Estimation of lithium-ion battery scrap generation from electric vehicles in Brazil

João Pinto Cabral-Neto1,2 · Rejane Magalhães de Mendonça Pimentel1,3 · Simone Machado Santos2 · Maísa Mendonça Silva2,4

Received: 11 January 2022 / Accepted: 15 October 2022 / Published online: 1 November 2022
© The Author(s), under exclusive licence to Springer-Verlag GmbH Germany, part of Springer Nature 2022

Abstract
Among the diversity of electronic waste, lithium-ion batteries (LIB), specifically those used in the propulsion of electric vehicles (EV), are considered pollutants of significant impact. When not used and disposed of correctly, LIBs can cause damage of various types to health and the environment. The electrochemical instability inherent in these batteries releases toxic gases, risks explosion, and is always associated with a series of electronic circuits composed of various metals, including heavy metals. As a result of public policies to encourage vehicle electrification, the Brazilian EVs sector has shown high growth, even within an economic crisis scenario. In this sense, this study presents a model for estimating the production of electric vehicles and the generation of scrap LIBs, based on time series, combining battery life, car sales data, and the mileage profile covered by a car in Brazil. Around 700 thousand EVs are expected to be circulating in Brazil by 2030, with approximately 500 thousand LIBs to be converted into scrap by 2040. Finally, the delaying effect of the scrap generated from LIBs is highlighted, in line with the battery life, which, in the future, may have a very negative impact on waste management.

Keywords  Lifespan · LIB scrap · Electric vehicles · E-waste · Forecasting model · Time series

Introduction
One of the essential elements in the electric vehicles (EV) assessment is batteries. Unlike most of the common types of vehicles, where the accumulator’s primary function is to start the engine, in EVs, the batteries have an additional role, providing energy for propulsion. In this light, despite the existence of several battery technologies, the LIB is the most widely used for this application due to its high energy density and a life expectancy that is higher than competing technologies (Du et al. 2019).

However, despite having significant energy efficiency advantages, these batteries are also associated with some problems. Sun et al. (2016) report the existence of more than one hundred types of toxic gases released by lithium-ion batteries, which are considered potentially fatal, and can cause severe irritation to the skin, eyes, and respiratory tract and harm the environment in a general way. In their study, these authors identified several factors that can cause an increase in the concentration of toxic gases emitted. A fully charged battery releases more toxic gases than a 50% charged battery, for example. The chemical compounds in the LIB and its ability to release charge also affect the concentrations and types of toxic gases released, and the use of LIBs in EVs is one of the forms of application that most require a battery charging capacity.

The battery is an accumulator responsible for storing electrical energy from the electrical grid and generator in the form of chemical energy, and subsequently converting it into electrical energy to power the vehicle. According to Xu et al. (2020), the lithium-ion battery is the most promising
option for EV applications, which comprises a battery family, with advantages and disadvantages.

The main types of lithium-ion batteries are as follows: LCO (lithium-cobalt-oxide), NCA (lithium-nickel–cobalt-aluminum, or LiNiCoAl), NMC (lithium-nickel-manganese-cobalt, or LiNiMnCo), LMO/LTO (lithium-manganese), and LFP (iron-lithium phosphate, or LiFePO4) (Miao et al. 2019).

The insufficient supply of lithium to meet the future demand is one of the main arguments against EV, defended by Greim et al. (2020). According to the United States Geological Survey (USGS 2017), there are more than 14 million tons of lithium in the world, with the largest reserves in countries such as Chile, Argentina, Bolivia, and Australia, which together account for about 80% of the world reserves. According to the Geological Survey of Brazil (CPRM 2018), Brazil holds 8% of the reserves already mapped. Its production was 43 thousand tons in 2018, which is equivalent to less than 0.1% of world production, which is dominated by Australia and Chile, which together account for 76% of world production, and Argentina, with 13% of the total. Europe leads the consumption ranking with 24% of all world consumption of lithium, all of which is imported. Brazil consumed only 9500 tonnes in 2016, according to data from the National Department of Mineral Production (DNPM 2017).

Although lithium is not used just in battery production, about 46% of the world’s production is used to manufacture batteries for the most diverse purposes, among them, electric vehicles. However, there is an expectation that, with the popularization of EVs, the percentage of lithium produced dedicated to the manufacture of batteries will increase even more in the coming years (Diniz 2019).

According to data from the National Association of Motor Vehicle Manufacturers (ANFAVEA 2019), the electric vehicles sector in Brazil, even within the scenario of economic crisis, is the one that has shown the highest growth rates in recent years, with 120% and 299% growth rates of licensed vehicles in 2018 and 2019, respectively. Such indicators reflect public policies that are aimed to encourage vehicle electrification in the country, such as Inovar-Auto (Brazil 2012) and Rota 2030 (Brazil 2018).

As a developing country, tackling solid waste management (SWM) problems in Brazil are still recent. When segmenting the management of LIB scrap, the challenge becomes even more considerable, especially concerning the lack of technologies for selective collection and recycling — which leads to dumping in inappropriate places — and the lack of knowledge for the implementation of regulatory legislation.

Brazilian law establishes the maximum limits for lead, cadmium, and mercury for selling batteries in the national territory and the criteria and standards for environmentally appropriated management. However, there are still no criteria and standards suitable for lithium batteries in general in the national legislation. The National Solid Waste Policy (NSWP) — Law 12,305/2010 (Brazil 2010) — deals generically with batteries without distinguishing the technologies, and requires manufacturers, importers, distributors, and resellers to structure and implement systems of reverse logistics of batteries after the end of the product’s useful life. According to Neto et al. (2016), most companies that provide battery scrap collection are focused on lead-acid technology despite what the legislation provides. There is no consolidated reverse logistics market for LIBs, mainly because Brazil is an importer of this technology. The leading manufacturers are Chinese, which makes reverse logistics even more difficult.

The LIB is composed of two electrodes, one positive and one negative, immersed in an electrolyte solution. The cathode (+) is the biggest determinant of the battery’s energy, safety, life, and cost. It is composed of various lithium metal oxides (e.g., LiCoO2, LiMn2O4, LiNiO2, LiFePO4, Li2FePO4F, LiNi0.5Co0.5Mn1/3O2) glued on an aluminum sheet that represents the cathode’s electrical conductor. Thus, the main differences between the battery families reside in the cathodes. The anode (−) is formed by a graphite structure composed of several carbon layers, with lithium ions among them. In turn, the graphite structure is glued to a copper sheet, acting as the anode’s electrical conductor. Both positive and negative active materials are usually bonded to the load collectors with a CMC binder (carboxymethyl cellulose) (Chang et al. 2019). According to Sun et al. (2017), most of the lithiated metal oxide compounds show chemical instability and decompose easily due to their temperature sensitivity.

The electrolyte is a component that has been studied continuously to obtain a solution capable of giving LIB suitable stability. LIBs employ electrolytes dissolved in non-aqueous solvents due to the extended stability window. The most commonly used electrolyte solution is composed of lithium salts dissolved in organic solvents (usually carbonates) and absorbed by the separator (polymeric membrane) (Smiatek et al. 2018). Despite their relatively simple composition, unlike other battery technologies, LIBs require a high degree of embedded electronics to ensure safety under almost all circumstances due to their electrochemical instability. Usually, all lithium batteries are associated with printed circuit boards embedded inside the battery (battery management system (BMS)). As established by the IEC 62,133–2:2017 standard of the International Electrotechnical Commission (IEC), the BMS is responsible for ensuring protection against excessive charge and discharge currents, protection against discharge below the minimum voltage value of the battery, carrying out load-balancing between batteries, and protection against excessive temperatures. However, these electronic circuits are composed of many materials that vary according to the manufacturer, with several metals, such as even lead, metallic alloys, and organic and inorganic compounds (Shim et al. 2021).

According to Castro and Consoni (2020), there is still no established process for recycling LIB. Authors agree that...
recycling a lithium battery is risky due to the possibility of fire and explosion due to the lithium and non-aqueous solvent. Attempts to open them can expose batteries to moisture in the air, causing violent reactions. In the critical stage of a mechanical opening by crushing or grinding, the processes use the chemical element argon in liquid form, or ovens with a high ventilation rate, subsequently having great difficulty in the component/material segregation step. Currently, this recycling technology is mainly used in Canada and the USA.

Since cobalt and lithium are the most valuable metals from recycling these batteries, several experimental processes have been developed for better recovery. One of them employs the dissolution of the batteries in diluted hydrochloric, nitric, or sulfuric acid, followed by chemical treatment of the acidic liquid, and the final residue’s processing yields an average recovery of 85% of cobalt and lithium. Despite this, this and other initiatives have not yet become popular due to their still very manual processing and high costs (Conte 2016).

Estimating future waste generation is crucial for establishing efficient collection and an adequate recycling system (Lebreron and Andrade 2019). Based on government incentives aimed at promoting vehicle electrification in Brazil, there are expectations from the government and the market that by 2030 Brazil will be fleeted with more than 2 million EVs (WEF 2016; BCG 2019; EDP 2019). Within this perspective, considering the growth of the electric vehicle market, the estimation of LIB scrap generation becomes the basis for more assertive decision-making, reverse logistics, and the correct recycling of scrap, according to the objectives of the NSWP.

Therefore, this study aims to estimate LIB scrap, combining battery life, car sales data, and the mileage profile traveled by cars in Brazil through time series modeling. Modeling through time series has been widely used in similar works to predict waste generation, helping in its management, as shown by the investigations of Chang and Lin (1997), Chen and Chang (2000), Navarro-Esbrí et al. (2002), Neto et al. (2016), and Santos et al. (2019). Also, it aims to contribute to solid waste management since, according to Cabral-Neto et al. (2020), few studies deal with LIB scrap generation, especially in developing countries such as Brazil.

Material and methods

Minitab® and Microsoft Excel® software were used to perform the time series modeling and statistical analysis.

Estimated EV fleet and LIB quantity

Considering that the EV fleet’s projection (2 million units) until 2030 occurred in a pre-pandemic period of COVID-19, and that the pandemic caused a global economic depression, it was more robust in developing countries like Brazil. There was a need to update these projections, taking into account the historical sales behavior of these vehicles and not just government incentives. Historical data from EV sales made available by ANFAVEA — an entity comprising manufacturers of automotive vehicles (cars, trucks, and buses) and agricultural machines (wheeled tractors, tractors, harvesters, and backhoes) in Brazil — were used and had attributions: (i) to study industry and automobile market issues and (ii) to compile and disseminate sector performance data.

It is known that each EV has its propulsion system moved through a LIB; determining the number of vehicles can therefore indirectly determine the number of batteries.

Time series modeling for EV fleet projection

In this study, the time series is constituted by the EV data licensed in Brazil between 2012 and 2019. The time series modeling refers to building a variable model measured at intervals over a certain period. Time series models are created to explore past movement patterns to predict future behavior (Pindyck and Rubinfeld 2000).

Since these are observations obtained in chronological order, it is essential to identify external factors that may influence the data series’s behavior. Since neighboring observations can be dependent, it is necessary to analyze and model this dependency, observing whether the series is stationary or not.

According to Neto et al. (2016), vehicle sales data compose a non-stationary series that presents both trend and seasonality behaviors. The tendency is understood as the long-term behavior of the series, which may be caused by demographic growth, or a gradual change in consumption habits, or any other aspect that affects the variable of interest in the long term. Seasonality corresponds to fluctuations in the variable’s values lasting less than 1 year, and which are repeated every year, generally depending on the seasons, holidays, popular festivals, and among others (Triola 2017).

Thus, it was decided to use the exponential smoothing model, as it is a forecasting method that isolates the seasonality from irregular variation (McKenzie 1984). Specific exponential smoothing techniques assume that extreme values of the series represent a random pattern. In this way, by smoothing these extremes, one can identify the basic pattern (Morettin and Toloi 2018). Exponential smoothing is so-called because it assigns exponential weights to the series data, increasing the weight as the data becomes more recent (Yaffee and McGee 2000).

Three exponential smoothing models were analyzed, considering the amount of EV, which provided the best adjustments for the data: the Holt–Winters multiplicative model, the integrated autoregressive model of moving averages — ARIMA (double exponential smoothing) — and the simple moving averages model. The Holt–Winters model
produces three smoothed values: $\alpha$ (level), $\beta$ (trend), and $\gamma$ (seasonal). On the other hand, the ARIMA model has two smoothing parameters: $\alpha$ (level) and $\beta$ (trend), while the moving averages only produce the seasonal adjustment for the forecast.

**LIB lifespan**

Usually, LIBs have their duration estimated based on the number of loading and unloading cycles supported (Impinnisi 2010). The speed at this number of cycles varies according to the mileage profile covered by a given vehicle fleet. Therefore, the calculation of the useful life of a LIB was estimated based on the average mileage traveled by the Brazilian population. Table 1 shows the average between the circulation values (km) of each State from Brazil (TO Tocantins, DF Distrito Federal, MT Mato Grosso, RR Roraima, GO Goias, MS Mato Grosso do Sul, RN Rio Grande do Norte, AC Acre, PB Paraíba, PR Paraná, SE Sergipe, MA Maranhão, SP São Paulo, AL Alagoas, MG Minas Gerais, AM Amazonas, SC Santa Catarina, PI Piauí, AP Amapá, BA Bahia, RO Rondônia, RS Rio Grande do Sul, PA Pará, CE Ceará, ES Espírito Santo, RJ Rio de Janeiro, PE Pernambuco).

The cycle of a lithium-ion battery converted into traveled mileage, according to data in the technical sheet of one of the most popular EV models (Bolt EV), and according to GM (2020), corresponds to approximately 416 km/cycle. A LIB lifetime was calculated by crossing these data with an estimated number of cycles of a battery obtained in the literature.

**LIB scrap**

Based on the projection of the number of vehicles and the respective number of batteries produced, and considering the calculated lifetime of a LIB, the respective amount of lithium-ion battery scrap expected to be produced by 2040 in Brazil can be designed.

**Results and discussion**

**EV fleet**

Licensed EV data, released by ANFAVEA, were collected year by year, for 8 years (from 2012 to 2019). Figure 1 shows the graph of the time series. As it is a non-stationary series, according to parsimony — the adoption of the simplest approach — exponential smoothing methods were used to analyze the time series.

The series has components of trend and seasonality. Thus, three types of methods were used: the Holt–Winters prediction models, ARIMA, and moving averages. By the annual car sales data (Table 2), for with each method, the constants, and the precision measures (Table 3), and the forecast for EV sales from 2020 to 2030 (Table 4) were obtained.

The results show that double exponential smoothing using ARIMA is the most suitable method for sales data for electric cars due to the lower MAPE (mean absolute percent error), MAD (mean absolute deviation), and MSD (maximum standard deviation). Figures 2, 3, and 4 show the adjusted data for the three methods used.

**LIB lifespan**

The number of cycles of a battery is variable according to the electrical consumption level. A lithium-ion battery operating at 100% of its rated discharge current reaches a range from 300 to 500 cycles (Cobo 2019). The number of cycles of a LIB was assumed as the average between the limit values of the established range (400 cycles). Considering that 1 cycle of a LIB corresponds to an EV autonomy of approximately 416 km and that the average annual circulation of a vehicle in Brazil is 13,059 km, the LIB lifespan can be calculated as

| State | Average circulation (km) | State | Average circulation (km) | State | Average circulation (km) |
|-------|-------------------------|-------|-------------------------|-------|-------------------------|
| TO    | 17,600                  | PR    | 13,100                  | AP    | 12,500                  |
| DF    | 14,600                  | SE    | 13,100                  | BA    | 12,500                  |
| MT    | 14,600                  | MA    | 13,000                  | RO    | 12,500                  |
| RR    | 14,300                  | SP    | 13,000                  | RS    | 12,200                  |
| GO    | 13,700                  | AL    | 12,900                  | PA    | 12,100                  |
| MS    | 13,700                  | MG    | 12,900                  | CE    | 11,900                  |
| RN    | 13,400                  | AM    | 12,800                  | ES    | 11,700                  |
| AC    | 13,300                  | SC    | 12,800                  | RJ    | 11,600                  |
| PB    | 13,100                  | PI    | 12,600                  | PE    | 11,100                  |
| Average Brazil | 13,059               |       |                         |       |                         |

Source: Adapted by KBB (2019)

Fig. 1 Series of sales of electric vehicles in Brazil (2012–2019)
The average useful life of a lithium-ion battery is 12 years for the Brazilian traffic situation.

Combining the LIB’s useful life with the projections of the number of EVs circulating on the market until 2030, obtained with the ARIMA model, the number of scrap batteries generated was estimated. It is considered that, for each new car, a LIB is produced and is replaced every 12 years. Therefore, in addition to the scrap generated, a new battery must be manufactured for replacement. The forecasting of LIB scrap up to 2040 is shown in Table 5, and the comparison between the annual car sales and the quantity of LIB scrap produced in the same period is shown in Fig. 5.

The commercialization of EVs in Brazil started in 2012, and the first scrap LIBs will only materialize in mid-2024. These results reflect the market’s lack of concern in developing recycling technologies for these batteries, as it is not yet a short-term problem. By 2030, the production of 10,666 scrap LIBs is expected, with 477,188 in the following decade. However, planning for the estimated waste generation...
must be considered in advance, not only when the problem has become established.

The gap between the sales projections for EVs and LIB scrap production is shown in Fig. 5. Due to the 12 years of battery life, the generation of scrap behaves like a rebound effect on vehicle sales. The different behavior of lead-acid batteries, with a useful life of approximately 3 years, causes cars to change batteries more often in a shorter time, leading to a cascade effect in the generation of waste (Neto et al. 2016). In the case of LIB scrap production, there is a positive aspect: the existence of time for correct planning regarding the reuse possibilities or the final destination of this waste. However, there is concern that because the LIB scrap management solution is not a short-term problem, it will be postponed, with unpredictable consequences.

The technological difficulties of recycling LIBs stimulate their reuse in other electronic devices (second life) that demand less energy than the device for which it was initially designed (Assunção 2016). Even for reuse, it is essential to manage the scrap properly since mechanical adaptations and refilling, which may have impacts on the environment, will be necessary.

The lack of a guideline dealing explicitly with lithium-ion batteries leads to a lack of planning and favors poor management and inappropriate disposal of LIB scrap. Considering the occurrences in Brazil, the emergence of clandestine recyclers is possible, who may be neglectful of environmental concern and work safety, as shown by Faria and Oliveira (2019) and Caetano et al. (2019).
Fig. 4 Moving averages model for annual sales of EV

Table 5 LIB scrap generation forecast (2020–2040)

| Year | 0 year New LIB/new EV | 12 years New replaced LIB | 24 years New replaced LIB | Total new LIB | Scrap |
|------|-----------------------|---------------------------|---------------------------|---------------|-------|
| 2012 | 117                   | -                         | -                         | 117           | -     |
| 2013 | 491                   | -                         | -                         | 491           | -     |
| 2014 | 855                   | -                         | -                         | 855           | -     |
| 2015 | 846                   | -                         | -                         | 846           | -     |
| 2016 | 1091                  | -                         | -                         | 1091          | -     |
| 2017 | 3296                  | -                         | -                         | 3296          | -     |
| 2018 | 3970                  | -                         | -                         | 3970          | -     |
| 2019 | 11,858                | -                         | -                         | 11,858        | -     |
| 2020 | 16,572                | -                         | -                         | 16,572        | -     |
| 2021 | 25,261                | -                         | -                         | 25,261        | -     |
| 2022 | 33,949                | -                         | -                         | 33,949        | -     |
| 2023 | 42,637                | -                         | -                         | 42,637        | -     |
| 2024 | 51,326                | 117                       | -                         | 51,443        | 117   |
| 2025 | 60,014                | 491                       | -                         | 60,505        | 491   |
| 2026 | 68,702                | 855                       | -                         | 69,557        | 855   |
| 2027 | 77,390                | 846                       | -                         | 78,236        | 846   |
| 2028 | 86,079                | 1091                      | -                         | 87,170        | 1091  |
| 2029 | 94,767                | 3296                      | -                         | 98,063        | 3296  |
| 2030 | 103,455               | 3970                      | -                         | 107,425       | 3970  |
| 2031 | -                     | 11,858                    | -                         | 11,858        | 11,858|
| 2032 | -                     | 16,572                    | -                         | 16,572        | 16,572|
| 2033 | -                     | 25,261                    | -                         | 25,261        | 25,261|
| 2034 | -                     | 33,949                    | -                         | 33,949        | 33,949|
| 2035 | -                     | 42,637                    | -                         | 42,637        | 42,637|
| 2036 | -                     | 51,326                    | 117                       | 51,443        | 51,443|
| 2037 | -                     | 60,014                    | 491                       | 60,505        | 60,505|
| 2038 | -                     | 68,702                    | 855                       | 69,557        | 69,557|
| 2039 | -                     | 77,390                    | 846                       | 78,236        | 78,236|
| 2040 | -                     | 86,079                    | 1091                      | 87,170        | 87,170|

*Italicized numbers indicate the number of LIBs/EVs provided by the mathematical model

*Bold numbers indicate the amount of LIB scrap estimated for the projected EV fleet
Fig. 5 EV sales growth compared to the amount of LIB scrap generated up to 2040

Conclusion

Considered a crucial step in SWM, planning, to be carried out properly, requires a reliable diagnosis of the amount and type of waste generated. The quantification of a particular waste, such as scrap batteries from electric vehicles, is emerging research in Brazil. Using a mathematical model of time series, combined with EV sales, LIB service life, and mileage profiles, estimating the amount of lithium-ion battery scrap is possible. Through the statistical adjustment of the precision coefficients, the results indicate that the time series adhere to the prediction processes for both vehicle sales data and LIB scrap projections. Among the models analyzed, ARIMA is the one that shows the most assertiveness, as it presents the smallest errors. Forecasts of the annual quantity of EVs sold (2020–2030), as well as the annual forecast of LIB scrap (2020–2040), indicated that the number of scrap batteries generated is entirely out of step with vehicle sales data, proving the delayed effect on the generation of these residues (rebound effect).

A significant contribution is a methodology used to determine the useful life of the batteries. As LIBs have their life span determined by the number of cycles and since these cycles correspond to a certain duration of the vehicle’s autonomy, it is expected that, depending on each country and region’s mileage profile, these batteries will last longer or less time. This model can be used to calculate the LIB duration in any other country/region, using data specific to each location’s mileage profile.

Based on LIB scrap generation predictions, relevant information is obtained for decision-making in the SWM system. It is possible to implement reverse logistics programs for the battery industry, the scrap recycling industry, and the government, highlighting the importance of creating regulatory policies for this new battery market.

Acknowledgements The authors would like to thank Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES).

Author contribution João P. Cabral-Neto: conceptualization, methodology, validation, formal analysis, investigation, resources, data curation, and writing — original draft. Rejane M. M. Pimentel: conceptualization, methodology, validation, visualization, writing — review and editing, supervision, and project administration. Simone M. Santos: conceptualization, methodology, validation, visualization, writing — review and editing, supervision, and project administration. Maísa M. Silva: conceptualization, methodology, validation, visualization, data curation, and writing — review and editing.

Data availability Data is available at the National Association of Automotive Vehicle Manufacturers and the link is—https://anfavae.com.br/site/issues-in-excel/?lang=en.

Declarations

Ethical approval and consent to participate Not applicable.

Consent for publication The authors approved for publication.

Competing interests The authors declare no competing interests.

References

Assunção ARS (2016) Technical and economic feasibility of reusing electric vehicle batteries integrated with photovoltaic systems in the residential sector. First ed. FCTUC, Coimbra (in Portuguese)

Boston Consulting Group – BCG (2019) Electric car in Brazil: from zero to billions in 10 years. Época Negócios 151:1–5 (in Portuguese)

Brazil (2010) Lei 12.305/2010 - National Solid Waste Policy (NSWP). http://www.planalto.gov.br/ccivil_03/_ato2007-2010/2010/lei/112305.htm. Accessed 12 December 2019 (in Portuguese)

Brazil (2012) Lei 12.715 - Incentive program for technological innovation and densification of the production chain of automotive vehicles. http://www.planalto.gov.br/ccivil_03/_ato2011-2014/2012/lei/112715.htm. Accessed 12 March 2020 (in Portuguese)

Brazil (2018) Lei 13.755 - Rota 2030 Program - Mobility and Logistics. http://www.planalto.gov.br/ccivil_03/_ato2015-2018/2018/lei/13755.htm. Accessed 12 March 2020 (in Portuguese)

Cabral-Neto JP, Pimentel RMM, Santos SM, Silva MM (2020) Perspectives and challenges of vehicle electrification: an academic review. Revista Brasileira de Geografia Física 13: 2802–2819. https://doi.org/10.26848/rbgf.v13.i.6.p2802-2819

Caetano MO, Leon LG, Padilha DW, Gomes LP (2019) Risk analysis in the operation of electronic waste recycling plants (WEEE). Gestão e Produção 26:2. https://doi.org/10.1590/0104-530X3018-19

Castro CP, Consoni FL (2020) Diagnosis of environmental management scenarios for the use and final disposal of lithium batteries in electric vehicles. Revista Científica E-Locução 17:439–457 (in Portuguese)

Chang N-B, Lin YT (1997) An analysis of recycling impacts on solid waste generation by time series intervention modeling. Resour Conserv Recycl 19:165–186. https://doi.org/10.1016/S0921-3449(96)01187-1

Chang WJ, Lee GH, Cheon YJ, Kim JT, Lee SI, Kim J, Kim M, Park WJ, Lee YJ (2019) Direct observation of carboxymethyl cellulose and styrene–butadiene rubber binder distribution in practical graphite anodes for Li-ion batteries. ACS Appl Mater Interfaces 44:41330–41337. https://doi.org/10.1021/acsami.9b13803

Chen HW, Chang N-B (2000) Prediction of solid waste generation via grey fuzzy dynamic modeling. Resour Conserv Recycl 29:1–18. https://doi.org/10.1016/S0921-3449(99)00052-X
Cobo PA (2019) Converter design with current-doubler and synchronous rectification for LiFePO4 battery charging. First ed. UniCan, Cantabria

Conte AA (2016) Reverse logistic, recycling and eco-efficiency of the batteries: review. RBCIAMB 39:124–139. https://doi.org/10.5327/Z2176-947820167114

Diniz F (2019) Lithium: white oil. https://www.wattson.pt/2019/01/08/7908/. Accessed 20 March 2021 (in Portuguese)

Du J, Liu Y, Mo X, Li Y, Li J, Wu X, Ouyang M (2019) Impact of high-power charging on the durability and safety of lithium batteries used in long-range battery electric vehicles. Appl Energy 255:113793. https://doi.org/10.1016/j.apenergy.2019.113793

BEDP (2019) Ultra-fast charging network for electric vehicles in Brazil. https://www.edp.com.br/noticias/edp-anuncia-a-primeira-rede-de-recarga-ultrarrapida-de-veiculos-eletricos-do-brasil. Accessed 25 April 2020 (in Portuguese)

Faria DAO, Oliveira AL (2019) Considerations on the disposal and recycling of cells and batteries in Brazil. Revista Interface Tecnológica 16: 312–324. https://doi.org/10.3151/inf.1v6i2.667

General Motors - GM (2020) Bolt EV Technical Sheet. https://www.gm.comhrs/escapedcontent/05963.html. Accessed 12 April 2021

Geological Survey of Brazil - CPRM (2018) Assessment of lithium potential in Brazil. http://rigeo.cprm.gov.br/jspui/bitstream/doc/1764/1/evento_lito_brasil.pdf. Accessed 14 April 2020 (in Portuguese)

Greim P, Solomon AA, Breyer C (2020) Assessment of lithium criticality in the global energy transition and addressing policy gaps in transportation. Nat Commun 11:4570. https://doi.org/10.1038/s41467-020-18402-y

Impinnisi PR (2010) Batteries for EV BNDES Setorial 32:267–310 (in Portuguese)

International Electrotechnical Commission - IEC (2017) Norm IEC 62133-2:2017 - Lithium systems International Standard. https://standards.ieee.org/catalog/standards/ciec/0a993eb-9217-4766-a4d3-1f8ea13368b7/en-62133-2-2017. Accessed 28 April 2020

KBB Brasil (2019) Do you know how much mileage impacts the used car price? https://www.kbb.com.br/detalhes-noticia/quantia-metrica-destacada-carro-estado?id=1802. Accessed 27 January 2020 (in Portuguese)

Lebretot L, Andrady A (2019) Future scenarios of global plastic waste generation and disposal. Palgrave Commun 5:6. https://doi.org/10.1057/s41599-018-0212-7

McKenzie E (1984) General exponential smoothing and the equivalent ARMA process. J Forecast 3:333–344. https://10.1002/for.3980030312

Miao Y, Hynn P, Joonan AV, Yokochi A (2019) Current li-ion battery technologies in electric vehicles and opportunities for advancements. Energies 12:1074–1094. https://doi.org/10.3390/en12061074

Morettin PA, Toloi CM (2018) Time series analysis. Second ed. Blucher, São Paulo (in Portuguese)

National Association of Automotive Vehicle Manufacturers - ANFAVEA (2019) Vehicle Statistics. https://anfavea.com.br/site/issues-in-excel/?lang=en. Accessed 10 July 2021

National Department of Mineral Production - DNPM (2017) Lithium. ANM Sumário Mineral 37:126–128 (in Portuguese)

Navarro-Esbri J, Diamadopoulos E, Ginestar D (2002) Time series analysis and forecasting techniques for municipal solid waste management. Resour Conserv Recycl 35:201–214. https://doi.org/10.1016/S0921-3499(02)00002-2

Neto JC, Silva MM, Santos SM (2016) A time series model for estimating the generation of lead acid battery scrap. Clean Technol Environ Policy 18:1931–1943. https://doi.org/10.1007/s10098-016-1121-3

Pindyck RS, Rubinfeld DL (2000) Econometric models and economic forecasts, 4th edn. McGraw-Hill Education, New York

Santos SM, Cabral-Neto J, Silva MM (2019) Forecasting model to assess the potential of secondary lead production from lead acid battery scrap. Environ Sci Pollut Res 26:5782–5793. https://doi.org/10.1007/s11356-018-04118-6

Shim J-S, Rogers JA, Kang S-K (2021) Physically transient electronic materials and devices. Mater Sci Eng R Rep 145:100624. https://doi.org/10.1016/j.mser.2021.100624

Smiatek J, Heuer A, Winter M (2018) Properties of ion complexes and their impact on charge transport in organic solvent-based electrolyte solutions for lithium batteries: insights from a theoretical perspective. Batteries 4:62. https://doi.org/10.3390/batteries4040062

Sun J, Li J, Zhou T, Yang K, Wei S, Tang N, Dang N, Li H, Qiu X, Chen L (2016) Toxicity, a serious concern of thermal runaway from commercial li-ion battery. Nano Energy 27:313–319. https://doi.org/10.1016/j.nanoen.2016.06.031

Sun G, Yin X, Yang W, Song A, Jia C, Yang M, Du O, Ma Z, Shao G (2017) The effect of cation mixing controlled by thermal treatment duration on the electrochemical stability of lithium transition-metal oxides. Phys Chem Chem Phys 19:29886–29894. https://doi.org/10.1039/C7CP0553OG

Triola MF (2017) Introduction to statistics. Seventh ed. LTC, Rio de Janeiro (in Portuguese)

United States Geological Survey - USGS (2017) Mineral Commodity Summaries U.S. https://www.usgs.gov/centers/nmic/rare-earths-statistics-and-information. Accessed 12 April 2021

World Economic Forum - WEF (2016) The impact of autonomous cars in big cities. Exame 1118:11 (in Portuguese)

Xu L, Yilmaz HU, Wang Z, Pogani et W-R, Jochem P (2020) Greenhouse gas emissions of electric vehicles in Europe considering different charging strategies. Transp Res Part d: Transp Environ 87:102534. https://doi.org/10.1016/j.trrd.2020.102534

Yaffe RA, McGee M (2000) An introduction to time series analysis and forecasting: with applications of SAS® and SPSS®, 1st edn. Academic Press, New York

Publisher’s note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.