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Recycling and reusing batteries: A significant way for effective sustainability of FCEVs and EVs

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HIGHLIGHTS

- Battery recycling, which will play a key role in the next decade for vehicles, is figured out.
- Safety on recycling techniques were expressed crucially.
- Fuel Cell Electric Vehicles batteries and platinum minerals importance is discussed.
- Newer and future aspects on battery recycling/reusing of EVs and FCEVs were added.

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ABSTRACT

In the last 20 years, the transportation sector has enabled the technology to evolve in its direction with both environmental and energy efficiency in the use of electric and fuel cell vehicles. The two important components of these vehicles are the batteries and electric motors. The batteries are produced within a certain life cycle, and unfortunately it is not possible to use them without conversion/recycling. In this study, the crucial importance of battery recycling/reusing is underliying and last researches will be given about battery recycling, above next ten years. Recommendations and future forseen advices will be presented about the current state of battery recycling technology, how recycling systems exist in different batteries, and the future of battery recycling standart. As a result, battery recycling and reusing for fuel cell and electric vehicles is considered to be an important keypoint in terms of both envirenmontial, economical and technologial menner for the transportation sector in the next decades.

Introduction

Energy storage devices provide the energy necessity of the systems in order to fulfill the functionality of the technological devices. Almost every electronic device use a battery that assure its energy. Even though it goes back to 300 years ago, its technology has developed considerably and has taken its place in the world order. The first voltaic battery was created by Volta, by the chemical reaction of two elements and an electrolyte. Over the years, all electrical devices have developed their technology to use this unique “heart".

Batteries have started to be named with its created elements and they have increased the number of production and usage areas with the developing technology. Especially last two decades electrification practices that more respect the usage areas of fossil fuels in order to provide a more environmentally friendly world with increasing emissions and greenhouse gases. It has resulted in increasing the importance and use of electric vehicles in the automotive sector. According to Global EV Outlook 2022 [1], 16.5 million electric cars (*that tripling in just three years*) were on the world's roads. Fig. 1 [1] represented the global electric car stock between 2010 and 2021.

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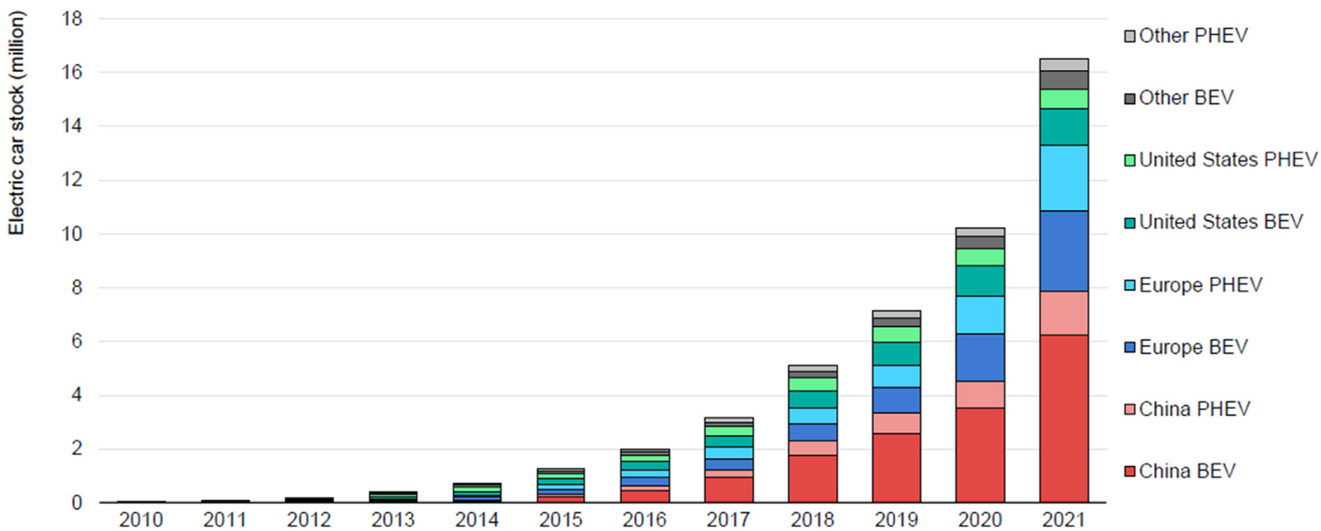

Fig. 1 – Global electric car stock; 2010–2021 [1].

Increasing interest in electric vehicles; constitutes a large market which included both vehicles and their components. In this study, battery recycling/reusing which is an important attention has drawn to a necessity that automobile sector will face in 10–12 years about batteries, that are the energy storage devices of these Electric Vehicles (EV, HEV (Hybrid Electric Vehicles), PHEV (Plug-in HEVs), FCEV (Fuel Cell EVs), FCHEV (Fuel Cell Hybrid EVs)). The types of batteries used in EVs have certain charging capacities, operating temperatures and intervals, charge-discharge states and ultimately a life cycle. Since the sources of the elements and electrolyte materials used in these batteries are limited; establishing the necessity and importance of battery recycling/reuse plants; is the main idea of this study.

Although different manufacturers prefer different batteries, they cannot be changed much in terms of their physicochemical properties. Mostly, EVs prefer the use of lithium ion batteries (LIB). The most important reason for this preference is listed as; high efficiency, relatively long life, satisfactory operating temperature range, functionally state of charge (SOC) and state of health (SOH) parameters and low discharge capabilities [23]. In an average LIB (60 kWh), the lists and weights of the key materials of EVs used, are given in Table 1 [2]. As it is seen clearly; average LIB is circa ~ 185 kg. When re-checked Fig. 1; emission suppression, COP26, considering the attitudes of the countries; EVs will continue to rise with the skyrocket. Considering that the LIB demand of global investors in 2030 is 9.300 GW-hours (GWh) [24] and if nearly 200 factories operate at full capacity; the lithium required for the production of these batteries reaches 3 million tons [25]. While the situation is so urgent for EV key minerals, it is vital importance of recycling and reusing EV batteries that takes its place in the supply-demand balance and supply chain. For this urgent manner, all stakeholders give extraordinary attention to EV battery recycling. Such a mini example, in terms of academia; (*search key word: battery recycling*) as of today's (*june 24, 2022*) checked of Sciencedirect (www.sciencedirect.com) search; there are 4436 studies on half of 2022, hence it was 5502 in 2021 full year. Detailed numbering studies analyses were figured out by Ref. [3].

Table 1 – 60 kWh LIB-weights of different components of EVs key materials [2].

[a]	NMC811	NMC523	NMC622	NCA+	LFP
Lithium	5 kg	7 kg	6 kg	6 kg	6 kg
Cobalt	5 kg	11 kg	11 kg	2 kg	0 kg
Nickel	39 kg	28 kg	32 kg	43 kg	0 kg
Manganese	5 kg	16 kg	10 kg	0 kg	0 kg
Graphite	45 kg	53 kg	50 kg	44 kg	66 kg
Aluminum	30 kg	35 kg	33 kg	30 kg	44 kg
Copper	20 kg	20 kg	19 kg	17 kg	26 kg
Steel	20 kg	20 kg	19 kg	17 kg	26 kg
Iron	0 kg	0 kg	0 kg	0 kg	41 kg

[a] NCM811: (80% nickel, 10% manganese, 10% cobalt), NCA+: Nickel Cobalt Aliminum Oxide, LFB: Lithium iron phosphate.

This study focuses the importance of battery recycling/reusing phonemenon. Differ from other studies [26–31], the author wants to fill the gap in the literature by focusing on three issues. First; underling the manner of "toxicity and hazaordous environmental factors to be considered in battery recycling processes", secondly "the importance of standardization by battery manufacturers to eliminate these production differences in battery recycling fabricating procedures" and lastly, "the status of platinum used in FCEV batteries and fuel cells components" will be considered with future recommendations.

Battery types of EVs and FCEVs

There are existing lots of battery types. In vechilar applications, it has been optimized the required power and the total empedance for better arrangement. Cell structure and battery packs of EVs were illustrated in Fig. 2 [4]. Last years, the sector of battery involved manufacturies tented to find other ways to obtain new technologies for production the batteries and

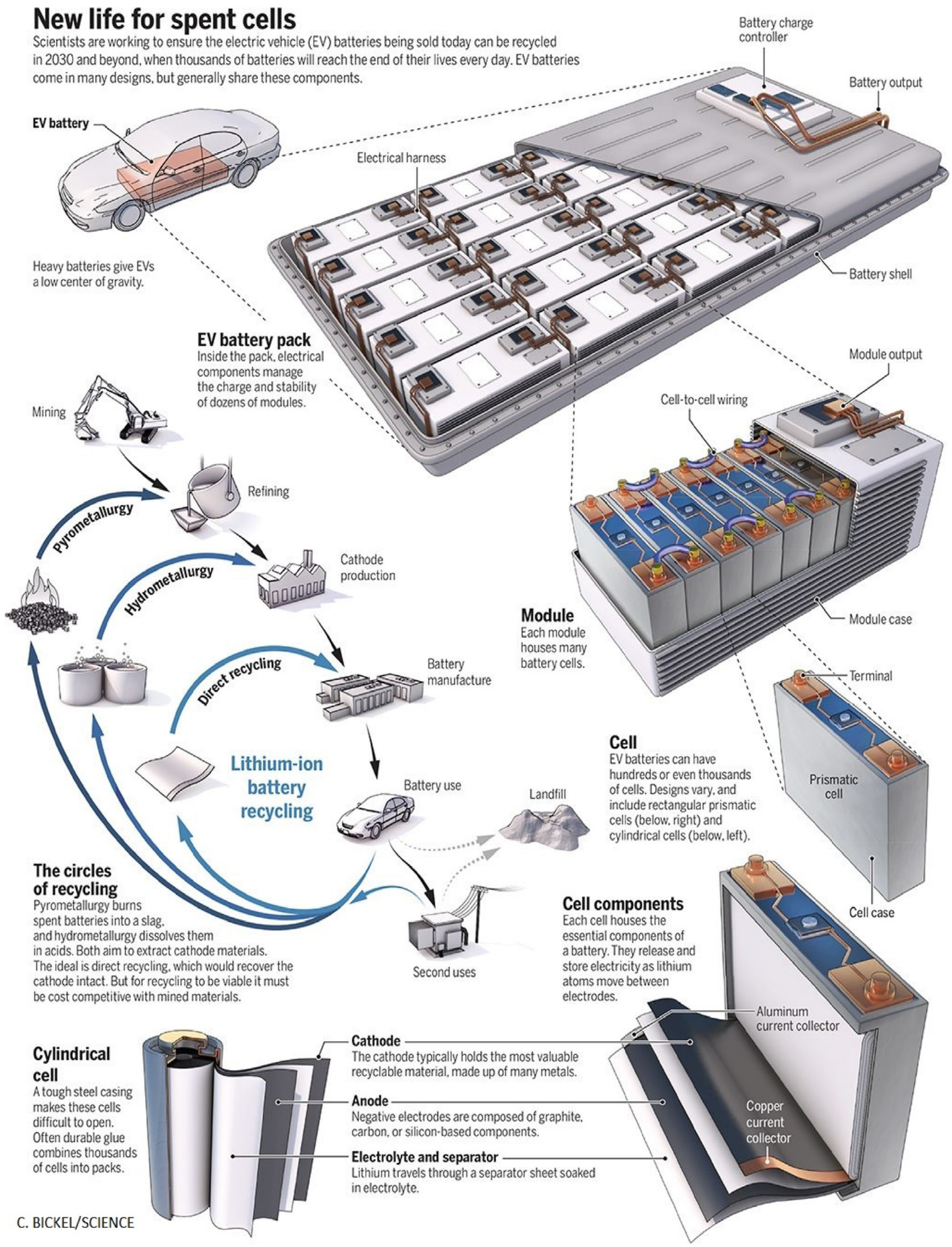

Fig. 2 – EVs cells, modules, packs and circles of recycling techniques and procedure [*illustrated by C. Bickel and collopse on one figure, faithfully to original, by* 4].

recycling the batteries. Especially; China, Japan, USA and Europa give hardly attention to "battery recycling" on their product forseens.

And in 2020, EU re-prepared the regulations of battery development and production with addition of recycling [5]. As already touched upon previously, battery metarials such as lithium, nickel, cobalt, manganes, copper, aliminium, etc were finite resoruces and large quantitiy of EV's supply, the manufacturers need to give attention to use them optimizated and reusing them sustainable. The top 5 companies and market shares were figured out in Table 2 [6,7].

With the developing technology, batteries with new materials is being tested in laboratory environments [8]. emphasizes that, in the near future; *sodium-ion, state batteries, lithium-sulfur batteries or lithium-air batteries* can be developed. There will be requireness for engineering development

Table 2 – Top 5 EV battery manufacturers and market share % [6,7].

Rank	Manufacturer Company	Served Automotive Company	% Market Share (2021)
1	CATL	BMW, Dongfeng MC, Honda, Tesla, VW, Volvo	32.5%
2	LG Energy Solution	GM, Group Renault, Stellantis, Tesla, Volvo,VW	21.5%
3	Panasonic	Tesla, Toyota	14.7%
4	BYD Co.	BYD, Ford	6.9%
5	Samsung SDI	BMW, Ford, VW	5.4%

and use for a certain period of time in order to produce batteries with different structures, equipped to vehicles. Although new studies are promising; Li-based batteries will continue to dominate EVs for the next 20 years [7]. Therefore, in order to handling for this development and acceleration to be both environmental and sustainable, battery recycling should be emphasized.

Battery recycling technology for EVs

In this substitle, the Li-based batteries recycling technology was indicated depply. In a basic term; if a battery recycled; it can be obtained from three main ways; i) pyrometallurgy, ii) hydrometallurgy and iii) direct recycling. The systematic and basic discrption is summirized by Castelvecchi [9,10] as; "*In a typical recycling plant, batteries are first shredded, which turns cells into a powdered mixture of all the materials used. That mix is then broken down into its elemental con-stituents, either by liquefying it in a smelter (pyrometallurgy) or by dissolving it in acid (hydrometallurgy). Finally, metals are pre-cipitated out of solution as salts.*"

These three main methods are; (which is illustrated in Fig. 2); defined in the studies included in references [1–22]; explained with both simple explanation and details. A detailed recycling procedure and types of recycling facilities illustrated in Fig. 3 by Ref. [11].

There are certain production stages that need attention in battery recycling processes. Batteries must be properly disassembled, especially in the first mechanically shredded section. Before this assembly; they must be fully discharged and "non-electric currentless" in order to be affected by any electrical activity [12]. mentioned as; battery discharging can be possible on two ways; that one is high ionic conductivity for short curcit battery (with pure water) and the second is more diffucult from the first, is electrical discharge.

At this point, it is necessary to mention one of the important issues of this study. While the battery suppliers produce the power storage according to their own manufacturing they use certain equipment and dimensions. Unfortunately, battery parts such as assembly, the location of the battery control unit, the stack status of the battery system, vary from manufacturer to manufacturer.

This clearly shows the necessity of performing the "identification & standardization procedure and barcode system before recycling", which is one of the important points in battery recycling.

After the de-assembling process is finished, pyro and hydro metallurgical processes are applied. With different leaching processes and different pretment techniques, the system goes into the separation phase, pyrometallurgy; it is the process of removing precious metals after a series of heat treatment applications. Hydrometallurgy, on the other hand, heals precious metals by using liquid chemicals. With the leaching process, it separates the ore and the main product by using liquid chemicals with solvent properties. Solvometallurgy (SX) is one of the methods used for the purification process [13]. also described this SX method as hybrid metallurgy (pyro & hydro).

In direct recycling, decomposition occurred with chemical structure changing. It is also called cathode-cathode recycling. More green and biological perspective view; biological processing can be added to recycling systems. In this one; microorganism leaching is used for extracting.

Comparison of each recycling procesess and merit & demerits of each processes tabled by Ref. [13].

On the other hand [32–34], indicate the key role of this crucial item with a case study and emphasized the social, economic, environmental aspects of recycling strategy.

Reuse opportunity of EV batteries

According to the authorities, the reuse of batteries or the second-use strategy in 2030 will be a major economic pathway. Like as in Ref. [10], where the waste management hierarchy was illustrated, and in most studies; coexistence of recycling and reuse tasks each other, shows how this sector will function in the future.

Firstly, in this subtitle, it is important for the integrity of the subject to refer to the Life Cycle Assessment (LCA) and EoL (End of Life), which researchers work intensively in most recycling studies.

Battery assurance in EVs guaranteed for 8–10 years or 100,000 km waranity. In Ref. [14]; two lifespan scenarios evaluated with three battery discard probability functions and three scenarios of EV sale projections and concluded that the short-term EoL volume (by 2025) can be particularly sensitive to the lifespan parameter [3]. figured out from seventy studies that; cost, environmental aspects and regulations studied heavily but less technological approach in EoL [15]. indicated that; keeping average battery lifetimes at 10 years were not realistic in battery sector. A detailed review is prepared by Ref. [16] that emphasize the importance of the second use of EV batteries. Life cycle impacts of battery production for different functional units figured out by Ref. [17] and chronological summary of battery recycling policies tabled for different countries. Process-based LCA for quantitatively analyze the environmental impacts of traction LIB recycling task was studied by Ref. [18]. [19,20 and 21] refs given detailed key information on LCA.

The expensive initial investment costs of battery recycling factories, the use of batteries with a long life in vehicles

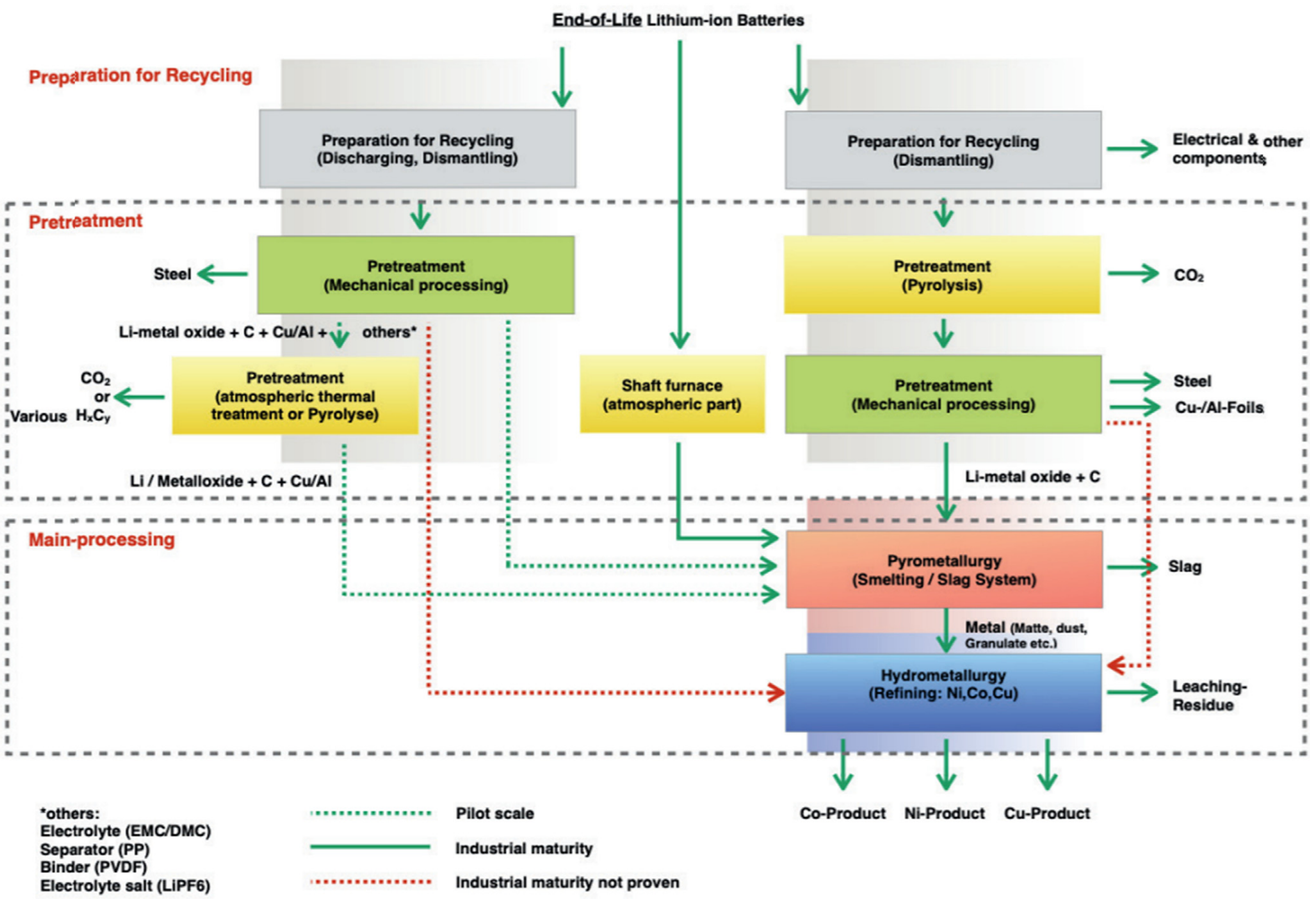

Fig. 3 – Lithium ion battery recycling paths [*faithfully to original, by* 11].

alternatively usage on household/industrial energy storage tool can be listed as reuse areas of EV batteries. Batteries, which can be feasible for reusing, have considered with efficiency below 60% or SoH between 50% and 30%. It is necessary to avoid short circuits that will affect the battery life in this reuse. On the other hand, in terms of energy and sustainability scale, it is much more effective way that first reuse the batteries and then put them in the battery recycling procedure.

Barriers of recycling/reusing and hazardous/toxicological manners

Although process differences have advantages and disadvantages among themselves, battery recycling has important barriers that should be considered as a system. These barriers should be determined in detail, and drawbacks should eliminate.

With the increasing EV population, governments should bring discounted practices to businesses that will doing this type of recycling fabrics and provide financial and land support for the EV key materials recycling. Ensuring safety in battery recycling facilities and its suitable for automation and robot-based integration should built as much as possible.

In this regard, it is necessary to establish a certain standard in the first production of batteries, and accordingly reuse or recycling roadmaps should be planned.

[22] mentioned that how to weld and join EV batteries; reported that the temperature parameter is especially important while the battery is on-road, and that the batteries should be welded with special laser joining. While the battery, whose pack formed with this type of welded connection, is being prepared for recycling, human-supported solutions were required. While these processes are conducted, risks of fire, poisoning, explosion, and flashing can be occurred.

In addition, liquid solutions used during leaching, especially in hydrometallurgy and direct processing, may produce harmful particles with chemical interaction. They should be disposed of and should not harm humans.

Additionally, the capital and economical concerns are important like as recycling/reusing facilities. It should be taken into consideration of mining or recycling the materials which are keypoints of EVs batteries. Diffrences from other types of batteries (lead-acid, alkaline and nickel-cadmiyum); it has to be more attention to LiOn batteries when it recycling in terms of cobalt and nickels “toxicity”, “fire and explosion” and “short circuited” [11].

Conclusion and future recommendations

All authorities are concerned about climate change and environmental emission situations. 2017 Paris agreement, COP26's and others; have been making significant efforts in recent years to minimize the effects of emissions and climate change. In the transportation sector, it contributes to this situation and directs its fossil fuel-powered vehicles to electrified ones. Electric vehicle (EV includes; HEV, PHEV, BEV, FCEV, FCHEV) manufacturing is increasing exponentially every year. One of the most crucial elements of electric vehicles; the heart of it, is the batteries. EV batteries created by using important metals and elements. For automotive suppliers, battery manufacturers and governments; in the next 10–15 years, the recycling/reuse of batteries will be a particularly important requirement. It is very essential to prepare for these developments in time, that effects positively both the sustainability of EVs, their impact on the environment, the correct and efficient use of energy, and economic gaining's.

Technical infrastructure, state of technology and key point analysis related to the recycling/reusing of batteries discussed deeply, in this study. Novelty of this study is figured out and lightened an attention to fill the gap in the literature by focusing on three issues.

Firstly; underling the manner of "toxicity and hazaordous environmental factors to be considered in battery recycling processes", secondly "the importance of standardization by battery manufacturers to eliminate these production differences in battery recycling fabricating procedures" and lastly, "the status of platinum used in FCEV batteries and fuel cells components" will be considered with future recommendations. In addition, the necessity of establishing this technology both in Türkiye with globally and it is in the economic/environmental context.

In addition, the future suggestions can be listed as.

- Global battery production and accordingly increasing supply of precious metals need to be mining in the most effective way and used sparingly.
- Battery recycling facilities need to progress with a certain standard and regulation.
- Hybrid/alternative recycling processes should be diversified in the light of new technological developments at the laboratory scale.
- Battery manufacturers and OEMs should feature certain standards in battery production.
- "Identification & standardization procedure of EV batteries with barcode" systems will start before recycling.
- EV/FCEV producing countries need to focus on this transformation, as EV battery recycling will create a sector and economy in terms of supply/demand in the coming decades.
- Processes will be carried out in fully automatic factories, price reductions and incentives for vehicles powered by recycling batteries will contribute to the faster growth and sustainability of this system.
- Studies should be done on the systems and raw materials, such as platinum, used in fuel cell EVs. The electricity necessity of EVs are still met in power plants that they using fossil fuels. As the people of the world, one of the biggest clean energy sources will be hydrogen in reaching our climate and emission targets.

As a result, in the next two decades, it is crucial corner for all counterparts of transportation sector that do not to miss this "recycling/reusing transformation" both in the market and in technology in terms of Türkiye's own vehicle (Togg) and for the world EV market.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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