k-1}) and the transfer rate for the next cohort as in (13). The previous equations are repeated for the IS, changing the transfers to IS.

$$\text{DS}_1 = \text{DS}(t_n - 1) + \int_{t_n-1}^{t_n} [O_{ds}(t) - \text{transfer DS}_1(t)]dt \quad (12)$$

$$\text{DS}_k = \text{DS}_k(t_n - 1) + \int_{t_{n-1}}^{t_n} [r_{k-1}(t) - r_k(t) - \text{transfer DS}_k]dt \quad (13)$$

Since predicting battery capacity loss is complex and subject to several parameters, we assumed a basic setting to model the remaining power capacity after the battery is removed from the vehicle and used as stationary storage, which represents a nonlinear decrease in the specific battery power every two years of use, adding in total 10 years of use in second life as stationary, as shown in Table 1.

The third sector models the installed capacity growth for photovoltaics and wind power. The Bass diffusion models (Bass, 1969) were also used and the structure of the model is similar to those of Figure 2, with potential market, potential adopters and adopters stocks for both wind and solar PV. The model parameters are shown in Table 2.

2.2 Model fit

There are a few tests used to check model fit, including structural and behavioral tests (Barlas, 1996). The model presented herein has undergone validity tests, including dimensional consistency, extreme conditions and behavioral reproduction.

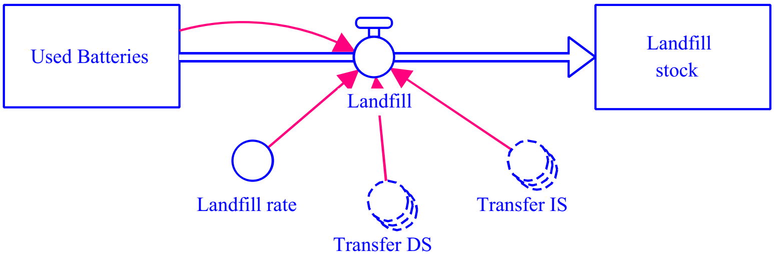


Figure 5.
Battery landfill sector

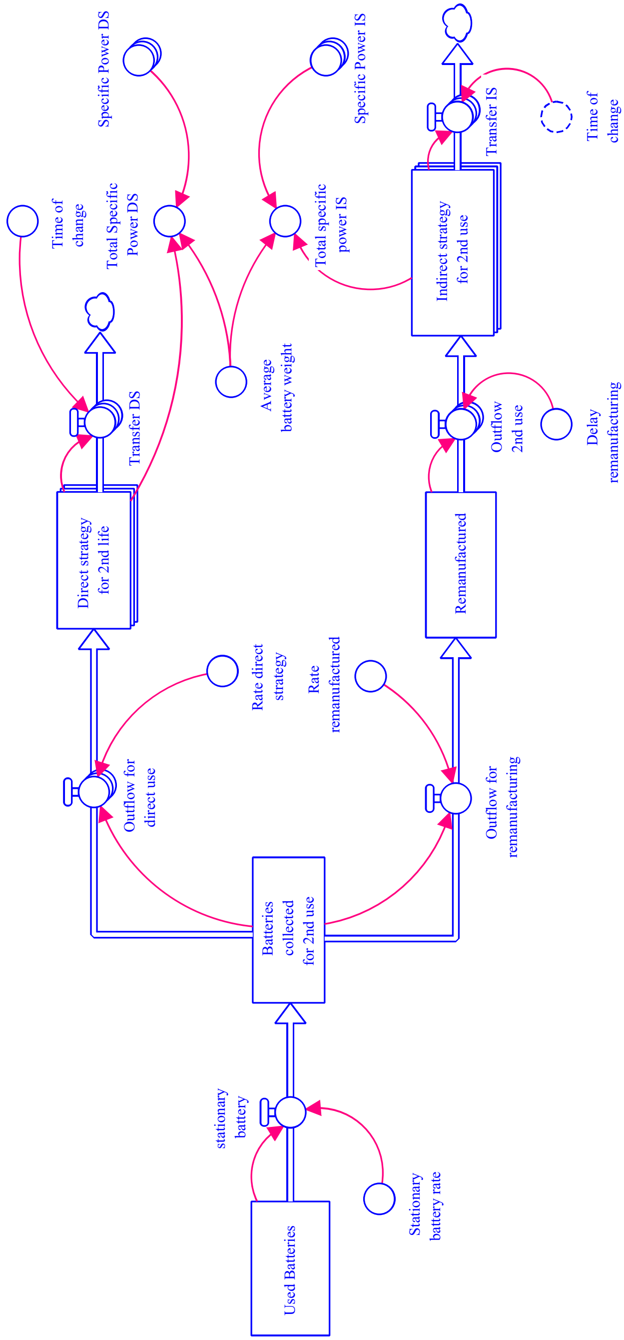


Figure 6.
Stationary battery sector

The model behavior was verified using historical time series data for: EV sales, installed solar PV capacity and installed wind energy capacity. For verification, we have used the coefficient of determination (R^2), root-mean-square error (RMSE) and the mean absolute error (MAE), as depicted in Table 3.

The reproduction of the model's behavior for the key variables is shown in Figure 7.

Based on the accuracy measures, the model fits historical data and, therefore, can be used to forecast future behavior.

2.3 Scenarios

In this section, we propose three scenarios for the management of EOL batteries, which will be compared against BAU (business as usual). They will enable to identify strategies that can be carried out in the long-term aiming at mitigating the effects of EOL battery accumulation, as well as forecasting future energy storage capacity for wind and solar generation in the country.

All scenarios adopt the assumption that there will be an improvement in battery lifetime from the current average of 10 years (SOH of approximately 80%) to 18 years by 2040 (Ai,

Year of use	W/kg (direct use - DS)	W/kg (indirect use- IS)
2	240	240
4	200	220
6	140	180
8	70	110
10	10	50

Source(s): Research data

Table 1. Specific power per year of use in stationary batteries

Parameter	Value	Source
Potential market - EVs	40,000,000 units	IEA (2019)
Potential market – Photovoltaic energy	700,000 MW	IRENA (2019)
Potential market – Wind energy	300,000 MW	IRENA (2019)
Fractional rate – EVs	1%	Authors' estimate
Fractional rate – Photovoltaic energy	1%	Authors' estimate
Fractional rate – Wind energy	1%	Authors' estimate
p-factor EVs	4×10^{-6}	Model calibration
q-factor EVs	0.65	Model calibration
p-factor solar PV	5.17×10^{-5}	Model calibration
q-factor solar PV	0.5978	Model calibration
p-factor wind energy	9.78×10^{-5}	Model calibration
q-factor wind energy	0.28	Model calibration

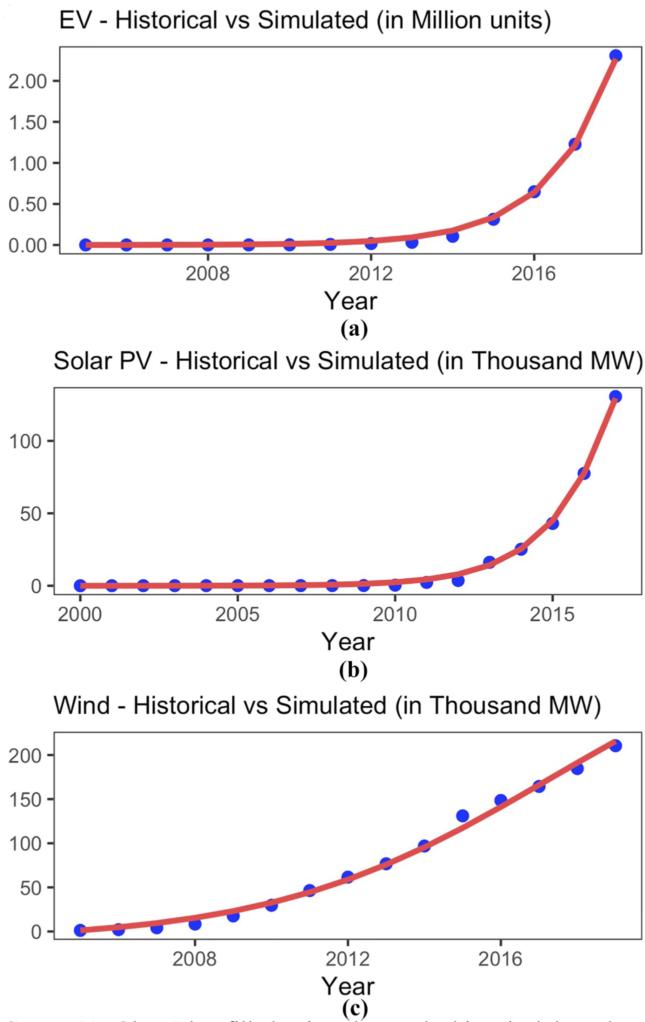
Source(s): Research data

Table 2. Parameters inserted in the simulation – diffusion of electric vehicles

Variable	R^2	RMSE	MAE
EV fleet (M units)	1	29220.61	20178.99
Solar PV (Thousand MW)	1	1442.13	896.92
Wind (Thousand MW)	0.99	5491.27	4340.74

Source(s): Research data

Table 3. Accuracy measures (from 2005 to 2019)



Source(s): Obs.: Blue-filled points denote the historical data; the red line indicates the simulated data

Figure 7.
Model behavior reproduction: (A) EV, (B) solar PV and (C) wind energy

Zheng, & Chen, 2019; Castro, Barros, & Veiga, 2013). These changes will benefit the environment by reducing the EOL battery disposal as lesser batteries will accommodate the same future energy demand.

BAU scenario: Since China dominates the second-life batteries market (Colthorpe, 2019), we assume that the country will achieve a recycling rate of 5% of used batteries per year, while the landfill rate will reach 94%, in accordance with the research of Heelan, Gratz, Zheng, Wang, Chen, Apelian, & Wang (2016), and the remaining 1% shall be repurposed as stationary batteries.

Scenario C1- A recycling future resembles the lead-acid battery sector in China, with a current recycling rate of 99% (Heelan, Gratz, Zheng, Wang, Chen, Apelian, & Wang, 2016), and considers large investments in plants and technology development for EV battery recycling. In this scenario, we assume a battery recycling rate between 80% and 90% by the year 2040, while the landfill and stationary battery rate account for equal proportions of the remaining 20-10%.

Scenario C2 – An energy storage future presents intense investment in R&D to repurpose batteries as backup stationary energy sources for solar and wind power generation, similar to what Toyota and Renault are planning for Japan and France, respectively. In China, the secondary use of EV batteries is being developed rapidly, mainly driven by government policies and the EV market. Government policies include guidance for industrial development, action plans, sector regulations and financial assistance and subsidies (Zhang, Liu, Pang, Sun, & Kokko, 2020).

In this scenario, we assume that the stationary battery rate will range between 75% and 95% by 2040, thus providing larger shares of renewable generation with backup power including household, businesses and even factories. Considering the intermittence of renewable sources, like solar PV and wind energy, we assume that intermittence is one of the major structural barriers to achieve higher power effectiveness; in this case, stationary batteries may serve as an energy storage system that helps overcoming such barrier.

Scenario C3 – A balanced future considers similar rates of battery destination, part of them being used as stationary and then recycled and part going directly to recycling. Thus, we define a variation of 35% to 45% for stationary batteries, and the difference (55% to 65%) divided equally between recycling and landfill. The recycling parameters were based on similar research that shows that the recovery rate, that is, lithium recycling, can reach approximately 20% before 2030 (Mohr, Mudd, & Giurco, 2012; Wanger, 2011).

Alternatively, it is important to note that, since the technologies that permeate EOL batteries are still immature, we envisage large and long-term efforts to their development. Therefore, we assume that even in the most optimistic scenario, an EOL battery share – even if small - will still be disposed onto landfills. Finally, we highlight that scenarios will be assessed through uncertainty analysis, with different ranges of uncertainty for each scenario. Thus, the model utilizes Latin hypercube sampling to generate 100 uniformly distributed samples of values within each range of uncertainty. The parameters used in the scenarios are summarized in Table 4.

3. Results and discussion

The BAU scenario shows that the amount of battery packs at the end of their lifespan is quite high (in 2040, there will be approximately 26 million battery units). The largest share (about 22.2 million) goes to landfills, generating negative environmental and economic impact (Figure 8). Only a small fraction (1.3 million) goes to recycling; however, the largest fraction is repurposed as energy backup storage (2.4 million units).

Parameter	BAU value (0–1)	Range of uncertainty in C1 (0–1)	Range of uncertainty in C2 (0–1)	Range of uncertainty in C3 (0–1)
Recycling rate	0.05	0.8–0.9	0.025–0.125	0.275–0.325
Stationary battery rate	0.01	0.05–0.1	0.75–0.95	0.35–0.45
Landfill rate	0.94	0.05–0.1	0.025–0.125	0.275–0.325

Source(s): Research data

Table 4. Parameter values and ranges of uncertainty for each scenario

3.1 Scenario C1 – a recycling future

The first scenario to be discussed is C1, where recycling is favored, with a target rate between 80% and 90% by 2040, meaning an expected 80-90% of all battery units being repurposed for component recycling. The results are shown in Figure 9.

The average is approximately 20 million battery units being destined for the recycling sector. When C1 is compared against BAU, an inversion of values is noticed, practically the same quantity of batteries is reallocated to recycling, unlike the landfill, a value close to 75%, besides it is completed with approximately 1.7 million batteries going to the stationary batteries sector.

To achieve this audacious C1 goal, several barriers must be overcome, including the lack of recycling profitability, lack of regulations, lack of economic incentives for collecting and recycling and support for plant facilities. These barriers are critical as they are the main means to ensure the effectiveness of battery collection and recycling (Salim, Stewart, Sahin, & Dudley, 2019b).

However, it is still suggested that there is still a substantial business opportunity for recycling LIBs, the cathode materials being the most expensive components of the battery. In a study carried out by Hsieh, Pan, & Green (2020), the authors affirmed that a Chinese private electric vehicle battery recycling industry could process nearly 20bn Yuan in metals per year until 2030.

3.2 Scenario C2 – an energy storage system future

The C2 scenario, in the opposite way of C1, presents intense investment to use EOL batteries as stationary batteries, with rates varying between 75% and 95%. The result of the simulation is shown in Figure 10.

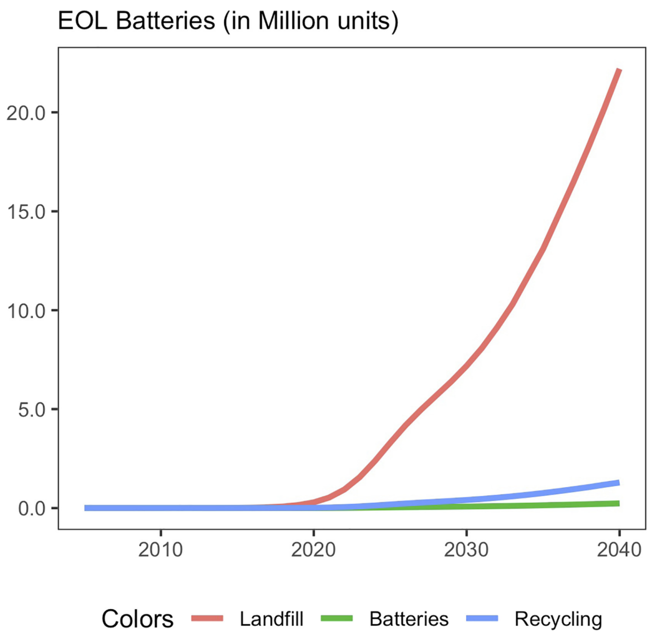


Figure 8.
Base case scenario for EOL battery management in China

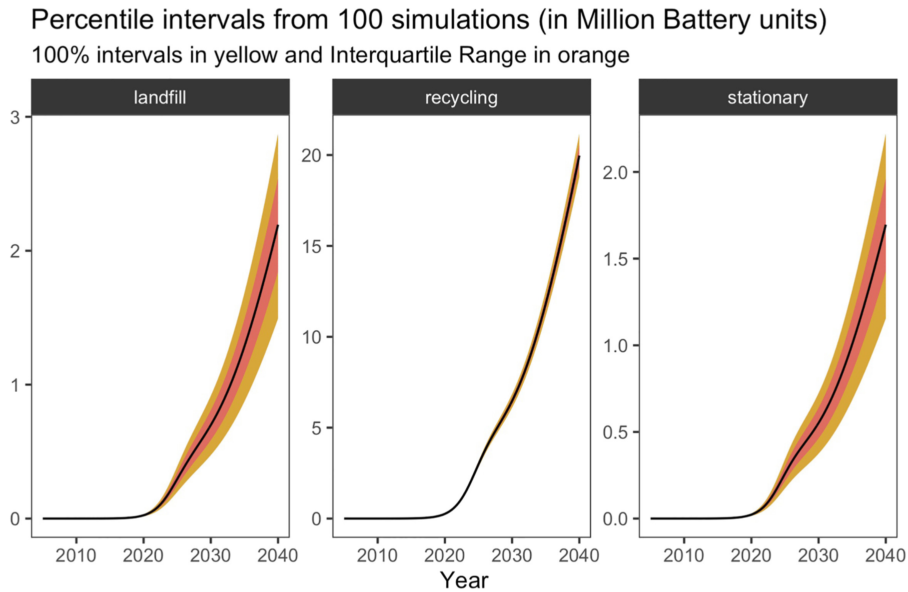


Figure 9.
Simulation results for scenario C1

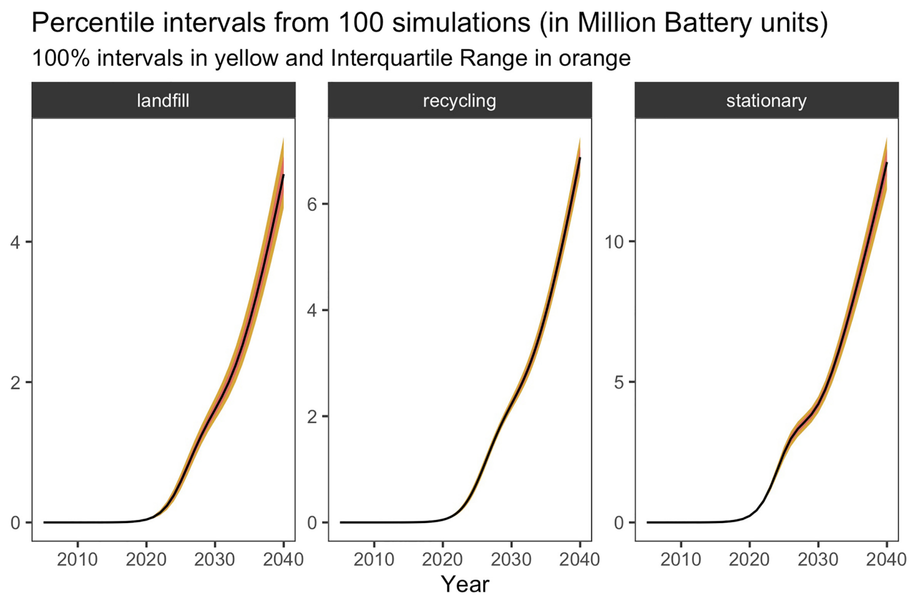


Figure 10.
Simulation results for scenario C2

At the end of the simulation period (year 2040), the confidence interval of the sensitivity analysis presents values between 11.8 and 13.7 million for stationary batteries; the median is 12.8 million.

The landfill sector presents a 77% reduction in the stock of batteries, most of which goes to the battery sector and later in the recycling sector. The latter gains more relevance because the batteries that are used as stationary, after a determined time, are available again to EOL management and can be sent to the recycling sector.

In this scenario, the focus of investment actions for EOL battery management strategies should not be given only to stationary batteries, which is why the batteries are only postponed from an end destination when they are used as stationary, in approximately 10 years, after which they enter the cycle again.

These measures will extend the EV industry's value chain. EV owners or EV manufacturers could recover part of the purchase or manufacturing cost of EV by selling LiB packages to energy companies that reuse them for electricity storage. This new business model will boost the EV market and increase the EV penetration rate to 50% in Meili (in Jiangsu Province, southeast China) by 2030, and to 75% by 2040 (Su & Urban, 2021).

It should also be noted that the C2 scenario is preferable when it comes to the high uncertainty of the recycling infrastructure capacity to properly recover valuable materials from a growing waste stream of batteries. In this context, potential benefits can arise from the reuse of used batteries as a storage system in second-life applications as this can delay the recycling process by up to 10 years, allowing the development of technologies and facilities more appropriate to the demands, reinforcing the study of Cusenza, Bobba, Ardente, Cellura, & Di Persio (2019).

3.3 Scenario C3 – a balanced future

In C3, the above-mentioned idea is emphasized and the importance of joint actions regarding stationary batteries and recycling is also highlighted. The batteries that leave the stationary sector without being recycled end up going to the landfill; thus, the postponed environmental problem continues to exist. Before this scenario, the batteries that are removed from the stationary sector are divided in a balanced way into recycling and landfill. Figure 11 presents the simulation results for this scenario.

The range of variation for C3, i.e. the stationary battery sector, was between 6.75 and 8.2 million units, with a median value of 7.49 million. This value is close to those of the landfill, which presented a median of 7.84 million units of batteries. The recycling sector demonstrated a higher median, around 8.95 million units of batteries.

The recycling sector, in comparison to BAU, grows more than 85.5%; from 1.29 million to 8.95 million battery units. The same occurs in the case of stationary batteries, with an increase of 96%, from 0.24 million to 7.49 million batteries. It is also noted that in C3, there is a reduction of 64% in the number of EOL batteries in the landfill sector.

Although LIBs are less toxic than other types of batteries, their improper disposal also has negative environmental impacts (Olivetti, Ceder, Gaustad, & Fu, 2017). These impacts inspired the creation of several policies, including the recycling targets proposed by the European Union's Batteries Directive (European Union, 2006) and landfill bans, in the American states of California and New York. Understanding the right path for batteries at the end of their life is complex, given the many options available and specially when considering the rapid trajectory of LIB technology, which results in ever changing sizes, shapes and cathodic chemicals (Olivetti, Ceder, Gaustad, & Fu, 2017).

Reuse and cascading use have the potential to spread costs over several lifetimes and reduce the overall environmental impacts of these products. Despite the economic and environmental benefits of reuse, significant barriers still remain. Most reuse avenues require significant test protocols and battery management systems that are compatible with the deployment of an "old" asset in a different (Richa, Babbitt, Nenadic, & Gaustad, 2017).

The focus of recycling efforts is on cathodic materials as they represent a high percentage of the battery's mass and total cost, and also contain the critical metals of interest. Obviously, secondary use scenarios, as described above, would delay the process of these materials in

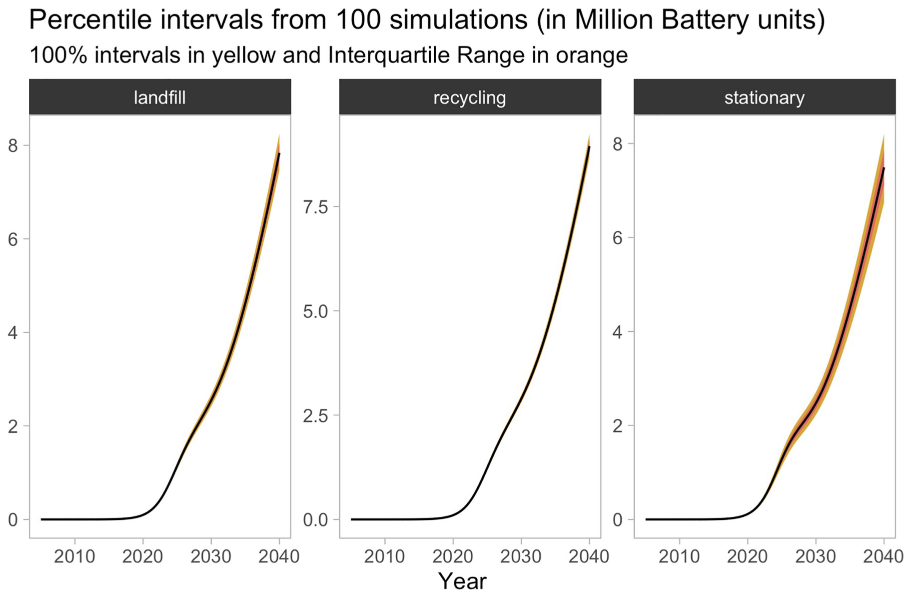


Figure 11.
Simulation results for scenario C3

reaching EOL recycling operations. Some forecasts estimate that the EV LIB recycling market may be worth up to $ 2bn in 2022; however, economic incentives for recycling will largely depend on the cathode chemistry of future vehicle batteries (Olivetti, Ceder, Gaustad, & Fu, 2017).

3.4 Comparative discussion with respect to energy storage systems

In none of the previous scenarios the landfill sector was fully depleted, even though it would have been the ideal path. This is due to the difficulty of controlling all EOL batteries, and the difficulty of implementing specialized technologies and organizations to manage the reuse or recycling routes of EOL batteries.

In this case, in addition to the development of regulations and policies, other interested parties should also be held responsible for the results. Thus, considering the specific case of consumers, environmental awareness should be further developed and internalized, which could encourage consumers to consequently demand a more responsible behavior from companies, organizations and governments.

With respect to renewable energy storage, in the BAU scenario, even though a low number of batteries are repurposed for second use, the total storage power capacity will reach 44.1 thousand GWh by 2040, which is enough to supply energy to 150 million households with an average consumption of 300 kWh. However, BAU serves only about 0.5% of solar PV and 1.2% of wind power generation (Table 5).

In contrast, even though C1 favors recycling (and not stationary batteries), it presents a larger share of 4% for solar PV storage and 9.9% for wind energy, that is, a capacity of 417 thousand GWh.

When comparing all scenarios, C2 shows the best result, with a capacity of more than 3 million GWh, reaching about 86% of the storage need generated by wind energy in 2040 and 36% of solar PV energy. Finally, C3 also presents a significant storage potential, a value close to 1.8 million GWh, which represents 22% of the need for storage of solar energy and 51% of wind energy. Figure 12 shows the results of each scenario regarding the accumulated storage capacity of stationary batteries, in millions of GWh. In Figure 13, we present the comparative results of the prospected scenarios in relation to the storage potential for solar PV and wind energy, in percentage, as previously discussed.

Giving a second life to these batteries can be seen by car manufacturers as a two-fold opportunity: first, it could indicate the opening of a new business line (either exploited by themselves or by third parties) where the benefits could directly impact on the price of the battery, therefore reducing the purchase price of EV. The second advantage would be the ability to respond to environmental issues related to the use and disposal of batteries (Rallo, Benveniste, Gestoso, & Amante, 2020).

4. Conclusions

The aim of this article was achieved through the modeling of SD; through such technique, it was possible to estimate the volume of EOL batteries and the potential energy storage capacity of solar and optical sources until 2040. In addition to the BAU scenario, three scenarios with different rates were formulated, which sought to identify behaviors in each EOL battery management route.

As previously seen, the BAU scenario indicates that EOL batteries can cause major future problems due to their accumulation, which occurs due to the lack of knowledge on technology, battery types, data reference and the demand for recycled or remanufactured products for second use. Given this, possibilities of a second use appear after the first use in EVs, in this study, options such as recycling and second use are cited.

Scenario C1 values investments in recycling, and at the end of the analysis period, it shows a big difference in the total amount of batteries. Through it, an alternative supply of elements (such as cobalt and lithium) is possible, to increase the availability and security of the supply of raw materials. However, this transition requires great efforts, such as the construction of factories, standardization of battery design, collection infrastructure, among others. Moreover, despite not being the central objective of this scenario, C1 presents, consequently, an increase of 3.24% in the capacity of stationary batteries to store energy and thus supply the existing demand for the sectors of solar and wind energy generation, going from a value close to 44,000 GWh to 350,000 GWh by the end of 2040.

Thus, the C2 scenario comes into play, with an intense investment of batteries as ESS. However, the second use of batteries as stationary can postpone the journey of the battery to recycling or landfill, increasing its useful life in addition to bringing an economic return. The study highlighted the storage potential of batteries and how they can contribute to the continued growth of renewable energies; for the year 2040, the capacity is over 3,000,000 GWh.

In scenario C3 the main intention was the balance of the system, where recycling and second use present parallel growth. Before the simulation, there is no overload in any of the sectors, which provides more time for the necessary changes to take place, such as increasing plant capacity, creating and developing business models, policies and regulations for EOL

Table 5. Key results for energy storage capacity from EOL batteries by 2040

Scenario	Storage capacity in 2040 (10^6 GWh)	Interquartile range in 2040 (10^6 GWh)	Simulated share of solar PV generation (%)	Simulated share of wind generation (%)
BAU	0.044	–	0.5	1.2
C1	0.417	0.35–0.48	4.0	9.9
C2	3.04	2.93–3.14	36	86
C3	1.81	1.73–1.90	22	51

Source(s): Research data

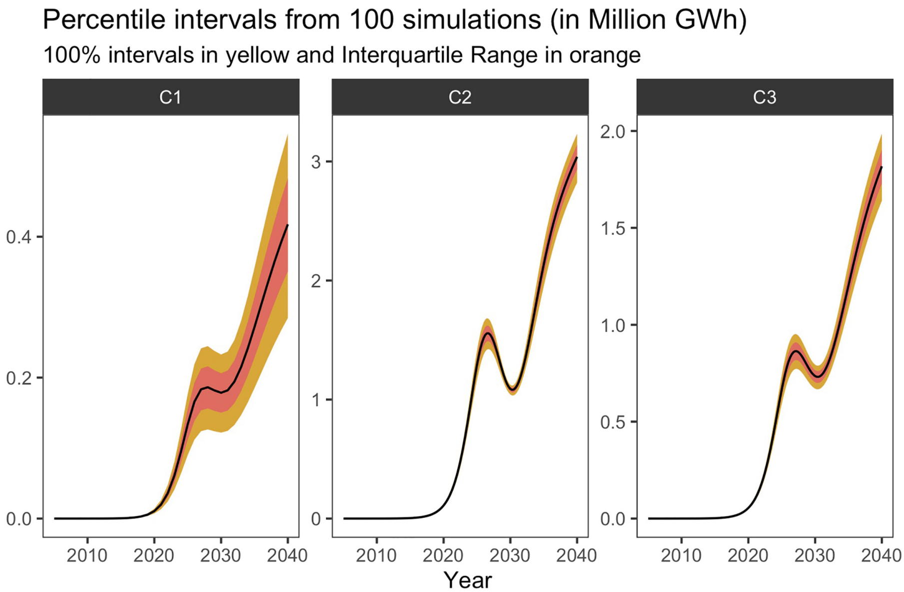


Figure 12.
Comparative results for total stationary battery cumulative storage capacity

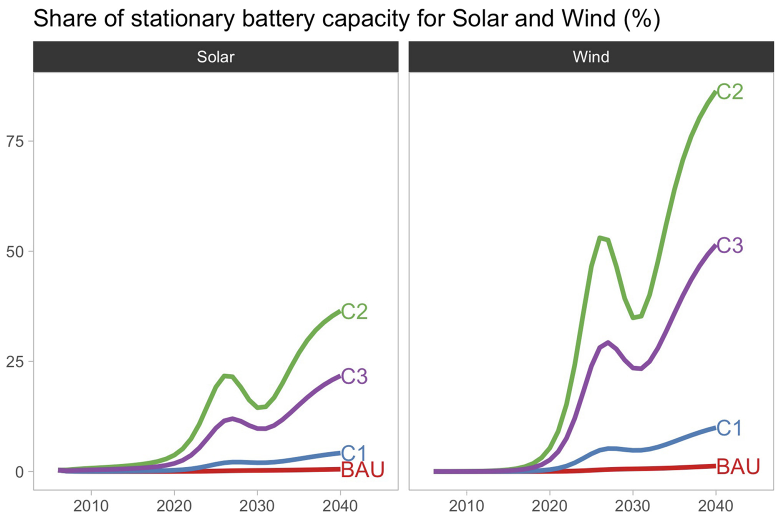


Figure 13.
Comparative results for the share of cumulative power capacity by energy source

battery use, among others. Again, despite not being the focus of this scenario, the outcome of the storage of energy by EOL batteries is positive, reaching about 1,815,000 GWh.

China has been leading sales of EVs. This expansion will lead, in the long run, to an accumulation of EOL batteries. If the recycling rate is low, China will not only create a series of environmental problems but it will also miss a significant economic opportunity. Thus, policymakers must help integrate the entire industry chain between automakers, battery manufacturers, used car dealers and scrap companies into battery recycling systems to achieve a more sustainable and circular society. With an established recycling-based LIB supply chain, not only will millions of tons of batteries be prevented from entering the waste stream and being characterized as hazardous but the pressure of supplying critical materials will also be mitigated.

On the other hand, using batteries in ESS applications can increase the use of renewable energy, making the country less dependent on nonrenewable energy. In addition, this use can provide the time needed for the development of recycling industries as the battery life cycle increases, and only after the end of the cycle it is recycled. The second use presents a few economic benefits arising from the possibility of developing new business models.

Although the theoretical implication is not the focus of the article but rather practice and policy, an important theoretical contribution is the accomplishment of a study using dynamic simulation in the specific case of batteries in China, considering uncertainty and possible developments from renewable sources.

This study, although applied to China, can be replicated to different countries in the world, both developed and developing, which deal with the problem of EV battery disposal and the intermittence of renewable sources in the upcoming decades. This characteristic of the model, described by Sterman (2000) as "family member", implicates that the model can generate the behavior of other instances of the same class, being considered generic.

The possibility of future forecasts may contribute to the formulation of policies and regulations, which may be applied both to actions in battery recycling that may return to the EVs and movements of incentives for the use of batteries as ESS since the second use may assist the management of the energy mix, in addition to serving as a backup when the systems are deactivated, that is, acting on other system's bottlenecks.

As a continuation of the study, we suggest the application of economic variables in modeling and simulation to quantify the volume of EOL batteries and to economically evaluate the management options to analyze which sector is more viable.

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