






Review

Electric Vehicles—An Overview of Current Issues— Part 1—Environmental Impact, Source of Energy, Recycling, and Second Life of Battery

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Abstract: The rapid transition to electric-drive vehicles is taking place globally. Most automakers are adding electric models to their lineups to prepare for the new electric future. From the analysis of the automotive market, it is evident that there is a growing interest in such vehicles. They are expected to account for half the models released after 2030. Electric-drive vehicles include battery-electric vehicles. As indicated in the research literature and emphasized by experts, electric vehicles (EVs) are supposed to be an environmentally friendly alternative to conventional vehicles. The rising number and variety of EVs contribute to a better understanding of their performance. With more EVs on the market, there are problems to be solved and challenges to overcome. This article is the first part of a two-article series reviewing the strengths and weaknesses of EVs. The article analyzes the environmental effects of EVs at each stage of their life cycle, compares large- and small-scale recycling methods, and explores the potential applications of second-life batteries. This article is an attempt to find out how environmentally friendly EVs are.

Keywords: electric vehicle; electric drive; EV safety; environment protection; source of energy; LCA; recycling; second life of batteries



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1. Introduction

The use of electric propulsion in motor vehicles is not a new idea. The pioneer of electrically powered vehicles was Thomas Deavenport, who built a small vehicle powered by a Volta galvanic battery in 1834 [1]. The development of the lead-acid battery in 1859 by Gaston Planté, and the construction of an alternator in 1866 by Warner von Siemens had a significant impact on the development of vehicles. The initial electrically powered vehicle function was based on a tricycle developed by Percy and Ayton in 1882, which was powered by batteries with a weight of approximately 45 kg. The operation of electric vehicles at the time, compared to steam vehicles, revealed many advantages, where the key ones included: quiet operation, ease of handling and driving, good dynamics, ease of motor installation (with smaller dimensions compared to steam), and simplification of the drive train. By the end of the 19th century, electric carriages for hire and small two-seater electric vehicles with a range of approximately 48 km appeared in some European cities. In 1898, the electric vehicle set a new speed record of 63.2 km/h. In addition to developments in the technology of the vehicles themselves, there have been developments in the accompanying infrastructure (e.g., chargers called Electrant—short for electric hydrant)

and energy storage technology (e.g., nickel–iron Edison cells). Electric vehicles of the time however did not replace horse-drawn vehicles. The main reasons for that were the short range of the vehicles, the high manufacturing costs, and the need to frequently recharge the exceptionally heavy batteries. Electric vehicles returned in the 1970s. The fuel crisis, combined with increasing air quality problems in cities has given rise to the search for alternatives to internal combustion engine vehicles (ICEVs). The EV1 presented by General Motors in 1996 was a breakthrough design. The vehicle remained in production until 1999 and enjoyed a positive reputation among users. Another design of importance in the history of electric cars was the Roadster presented by Tesla Motors in 2007. The vehicle was equipped with lithium-ion batteries and had a range of nearly 400 km on a single charge. Today, most car manufacturers have electric models in their range. There are also corporations entering the market that produce only electric vehicles, such as, for instance, Tesla Motors and BYD Auto.

Electric-powered vehicles are gaining an increasing share of the passenger and commercial vehicle market. Electric vehicles include battery electric cars (BEVs), vehicles in which an internal combustion engine cooperates with an electric drive (HEV—Hybrid Electric Vehicles, PHEV—Plug-in Hybrid Electric Vehicles) or vehicles equipped with fuel cells or electrochemical batteries (FCEV—Fuel Cell Electric Vehicles). Electric drives in various types of vehicles are subject to constant research and improvement. Vehicles in which electric drives cooperate with other energy sources require complex systems related to energy flow management or the battery charging process [2]. For example, in FCEV technology, analyses related to thermal safety and degradation of fuel cells, aging suppression to trade-off energy sources durability, and hydrogen mass consumption [3,4].

Several challenges can be identified ahead of electric propulsion technology at present with optimism regarding its future. New technologies applied to electric vehicle propulsion systems have the potential to make a significant contribution to the development of intelligent and sustainable transport and to significantly reduce energy consumption and emissions under various road conditions [5,6].

Today, electric cars account for 15% of all passenger cars currently used on a world scale. The increasing number of cars currently in use allows for testing the electric drive technology under regular operating conditions. User feedback and data derived from electronic on-board systems installed in the vehicles provide valuable information for manufacturers and serve as the basis for further EV development. However, every so often, some voices and situations make it clear that electric cars need significant improvements.

However, you should be aware that with the popularization of electric vehicles, certain problems also arise. Undoubtedly, the advantages of EVs include zero emissions of pollutants and noise. However, there will be environmental concerns. Selected issues include the impact of EVs on the environment during the production phase, the purity of the electricity used to charge these vehicles, and the risks associated with recycling.

For the most part, scientific papers on EVs focus on issues related to EV operation (i.e., efficiency of the drive under given conditions, accuracy in estimating range and energy consumption, lithium-ion battery technology), cost of use and purchase, factors relevant to purchase, battery charging technology, or planning the location of charging infrastructure. This paper aims to present the environmental aspects of the life cycle of an electric vehicle. This work attempts to assess whether the production, use, and recycling phases of an electric vehicle impose a burden on the environment and natural resources. This article provides a critical analysis of the effects EVs may have on the environment during their life cycle. It attempts to answer the following questions:

- Are EVs environmentally friendly over their entire life cycle?
- Can EVs be considered zero-emission vehicles?
- Can maximum efficiency be achieved while reclaiming the critical raw materials (CRMs) from spent EV batteries?
- Will solutions like ‘second-life batteries’ reduce the negative impact of EVs on the environment?

The critical study of EVs presented in this article aims to highlight the fact that the long-term implications of electromobility may be in some aspects negative. The analysis was based only on data found in the research literature.

The review aimed to highlight the following problems that the development of electric vehicles must face:

- The environmentally friendly electric vehicles assessment significantly depends on the emission assessment method used,
- A small share of renewable energy sources in the electricity production structure has a significant impact on the environmental friendliness of electric vehicles,
- Recycling of electric vehicle batteries should ensure maximum recovery of rare earth metals,
- There is a need to develop second-life solutions used on a global scale that will extend the life of electric vehicle batteries.

The following literature review methodology was used. The literature review was completed in August 2023 using various databases (mainly Web of Science and Scopus), press releases, and the European Union legal acts database. The literature was identified using: a title, abstract, and keywords in accordance with the search profile of the mentioned literature sources. The focus was on the following terms: electric vehicles/cars, battery electric vehicles, environmental impact of electric vehicles/cars, electric vehicles/cars battery recycling, battery second life, and recycling process.

The article is divided into two parts. In this—Part 1, the electric drive is presented in terms of its use in motor vehicles. The advantages of this propulsion system and the risks arising at the manufacturing, operating, and recycling stages of the vehicle are indicated herein. The remaining, particularly important issues concerning the availability and types of infrastructure dedicated to EVs and the safety of EV use are presented in Part 2.

This article discusses the selected problems related to the impact on the natural environment posed by the production, use, and disposal process of EVs; it also discusses the structure of electricity generation sources in selected countries; the methods of recycling Li-ion batteries as well as their potential, and subsequent applications. The analysis of the areas mentioned above presents a unique perspective related to the review nature of the article.

The article is divided into chapters. Section 2 assesses the environmental impact of EVs. Attention was focused on the entire life cycle of the electric vehicle, i.e., from the sourcing of materials through to the production of the assemblies and vehicle, its operation, and disposal. The manufacturing processes of electric and conventional vehicles were compared mainly in terms of CO₂ emissions. Section 3 seeks to answer the question of how green an electric vehicle is. To answer this question, an analysis was made of the contribution of individual energy generation sources to the total electricity generation process. The concept of the energy mix was introduced for this purpose. This section presents a detailed analysis of the energy mix carried out for European Union countries. Section 4 describes EV battery recycling and reusability. EU regulations related to recycling efficiency targets for Li-ion batteries were cited. The most popular commercial recycling methods for Li-ion batteries are described and compared. The possibility of a second life for batteries from EVs was identified and provided together with the citations of such solutions.

2. Assessment of the Environmental Impact of EVs

When analyzing the impact of motorization on the environment, it is possible to distinguish impact categories that define the types of environmental effects. Examples of impact categories include climate change, ozone depletion, eutrophication, acidification, smog formation, poisoning of ecosystems, deterioration of human health, reduction in fossil fuel, mineral and water resources, and conversion of land with natural ecosystems. A vehicle fleet consisting solely of hybrid vehicles which still use the internal combustion engine may not be sufficient to meet the CO₂ emission value targets as specified in the

European Green Deal. The solution is to increase the share of electric vehicles among all vehicles in the EU.

Electric vehicles are described as zero-emission and eco-friendly, as they do not emit any dust and gas compounds at the point of use (this is the Tank-to-Wheel (TTW) phase). Therefore, in the comparison of an electric car with a hybrid and conventional vehicle during ICEV operation, the EV seems as the most 'green'. In order to objectively assess the environmental impact of a vehicle, emissions during manufacture and disposal (known as WTW—Well-to-Wheel) must be taken into account in addition to its useful life. However, numerous studies assessing the environmental impact of BEVs overlooked these stages.

The period from the sourcing of materials, production, and assembly through to the operation and disposal of the vehicle is referred to as their life cycle. By considering the life cycle of a vehicle, it is possible to have a closer look at the emissions at each stage of the cycle (LCA method—Life Cycle Assessment) and to estimate the total cost (LCC—Life Cycle Cost). The vehicle life cycle includes the following stages [7,8]:

- Design stage;
- The manufacturing stage, which also includes the extraction of raw materials, the manufacture of components and parts;
- The stage of assembling the vehicle and transporting it to the storage facility or the end user;
- The operational phase, consisting of the use and maintenance of the vehicle;
- The disposal stage, including dismantling, sorting, partial reuse, recycling, or landfilling.

LCA takes into account the total emissions from the sourcing of the materials for a product to its disposal or so-called 'cradle-to-grave' [9]. While assessing the life cycle of a vehicle, the main input information includes fuels and other consumables, minerals, construction materials, electricity, and heat. The key products, however, include emissions, solid and liquid waste, noise, and electromagnetic radiation. This makes it possible to identify and quantify the materials used and forms of energy and waste introduced into the environment as well as to assess the environmental impact of these materials, energy, and waste.

Another form of help in assessing the environmental impact of an electric vehicle includes the estimation of the 'carbon footprint' (CFP). This method includes estimating the total amount of greenhouse gas emissions produced at each stage of a vehicle's life cycle. The carbon footprint is defined as the total value of CO₂ and other greenhouse gas emissions converted into CO₂ equivalents, which arise from the extraction of the raw materials necessary to manufacture the vehicle, through its production, use, and disposal (so-called from-cradle-to-grave) [10–12].

The initial phases of the vehicle life cycle can be described as 'from-cradle-to-gate'. These are the stages that take into account the sourcing of materials for vehicle components and parts, their manufacture, the assembly of components, and the complete vehicle. Taking into account the extraction of metal ores and materials, the production of parts and components, and their assembly for all vehicle components, excluding the engine and drivetrain, the CO₂ emission levels for electric and internal combustion vehicles are similar [13]. A comparative study dealing with the lifetime of electric and conventional VW Caddy vehicles [13], based on the data provided in the Ecoinvent Database, indicates that batteries are the major contributor to high CO₂ emissions associated with EV production (Figure 1).

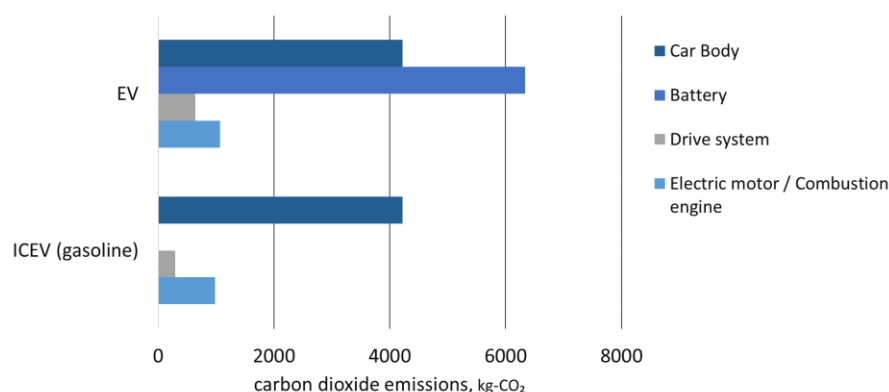


Figure 1. Cumulative carbon dioxide emissions in the production phase, in kg-CO₂ (based on [13]).

In the production of a complete vehicle, the ICEV has about 60% lower CO₂ emissions than the electric vehicle [14]. That is due to the high level of greenhouse gas emissions in the production of lithium-ion batteries, electric traction motors, and electronic controllers. The authors of the paper [15] also noted that EVs display higher mercury emissions in the production stage. It was found that with current technologies, the lifecycle mercury emissions of electric vehicles with a range of 300 miles are 92% higher than those of conventional internal combustion engine vehicles.

At the EV production stage, the electrochemical battery is one of the most critical components in terms of greenhouse gas emissions in this area. According to research presented in the paper [16], the global warming potential (an indicator to quantify the greenhouse effect of a substance) associated with the production of electric vehicles is between 87 and 95 g of carbon dioxide equivalent per kilometer (g CO₂-eq/km). In the case of the production of a conventionally powered vehicle, this value was 43 g CO₂-eq/km and is about twice lower than for EVs. The higher carbon dioxide levels from the production of EVs are compensated for by lowering the CO₂ emissions from their use. This, however, is dependent on the emissions related to the structure of electricity production.

Figure 1 shows the total carbon dioxide emissions during the production of an electric and gasoline vehicle.

Battery production contributes to between 35% and 41% of the global warming potential at the EV manufacturing stage [16]. The battery manufacturing process is responsible for a significant proportion of the emissions due to the highly energy-intensive processes required to obtain the materials used to make the batteries. Replacing conventional vehicles with electric vehicles represents a significant change in natural resource use patterns around the world. In particular, the global demand required for battery production of lithium, cobalt, graphite, other rare minerals, and earth elements is expected to significantly increase [17]. Moreover, many works point to an unstable supply chain for the raw materials used in the production of lithium-ion batteries. The uneven distribution of the basic minerals needed to produce Li-ion may be affected by various types of geopolitical and economic turmoil. The extraction and processing of the raw materials of rare minerals and earth elements are scattered around the world, unlike oil deposits. The fossil fuel supply chain has already been established and remains relatively stable, while the Li-ion supply chain is under development and continues to evolve rapidly [18–20].

Considering the ever-changing manufacturing technologies manufacturing, it is difficult to fully estimate the values of greenhouse gas and energy emissions in the production of powertrain components and elements. Based on a review of 51 papers regarding the LCA of conventional and electric vehicles, the authors of the paper [21] concluded that there are numerous analyses and differences in the environmental impact of EV and ICEV production. The work [22], based on a broad review of work on LCA of vehicles with different powertrain types, concludes that the assessment of environmental impacts in combination with resource procurement, material processing, and parts manufacturing is an area where knowledge is lacking and requires further research. However, it should

be mentioned that electric powertrain components require significantly larger volumes of raw materials and rare earth metals during production compared to ICEVs. While driving, BEVs emit virtually no harmful particulate and gaseous emissions (except for the wear products, e.g., friction linings, and tires). This results in low overall greenhouse gas emissions during the operational phase. As much as 75–95% of the life cycle GHG emissions of ICEVs arise from the combustion of fuel during operation [23]. In the use phase, the environmental performance of EVs is strongly dependent on the size and energy capacity of the battery, and the type and method of power generation used to charge the battery [24,25]. As the results of the analyses presented in the paper [26] have shown, increasing the energy density of batteries by 100 Wh/kg can reduce air pollutant emissions over the life of an EV by 14–20%. It is important that EVs have the longest possible lifetime mileage, as close as possible to that of an internal combustion vehicle. Significant environmental benefits can thus be achieved [27,28]. However, the battery life is much shorter than that of the vehicle. This carries with it the need to change the battery during the use of an electric vehicle. The energy storage efficiency of a lithium-ion battery decreases with time because its degradation progresses with time. The user is thus faced with the dilemma of whether to replace the battery or the vehicle.

Figure 2 shows the total CO₂ emissions by electric (VW e-Golf) and gasoline vehicles (VW Golf VII 1.4 TSI 140 KM) over their life cycle. The calculations of the cumulative CO₂ emissions associated with both types of vehicles took into account the European conditions (average “European mix”). The calculations cover the whole EV lifespan, from production to disposal, with a long period of use of 10 years and a total of 150,000 km of driving.

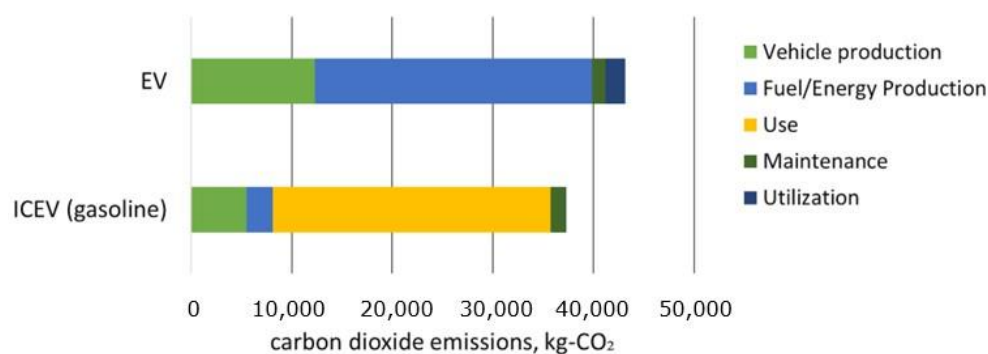


Figure 2. Emissions in the entire life cycle of a vehicle (150,000 km, 10 years) in kg-CO₂ (based on [13]).

During the use of EVs, an important issue is how the electricity is produced, as this is the main cause of the environmental impact of EVs during the operational phase. Only when global electricity generation is clean and essentially free of CO₂ emissions from fossil fuels will electric vehicles be able to realize their full potential in reducing greenhouse gas emissions from transport.

In the end-of-life phase, the end-of-life vehicle is taken directly to a dismantling station, where it is dismantled. The automotive waste generated in such a project is selected and then disposed of by recovering parts and recycling raw materials. The essence of recycling is to minimize waste while reducing the need for raw materials and energy by incorporating recovered raw materials and materials into recycling. A wide variety of materials can be sourced from end-of-life vehicles; these materials include ferrous metals (71%), glass (3%), plastics (8%), rubber materials (5%), and light metals (7%) [29–32]. Electric vehicle powertrain components contain valuable resources that can be recycled or remanufactured. However, in particular, in the case of electric motors and lithium-ion battery systems, it involves the need to adapt the dismantling and recycling process [33,34].

As reported in the paper [35], more than 1.3 million tonnes of batteries from electric vehicles will be taken out of service by 2025. Such a large number of end-of-life Li-ion batteries pose a risk of serious environmental pollution and waste of resources. It is

therefore necessary to introduce systems and chains for the effective collection and disposal of batteries. The battery recycling process depends on the type of battery, necessitating the development of a battery-specific approach [36,37]. According to the authors of the paper [38], the recycling of the steel, aluminum, and cathode material of the traction battery contributes to 61%, 13%, and 20%, respectively, of the total greenhouse gas value reduction produced during the life cycle of an electric vehicle.

In the long term, battery recycling may also play a key role in reducing demand for CRMs (c), more specifically, lithium and nickel. Recycled metals could meet 5.2–11.3% of the demand for new materials [39]. In particular, since, as stated in the work no. [40], there exists a potential risk of depletion of nickel, cobalt, and lithium reserves by 2050 [41].

Battery packs recovered from end-of-life electric vehicles can be reused in stationary applications, e.g., as part of the so-called ‘smart grid’ or as energy storage for photovoltaic systems [42,43]. Using electric vehicle batteries to store energy and save energy during peak hours is a strategy that can provide savings for residential users, thereby reducing the load on the electricity grid. Based on an extensive literature review of work on battery recycling from electric vehicles, the authors of the paper [44] concluded that a holistic approach to the integrated assessment of closed-loop and environmental aspects of batteries is, however, lacking. It was noted that in addition to repurposing and recycling, the EV life cycle should also include repair and maintenance, retrofitting, and/or battery reconditioning.

The analysis provides an answer to the first question, i.e., whether or not EVs can be regarded as environmentally friendly over their whole life cycle. In summary, the results of LCA analyses of vehicles with different types of powertrains presented in many papers show that the massive expansion of electrification of transport could shift the impact of greenhouse gas emissions to environmental burdens such as particulate matter (PM_x) formation, acidification or resource depletion [45,46]. The shift of environmental burdens from the use phase to the extraction phase of raw materials and production implies a delocalization of impacts, which poses new challenges at environmental, social, and legal levels. Approximately 80% of the environmental burden of an EV’s life cycle depends on both the battery and the energy consumption during operation [47], where the battery accounts for 40–50% of total greenhouse gas emissions [48]. For the purpose of being able to talk about the positive impact of EVs on the environment, these vehicles should have a lower environmental impact than conventional vehicles during their lifetime. In the final phase of the EV life cycle, the possibility of recycling is limited due to the chemical composition of the batteries and the drive components [49,50]. Electric vehicles have been used in road transport for a relatively brief period compared to vehicles driven by an internal combustion engine. The analysis of the entire life cycle of vehicles allows assessing which type is more eco-friendly. The current decisions of lawmakers encourage the widespread use of electric vehicles. For that reason, the next decade is expected to bring improvements in the EV production process, as they currently generate more than twice as much CO₂ as the production process of vehicles with internal combustion engines.

3. The Energy Mix

As demonstrated in numerous publications, the use of EVs can make a significant contribution to reducing emissions. As emission levels are still high in a great number of large city centers, works are underway to identify emission sources in detail together with the manner of reducing them [51–53].

During use, electric cars do not generate emissions in this respect. However, these emissions may arise at the site of electric electricity generation. Therefore, the answer to the question: *how green is an electric vehicle?*—is not easy. In the countries where electric vehicles are in use, the share of clean energy available for installations varies. Indeed, the environmental performance of an electric vehicle is directly related to the emissions of harmful compounds [54] generated during the generation of the electricity required to charge the vehicle’s batteries.

The share of energy generated from different sources is specified by the so-called energy mix. The energy mix is the structure (share) of individual sources in the production of such energy. The energy mix is constantly changing [55]. Electricity may come from a variety of sources: renewable and non-renewable, emitting and non-emitting [56,57].

In most countries, electricity may be generated by plants using non-renewable fossil fuels: coal (hard coal, lignite), oil, natural gas, nuclear, and renewable energy sources: hydroelectric plants, wind power [58], photovoltaic farms, etc.

Depending on the specific characteristics of a country, its location, availability of fossil fuels, terrain, or atmospheric factors, the shares of each can vary significantly [59,60].

Within the EU, the emphasis on clean renewable energy generation is linked to the introduction of Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast) [61]. The European Commission has adopted a set of proposals to align the EU's climate, energy, transport, and taxation policies aiming to reduce net greenhouse gas (GHG) emissions by at least 55% by 2030 compared to the levels registered in the 1990s [62]. All 27 EU Member States have committed to making the EU the first climate-neutral area by 2050. In 2020, the EU's target was a reduction of 20% in GHG. In fact, an average reduction of 31.7% was achieved within the EU [54]. Thus, the objective has been achieved. The 50% GHG reduction level was recorded in Europe by four countries: Estonia, Latvia, Lithuania, and Romania.

Renewable energy may also have an impact on the economies of the other Member States [56,60,63,64]. The ETC Carbon Emission Trade scheme related to the cost of CO₂ allowances also has a major impact on emitting energy sources; hence, the need for changes in the structure of energy procurement [65].

In several countries, works are carried out to define the direction of energy systems, specifically regarding renewable energy sources [66,67]. In the EU, national energy participation issues are also being addressed. Articles [68,69] analyzed the impact of fossil sources on the energy mix. Based on Eurostat data, the energy mix in the European Union in 2021 was dominated by renewable energy—49%, nuclear energy—31.3% and solid fossil fuels—18.1%, natural gas—6.4%, crude oil—3.1%. It is however important to remember that within the EU, energy production only covered 44% of the energy needs; the remaining 56% were imports [70].

Energy production varies considerably between the EU Member States. Among European countries, there are several countries where the share of energy obtained from renewable sources is very high, e.g., Malta and Iceland—(100%), Latvia (99.5%), and Cyprus (95.9%). Nuclear energy has a high share in France (75.6%), Belgium (70.4%) and Slovakia (58.3%). Electricity drawn from the combustion of solid fuels dominates in Poland at 71.5% [71], Estonia at 55.9%, and the Czech Republic at 44.5%. Natural gas is the main source of electricity in the Netherlands, as it accounts for 58.4%, while in Norway, it is 47%, and in Ireland, it is 41.6%. Crude oil supplemented the energy balance in most countries, including Norway (45.4%), Denmark (34.7%), and Croatia (16%) [70].

Such diverse shares of the energy mix are the result of country-specific characteristics, locations, deposits, and policies. A summary of the data for each country is presented in Figure 3.

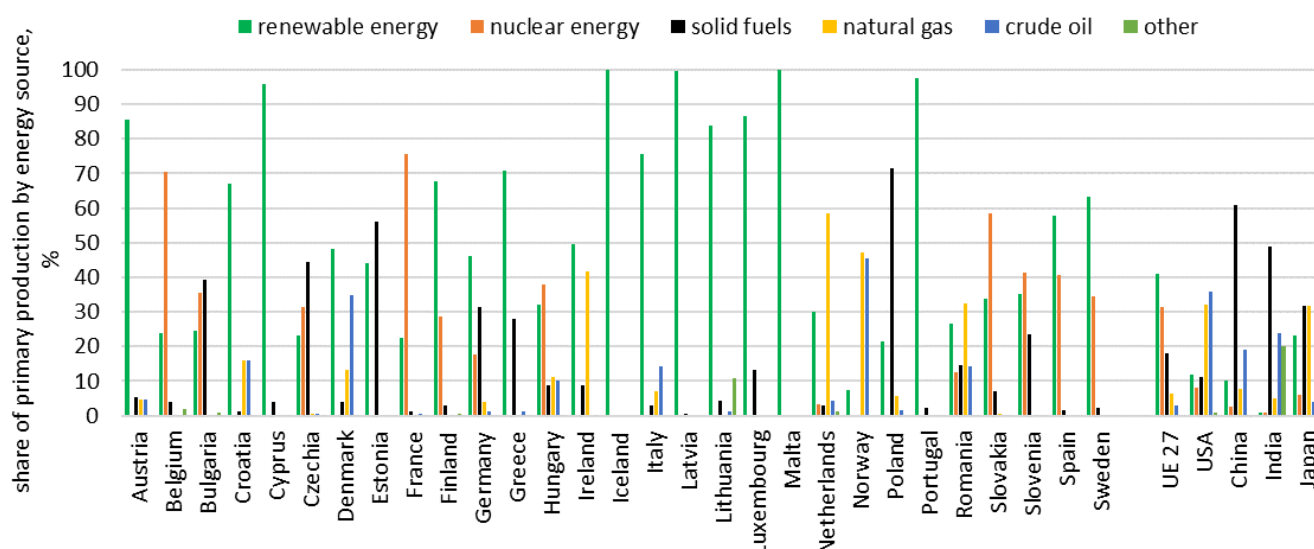


Figure 3. The share of primary production by energy source (based on data from [72–76]).

Electricity production issues are being addressed worldwide. In the UEA, works are underway to identify an appropriate energy mix by 2030 which would guarantee energy security for the projected population, keeping energy prices at a certain level while minimizing CO₂ emissions [70]. Considering the fact that China [73], the USA [74], Japan [75] and India [76] are among the largest electricity consumers in the world, many publications also address these issues [77–80]. Therefore, it is worth pointing to the relatively low share of renewable energy in the USA and China Energy Mix—about 10%. This is four times smaller than average value for the EU 27. In China or India, the participation of energy from solid fuels is quite high. The high share of energy from renewable energy sources reduces CO₂ emissions during electricity production. The more it produces energy from renewable energy sources, the greener electric cars become. This results in less environmental pollution when charging the battery.

To power EVs, we use locally produced electricity. Thus, the answer to the next question addressed in this article, i.e., whether EVs are zero-emission vehicles, is negative. Since the charging of EVs adds to the overall electricity demand in the country where they are used, EVs are a real strain on the national power grid, and consequently, the national energy mix.

In light of the above, the technology allowing the production of electricity that generates low-emissions or renewable electricity sources used in EVs are areas of exceptional importance. Replacing combustion engine vehicles with EVs is going to require the generation of a significant amount of electricity to satisfy transport needs. Currently, the methods of generating electricity vary between different countries or parts of the world as they depend mainly on natural resources, climate conditions as well as regional policy. For this reason, appropriate legal regulations may appear in this area, bearing similarity to those that are currently in force with respect to vehicles with internal combustion engines (which determine the amount of bio-components in the fuel) while in effect stimulating the development of the green energy market. Although electric vehicles do not emit greenhouse gases while in operation, they display high emissions in both the production and recycling stages and require significant energy input.

The current global trend (or process) of replacing fossil fuels with low-emission or renewable energy sources for the purpose of meeting the demands posed by electrified transport is going to require significant financial outlays and may thus cause the extension of the process throughout time.

4. EV Battery Recycling and Second-Life

Lithium-ion batteries (LIBs) have emerged as the battery of choice used in hybrid and electric cars as a result of the continuing process of improvement and refinement of energy storage devices [72,81]. The main advantages of LIBs include [82] their small size, relatively long lifespan, high energy density, high number of recharges (which translates into long service life), low maintenance costs, high power, low weight, no memory effect and low self-discharge rates per day. With these qualities, lithium-ion batteries provide vehicles with sufficiently high torque to achieve high speeds and a relatively long driving range.

If the LIBs capacity falls below 80%, they are believed to be no longer eligible for powering hybrid vehicles [81]. These batteries can be recycled or used in other applications. Recycling provides opportunities for reusing products, securing the supply chain, and overcoming dependency on imported raw materials.

The recycling process becomes particularly important as it is estimated that the demand for key raw materials that are essential for battery production will increase, while their availability will decrease (due to finite/exhaustible resources) [83].

Based on research on chemical compounds (continuing since the 1980s) that can be used in accumulators/batteries to power engines or electric motors in BEVs or HEVs, the following types of accumulators/batteries have been developed: sodium–beta, nickel–zinc, nickel–iron (Edison cells), nickel–cadmium (Ni–Cd), lead–acid, nickel metal hydride (Ni–MH), lithium–ion (Li-ion), lithium polymer, lithium–ion polymer, lithium–nickel–manganese, lithium–magnesium, sodium–nickel–chloride, sodium–sulfur (high-temperature battery) and several other types. Currently, Ni–MH and lithium batteries stay on top of the competition [82,84].

4.1. Selected EU Legal Regulations

One of the main reasons why an increasing number of vehicles are fitted with electric or hybrid drive systems is that manufacturers are legally required to meet stringent exhaust emission standards, which are complemented by an increasing body of legislation aimed to replace combustion engines with zero-emission engines. In an effort to boost recycling and promote environmental measures, the European Union policy makers have introduced laws imposing an obligation on vehicle manufacturers to keep reusability, recyclability, and recoverability requirements in mind when designing new vehicles, e.g., to employ solutions to make recycling and recovery easier [81,84,85]. New vehicles may only be sold in the EU if they may be reused and/or recycled to a minimum of 85% by weight or reused and/or recovered to a minimum of 95% by weight. Also, critical raw materials (CRMs) include lithium and cobalt, which are both vital for the production of batteries, while the European Union is heavily dependent on the importation of these materials from outside the EU [86,87]. In order to eliminate bottlenecks in the supply chains and diversify the supply sources of critical raw materials, the EU focuses on the recovery of materials in the recycling process on the path to a circular economy. In accordance with Directive 2006/66/EC, as amended [88], the EU Member States shall take necessary measures to maximize the separate collection of waste batteries and accumulators and to minimize the disposal of batteries and accumulators as mixed municipal waste in order to achieve a high level of recycling for all waste batteries and accumulators. The directive also requires that manufacturers design their appliances in such a way that waste batteries and accumulators can be readily removed.

According to [89], sustainable batteries and vehicles underpin the mobility of the future. To progress swiftly in enhancing the sustainability of the emerging battery and accumulator value chain for electro-mobility and boost the circular potential of all batteries, a new regulatory framework should be introduced. Work on the new legislation to introduce changes in the handling of batteries and used batteries was initiated in 2020. The published legislative proposal [90] is designed to repeal and replace the current Directive 2006/66/EC by Regulation. It is worth noting that in the EU legal order, a regulation and a directive have different legal meanings. A regulation has general application and is directly applicable to all EU members. A directive is binding on each EU member to which

it is addressed, leaving the national authorities free to choose the forms and means as to the result.

The draft regulation is one of the instruments for implementing the European Green Deal. The target recycling efficiency for portable lithium batteries is scheduled to reach 65% by 2025 and 70% by 2030 (by weight). The regulation also proposes recovery levels of raw materials at all recycling levels: 35% by 2026 and 70% by 2030 for lithium. According to the current directive, the recycling rates of materials from waste batteries and accumulators is assumed at 50% by weight. The regulation establishes extended producer responsibility for batteries that are supplied in a Member State for the first time. It entails a requirement for producers of batteries to ensure the attainment of the waste management obligations. The regulation also defines the waste status and the requirements for repurposed (second-life) batteries and the regeneration of industrial batteries and EV batteries (second-life cycle).

4.2. Recycling

Waste vehicles and EV batteries pose a serious threat to the natural environment and are a valuable source of various metals, including rare earth metals [91]. The recycling of electronics classified as waste has become essential for environmental reasons. To recycle BEVs, PHEVs, and HEVs and more sustainably use scarce resources, it is necessary to dismantle electronic and electrical components, which are then redirected for further use or material recovery [84]. By recycling materials used in batteries and accumulators, the EU can become less dependent on the imports of raw materials in the future. Moreover, approximately 70% of the world's lithium deposits are located in South America (Argentina, Bolivia, Chile). Geopolitical instability in this area may affect the supply conditions and the price of batteries and, consequently, the production costs and the final price of electric vehicles [92]. The exploitation of scarce and hard-to-reach resources will affect the cost of battery production and increase the environmental footprint, which makes the recycling of electric car batteries even more important [93]. Lithium-ion batteries are most commonly used in BEVs and PHEVs, while nickel–metal hydride (Ni-MH) batteries are commonly used in HEVs [94]. Table 1 lists examples of battery recycling processes.

Table 1. The recycling process of Ni-MH and Li-ion batteries [84].

Nickel–Metal Hydride Battery (NI-MH)	Lithium–Ion Battery (Li-Ion)
<ul style="list-style-type: none"> • sorting, • draining residual energy, 	
<ul style="list-style-type: none"> • thermal decomposition of organic components, mainly plastics, • extraction metallurgy, i.e., melting and purification of metals, • recovery of nickel and iron for use in the production of stainless steel, • shipping metal hydride components as slag (low-value material used as road aggregate etc.) 	<ul style="list-style-type: none"> • cooling the battery to a temperature of at least $-160\text{ }^{\circ}\text{C}$ using liquid nitrogen (lithium, which is explosive at room temperature, is considered relatively safe at this temperature), • battery cutting and shredding, • separation of shredded material (sorting), • lithium conversion to lithium carbonate or lithium oxide, • neutralization of electrolytes into stable compounds, • cobalt recovery from lithium cobalt oxide (Li CoCO_2), if present
<p>Additional processes:</p> <ul style="list-style-type: none"> • cadmium oxidation at $760\text{ }^{\circ}\text{C}$, • distillation at $900\text{ }^{\circ}\text{C}$ for 24 h, • purification and preparation of Ni-Fe residues. 	

As shown in Table 1, the recycling process for the two types of batteries considered involves not only relatively simple (e.g., sorting) but also complex activities, which may need to be performed under special conditions.

The recycling of LIBs is primarily designed to recover elements contained in the active electrode materials, i.e., lithium, cobalt, graphite, nickel, and manganese [95]. A detailed review of LIBs recycling processes is presented in the literature [83,96].

The recycling process involves pre-treatment to make battery recycling more efficient and to reduce energy consumption downstream. Laboratory-scale pre-treatment typically involves battery discharge (24 h bath in, e.g., distilled water), dismantling (usually manually), and separation [83]. Pre-treatment at the industrial scale typically includes discharge (same as laboratory-scale pre-treatment), dismantling (manual or mechanical), dry or wet grinding and crushing in a protective atmosphere (this is necessary for, e.g., hydrometallurgical recycling), classification (the size of fractions obtained reflects the content of materials eligible for recovery), separation (size-dependent fraction separation), dissolution (of active materials that still remain attached to the current collectors), and thermal treatment, e.g., vacuum pyrolysis. Thermal processing can be skipped or applied before or after mechanical methods as there are many approaches to mechanical pre-treatment in LIBs recycling. It is worth noting that recycled batteries are not flammable during vacuum pyrolysis and can be safely processed mechanically without the risk of fire [83]. The products of pre-treatment are partly separated metals, plastics, and black mass. In some of the pre-treatment processes, electrolytes can also be recovered from batteries [97]. Electrolyte recovery is a novelty in the recycling process. Example of black mass composition (% by weight) [98]:

- Lithium compounds: 2–6%;
- Cobalt: 5–20%;
- Nickel: 5–15%;
- Copper: 3–10%;
- Aluminum: 1–5%;
- Iron: 1–5%;
- Manganese: 2–10%;
- Residue: graphite with flakes of iron, aluminum, and copper.

Black mass is industrially processed using pyrometallurgical and/or hydrometallurgical methods [81–83]. A high-temperature furnace is used for the pyrometallurgical recycling process to reduce and refine valuable metals. Roasting, calcination, and smelting are the most common techniques used for pyrometallurgy [83]. Battery components decompose at high temperatures (usually up to 1400 °C). This method is designed to separate and collect precious metals, mainly cobalt, nickel, and copper, using thermodynamic reactions [99]. In conditions of high temperature, organic solvents contained in the batteries, lithium and fluoride, evaporate and are not recovered [100]. Hydrometallurgy recycling involves physical and chemical operations in liquid media. The recycling of batteries by pyrometallurgy may include the following steps: leaching (dissolving or leaching metals with an alkaline or acidic agent); removal of impurities (clarification of the leaching solution); and the recovery of nickel, cobalt, manganese, and lithium [83]. Metals dissolved in a liquid solution can then be precipitated individually, usually as salts, which requires additional chemical treatment to obtain the correct composition before they can be reused in batteries [99]. Electrochemical (electrohydrometallurgical) methods can also be used to recover valuable metals from LIBs [99]. The selective extraction and recovery of high-purity metals is carried out by electroplating using a leaching solution containing dissolved metals. The electro-hydrometallurgy reduces the pollution of water used in recycling processes.

The disadvantage of the current metallurgical processes is the environmental impact, i.e., the emission of toxins into the air or a significant amount of sewage generated [83]. The advantages and disadvantages of both mainstream industrial methods are compared in Table 2. The comparison presents the advantages and disadvantages of LIBs recycling methods most frequently found in the literature. Common names for LIBs recycling mainly refer to the names of the companies that use them. Selected LIBs recycling companies and the methods they use are listed in Table 3.

Table 2. Advantages and disadvantages of industrial recycling processes involving pyrometallurgical and hydrometallurgical methods [83,99].

	Pyrometallurgy	Hydrometallurgy
Advantages	<ul style="list-style-type: none"> Recycling of Li-ion batteries representing various compositions/configurations Pre-treatment is not mandatory High metal recovery 	<ul style="list-style-type: none"> High efficiency of metal recovery No emission of toxins into the air High purity of recycled products
	<ul style="list-style-type: none"> Lithium–iron–phosphate (LFP) batteries are not recyclable High energy intensity (high energy consumption) Purification measures are necessary to prevent toxin emissions into the air Graphite and binders are lost (not recovered) 	<ul style="list-style-type: none"> Mechanical pre-treatment is mandatory High water consumption Anode materials are not recyclable

Table 3. Selected LIBs recycling companies and the processes used [81,83,96–99].

Method Used	Process/Company Name	State
Pyrometallurgical, hydrometallurgical	Umicore	Belgium
Mechanical	uRecycle	Sweden
Electro-hydrometallurgical	AquaMetals	USA
Hydrometallurgical	Valibat	France
Hydrometallurgical	Brunp	China
Mechanical, Hydrometallurgical	Duesenfeld	Germany
Mechanical, Hydrometallurgical	Retriev	Canada, USA

As can be seen from Table 2, where the battery recycling methods are compared, hydrometallurgical processing is the most widely used. A key benefit of this approach is the high effectiveness of the process, high purity of the recycled materials, relatively low energy consumption, and non-toxic emissions. The data in Table 3 showing the global LIB recycling leaders and the methods they use reveal an increase in the popularity of hydrometallurgical processing.

Direct recycling is a new method of recycling, which is currently performed at the laboratory scale. The recycling process consists of multiple physical and chemical steps characterized by low energy consumption [81,99]. In this method, the cathode needs to be carefully separated from the rest of the battery, which usually requires manual work due to variations in the design of batteries. For recycling to be effective, an individual approach needs to be employed to cater to the diversity of battery structures and chemical compositions. Biological technologies using microorganisms also raise high hopes as a new exciting recycling method [81].

The above considerations indicate that only part of the materials can be recycled irrespective of which battery recycling method is used. EV batteries are characterized by a complex structure, which contains materials with supplies that are or may be at risk in the near future (as they may receive a status of CRMs, i.e., Critical Raw Materials). For that reason, it is necessary to improve the technology which is going to allow us to obtain the largest possible share of materials through recycling used batteries. In the near future, it seems that recycling companies may become important partners in the automotive sector. Replacing vehicles driven by internal combustion engines with EVs is going to require the development of efficient recycling processes for the purpose of ensuring the recovery of exhaustible minerals. Considering the varying structure and chemical composition of EV

batteries, it is also necessary to normalize and standardize the batteries used in electric vehicles in the near future. This, on the other hand, brings forth another question: are vehicle manufacturers prepared to cooperate in this specific area and should lawmakers initiate them?

4.3. The Second Life of a Battery

According to [100], the second life of a product is any action aimed at reusing products or its components that are not waste for any other purpose than the first use. This is the overarching goal of the circular economy as it allows the maintenance of the value of products while minimizing the generation of waste. In the EU, the priorities for products are in descending order of priority:

- Extending the product's service life;
- Avoiding waste generation;
- Re-use and second life;
- Recycling.

According to [100], before deciding to send the batteries to recycling, the EV batteries are subject to a diagnosis. The diagnosis determines if the batteries' operational life can be extended and if it is appropriate a waste-prevention measure. There are many prospective applications for battery reuse, including applications related to the use of batteries for electricity storage ranging from residential purposes to applications for urban electromobility [93]. To address the issue of a growing number of electric vehicle models and batteries, automakers may be designing their EVs with second-life applications in mind, as the supply of second-life batteries for stationary applications is projected to exceed 200 GW hours per year by 2030 [101].

The United States Advanced Battery Consortium (USABC) tests operated by the US Council for Automotive Research (USCAR) are one way to determine the service life of batteries used in BEVs. The USABC was established in 1991 to promote the research and development of electrochemical energy storage systems. USABC regulatory documents specify the end of life (EoL) of a battery if the following criteria are met [102,103]: (1) the delivered batteries (module, cells) retain less than 80% of their original capacity, (2) the maximum peak power is less than 80% of the rated power at 80% depth of discharge. A dynamic stress test (DST) is used to test for compliance with the first criterion, and the battery power in the second criterion is determined using the peak power test.

The following factors have a direct impact on battery aging: operating temperature, depth of discharge (DoD), discharge rate (C-rate), state of charge (SoC), and time. Increasing the battery capacity will improve the battery service life and the battery cycles will have a lower DoD; the lower the C-rate, the longer the service life and the lower the operating temperature [104]. In most cases, large capacity batteries are not required for EVs to support the current driving routines, i.e., the average battery capacity exceeds (about 10 times) total daily energy use in battery-powered electric passenger cars, which translates in an ineffective use of resources for battery construction [104].

Battery aging, manifested by a decrease in its capacity and power, is one of the key challenges in LIBs [97]. The first modern electric vehicles had a driving range of up to approx. 100 km and batteries with a capacity of 16–24 kWh. Manufacturers were concerned about battery aging and the inability to meet customer transport requirements, and they set the EoL for these batteries at around 80% [97]. Meanwhile, the capacity of batteries used in vehicles has changed with the growing number of electric cars produced. Initially, the battery capacity was 16 kWh and 24 kWh. With decreasing production costs, new vehicles driving on roads were fitted with batteries with a capacity of 30, 40, 70, and 90 kWh [104].

So, should the 80% criterion be obligatorily applied to LIBs? The decision on battery EoL rests solely with the vehicle user and should take into account the vehicle's maintenance and driving routines. There are two approaches to using battery systems for grid applications [82]:

- Stationary storage applications of second-life batteries (electricity storage);

- Vehicle-to-grid (V2G), in which a battery remains in the vehicle and is used for energy storage to be returned to the grid.

Stationary second-life applications of EV batteries can be divided into two groups [93]: integration with the national energy grid (e.g., for seasonal energy storage and distribution, integration with renewable energy sources, grid regulation), and end-user-oriented applications (e.g., energy management, transport solutions, integration with distributed solutions using renewable energy sources in various areas, e.g., construction, services, residential) [93]. Rechargeable battery systems are recognized as one of the most promising solutions for generating electricity from renewable energy sources [82], which presents a potential opportunity to reuse withdrawn batteries that were used to power electric vehicles. To meet the energy requirements, more than one battery from an electric vehicle will be required in most cases, and their heterogeneity is a drawback. Problems with the collection and second life of batteries in mobile and stationary energy storage applications can be traced to the high diversity (heterogeneity) of battery models, forms, chemical compositions, electrical properties, and state of health (SoH) [93,104].

The specificity of battery reuse depends on the rate and reason (e.g., aging, accident) of phasing out electric vehicles and is independent of the decision maker who changes the original purpose of the battery [93]. Once retired, most EV batteries will have a SoH higher than 75% over the next 20 years, which opens up a market for companies to give EV batteries a second life. However, battery reuse is an option that, given the growing market of electric vehicles, will quickly cater to the demand for stationary energy storage [104].

The second life of EV batteries can evolve in the following directions [93,105]:

- Direct reuse—lower costs, no or little adaptability to connect to other batteries;
- Battery dismantling to the module level—versatile reuse options; a new battery management system (BMS) and control systems need to be used;
- Battery dismantling to the cell level—most often implemented by regeneration companies, high versatility of applications, high costs (more labor-intensive processes), selection of cells depending on their SoH.

In the EV battery reuse model, batteries are collected after the end of their first life, at which point the first selection takes place (Figure 4) [98]. Damaged batteries are recycled, while the remaining ones are handed over to regeneration plants, where they are tested to determine their SoH. Batteries with an SoH above 88% can be directly reused again as spare parts in their original application. Batteries with an SoH of 75–88% are suitable to be repurposed for stationary energy storage applications or other transportation services with lower power requirements and demands on the battery performance (power source for hybrid trucks in urban driving). Batteries with an SoH below 75% can be dismantled into modules or cells for repurposing in less demanding applications, for example as a power source for portable computers, mobile systems to help people (e.g., cleaning robots), electric vehicles with low requirements (e.g., electric bicycles, golf vehicles, forklifts). Possible applications for EV battery second life are presented in Figure 5.

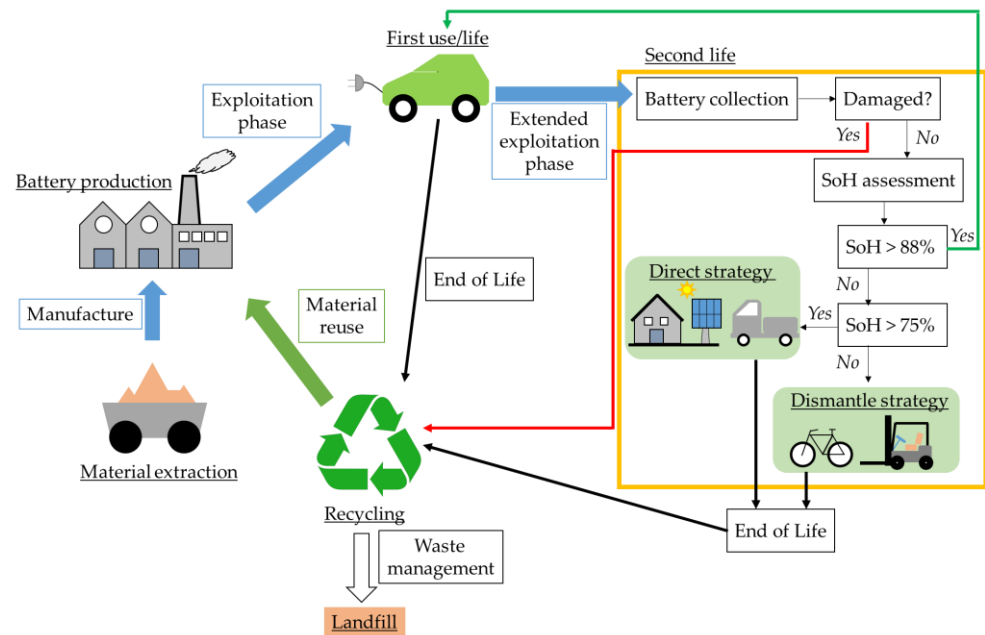


Figure 4. Battery electric life in a circular economy and diagram of decision making in LiBs second life (based on [93,105]).

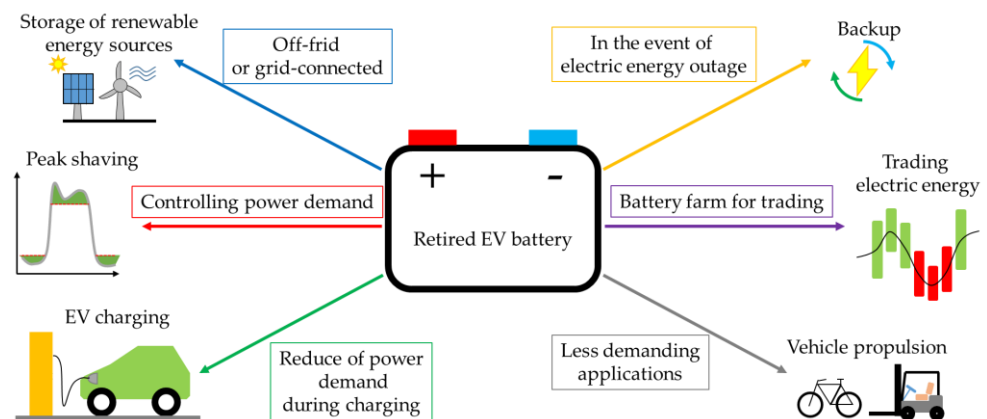


Figure 5. Battery selected possible applications of used EV batteries (based on [106]).

Examples of EV batteries second-life applications:

- 13 MWh energy storage installed at a recycling facility in Lünen (Germany) [107–109]—in 2015, Daimler AG, The Mobility House, GETEC, and REMONDIS started the 13 MWh battery storage project. The stationary storage unit is composed of over 1000 used batteries from electric vehicles. The installation is the demonstrator of potential secondary use.
- Nissan Leaf batteries used for commercial distributed stationary energy storage systems [101,110–112]—in 2010; Nissan in cooperation with Sumitomo Corporation established 4R ENERGY Corporation (joint venture) to reuse battery packs from the Nissan Leaf for stationary storage systems. According to the companies, the second life of batteries is aimed at increasing sustainability and is referred to as “4R business” (Reuse, Refabricate, Resell, Recycle). In 2015, Nissan Motor Company and Green Charge Networks (commercial energy storage systems supplier) collaborated to implement commercial energy storage using second-life Nissan Leaf batteries. The first unit of this type was installed at a Nissan supplier to meet peak electricity demand.
- BMW and MINI batteries as mobile power units [113,114]—in 2020, BMW Group UK announced a cooperation with Off-Grid Energy. Retired BMW and MINI batteries,

which can no longer efficiently be used in EVs, were adapted to create mobile power units. The first prototype unit has a 40 kWh capacity with a 7.2 kW fast charge.

- Chevrolet Volt batteries used as energy storage for lighting used at the GM's Enterprise Data Center [115]—in 2015, GM released news about the retired Chevrolet Volt batteries provided electricity to help keep light in the building. The second-life battery application was included in the grid of renewable energy sources (two 2 kW wind turbines and a 74 kW solar array).
- Stationary energy storage based on Renault vehicle batteries [102,116]—in 2018, the Renault Group announced the launch of the stationary energy battery storage project called Advanced Battery Storage. The project is based on retired Renault Group electric vehicle batteries. The stationary energy battery storage acts as a buffer to help manage the discrepancy between the supply and demand of electric energy. The project is set to be deployed in Europe to reach a capacity of 70 MWh.
- Stationary energy storage based on Kia vehicle batteries [117]—automaker Kia and Deutsche Bahn (Germany's rail and logistics company) have partnered to use retired Kia EV batteries to create efficient and cost-effective energy storage systems. The developed energy storage units are modular and can be used in many different applications, e.g., collecting surplus electricity from photovoltaic systems or, as part of a distributed system, supplying energy throughout the day to Deutsche Bahn depots where trains are prepared for operation. The first pilot project was launched at the EUREF Berlin campus in July 2022.
- The energy storage at EV recharging stations and buildings based on Volvo vehicle batteries [118]—Volvo Buses, in cooperation with Stena Property and BatteryLoop, have developed energy storage systems based on retired bus batteries used in charging stations and residential buildings. Batteries are used to store renewable energy for residential complexes, e.g., Fyrklövern in Gothenburg.
- Nissan Leaf batteries used for energy storage at Amsterdam ArenA [118]—the energy storage with a capacity of 4 MWh is used to provide appropriate support in crisis situations when events are taking place at the stadium. The storage is powered by renewable energy sources. Previously, diesel generators were used for this purpose.
- BMW i3 batteries as energy storage for renewable energy sources at the manufacturing site where this model is produced [118].

In [119], the following three main factors were identified to determine a battery's second life: battery ownership, cross-industry partnerships, and government support. The factors were identified based on research conducted covering innovative business models of various stakeholders of the electric vehicle industry (electric car manufacturer, recycling company, charging infrastructure supplier, and joint venture company dealing with the second use of batteries). There is an important prerequisite for second-life business models: *Who is responsible for the EoL of EV batteries?* Clear global regulations regarding liability for retired EV batteries will initiate large-scale second-life solutions. Moreover, reusing retired EV batteries for secondary uses delays their recycling phase. Extending battery life also helps reduce waste and resource exploitation. Solutions for reusing used EV batteries therefore become a link between the energy sector. The profitability of second-life solutions in the energy sector is determined, among others, by regulations regarding the range of energy prices during peak hours. The lack of a range of energy prices during peak hours may limit the economic viability of second-life solutions. Start-up FreeWire Technology introduces an innovative business model for charging services that provides the first solution combining electric vehicle charging with grid-level energy management by creating a network of grid-adapted mobile electric vehicle chargers. The start-up uses used Nissan Leaf batteries supplied by 4R Energy (joint venture, industry partnerships between Nissan and Sumitomo). The second use of batteries is therefore a catalyst for innovation in business models.

From the point of view of a company (e.g., supplier of energy storage solutions, EV manufacturer), the second life of retired EV batteries makes sense if it allows reducing costs

and extend the battery life. In [106], four business model scenarios were analyzed taking into account the principles of the circular economy:

- No. 1—production and use of batteries in the vehicle and recycling of used batteries—Original Equipment Manufacturer (OEM) uses non-standard batteries (not regulated by external regulations). Used batteries after their first life are collected by dismantlers (cooperating with the OEM) and sent for recycling.
- No. 2—production and use of batteries in the vehicle and improved recycling—the recycler collects batteries from workshops or dismantling points. The recycling company uses an automated process to handle large volumes of used batteries.
- No. 3—production and use of batteries in a vehicle, repair and reuse in a vehicle, and recycling—after their first life, batteries are subjected to diagnostics (by the workshop worker) or dismantling to assess their condition and the possibility of reuse. In cooperation with the OEM, the battery is regenerated or repaired and then used in the same or other vehicle (with lower requirements). Batteries that cannot be repaired are sent for recycling.
- No. 4—production and the use of batteries in a vehicle, repair, and reuse in various applications, and recycling—after removing the battery from the vehicle, it is assessed in terms of condition and the possibility of its reuse. Unlike model no. 3, early diagnostics allows you to determine second-life applications, which allows you to reduce maintenance and transportation costs because the reclaimed battery goes to the right place.

Model No. 1 is mainly aimed at optimizing the profits of OEM and EV manufacturers without taking actions aimed at the second life of the battery. Model No. 2 is burdened with uncertainty due to the unknown structure and chemical composition of future EV batteries. Model No. 3 may be used in the vehicle segment whose customers are fleet operators. Model No. 4 requires close cooperation throughout the entire chain.

Government support is important for second-life applications. The problem has been noticed in the EU, and regulation [90] will specify the extended manufacturer liability for batteries delivered in member countries for the first time. Extended producer responsibility includes a requirement for battery manufacturers to ensure that waste management obligations are met. The regulation will also specify when a battery will have the status of waste and requirements related to the use for other purposes and regeneration of industrial batteries and electric vehicle batteries (second life cycle).

Decommissioned batteries used in electric vehicles which no longer meet the requirements for their original use can be successfully used in less demanding applications, as presented above. The lack of legal regulations and requirements for extending the lifespan of used EV batteries means that they are treated as waste to be recycled. The current trends in the development of the battery recycling sector show that they have a chance to become an important element within the energy sector (for instance, energy storage) in the years to come. The transport industry solutions in less demanding applications, such as bicycles and electric motorcycles, are still underestimated. Such scenarios for the life cycle of an EV battery requires solutions at the design stage that are going to allow for both the first- and second-life applications of the product. It is also worth noting that postponing recycling allows for the development of more efficient recovery methods of CRMs.

5. Conclusions

The continuing growth in popularity of EVs in all countries of the world and the reported future restriction of registration of combustion engine vehicles in EU countries means that EVs are now being considered as the main mode of propulsion in vehicles of the near future. The various financial incentives and subsidies applied by countries to facilitate the purchase of electric cars are stimulating the growth of EV sales and contributing to an increased share of EVs in the automotive market. A significant portion of the literature is about the indisputable advantages of electric propulsion. However, considering the site

of operation and local conditions, it is possible to identify certain problems that may arise during their use and that need to be resolved in the near future.

Considering the widely reported advantages of EVs, the paper aimed to discuss aspects related to the production, use, and decommissioning of EVs. The critical analysis of EVs presented in this article aimed to answer four questions: Are EVs environmentally friendly over their entire life cycle? Can EVs be considered zero-emission vehicles? Can maximum efficiency be achieved while reclaiming the critical raw materials (CRMs) from spent EV batteries? Will solutions like 'second-life batteries' reduce the negative impact of EVs on the environment? From a review of the research literature on the subject, it can be concluded that over their whole life cycle, EVs, just like ICEVs, have a negative impact on the environment mainly because of their reliance on critical raw materials and the production of GHGs, causing harm to living organisms. Unlike conventional vehicles, EVs have a negative impact on the environment not only during the extraction of raw materials but also at the vehicle production, use, and recycling stages. The most problematic is the production and disposal of the components of the electric transmission system, particularly lithium-ion batteries.

The work is divided into two parts, which include a discussion of both the benefits but also some of the risks of using these vehicles. This first part identifies the environmental issues associated with the entire life cycle of an EV. An electric vehicle and battery recycling system are also presented. Electric vehicles are now one of the proposed solutions aiming to reduce greenhouse gas emissions in transport as a global effect.

The main question we were guided by when writing this paper is: is an electric car fully ecological? The answer to this question is not obvious. Therefore, in order to fully assess the environmental friendliness of EVs, the entire life cycle of the car was analyzed. An attempt to identify the main threats related to the use of EVs may constitute the basis for taking actions aimed at eliminating them.

The share of individual sources in electricity production in EU countries (energy mix) is also discussed. Unfortunately, at the stage of use, the level of ecology of EV vehicles is directly dependent on the method of obtaining electrical energy, and therefore in countries where energy produced is obtained from fossil sources, it is still difficult to achieve high reduction in emissions. Unfortunately, this can mean that the combined environmental performance ratings of an electric vehicle may not be as 'ideal'. Activities of many countries aimed at accelerating energy transformation are an opportunity for increasing the share of EVs and reducing the ecological costs of their use. From this aspect, the article demonstrates the vital importance of the manner in which electricity is generated/sourced and the use of renewable ('clean') energy sources in both the production and operation phases of EVs. In terms of, 'green energy,' there is great variation between countries because energy is obtained from a variety of sources. In the European Union, the energy mix is dominated on average by renewable energy—49% and nuclear energy—31.3%. However, due to their location and local conditions of the countries, these sources vary greatly. For instance, Malta and Iceland have 100% renewable energy sources; on the other hand, fossil fuels such as coal are mainly used by Poland (71.5%), Estonia (55.9%), or the Czech Republic (44.5%), while natural gas is mostly used in the Netherlands (58.4%). The analyses of the energy mix of EU countries lead to the conclusion that in countries that predominantly use fossil fuels for energy production, the electric vehicle cannot be considered as completely emission-free.

Based on the literature analysis carried out, it can be concluded that electric drive technology in vehicles requires further development. Although electric vehicles do not emit greenhouse gases while in operation, they display high emissions in both the production and recycling stages and require significant energy input.

The important conclusion of this review is the need to change and improve the entire life cycle of an electric vehicle. The design stage makes for an important consideration, as the materials and raw materials selected should be recyclable to the greatest extent possible and later reused. In addition, the rare minerals and earth elements used constitute a need

to adopt an appropriate system for their acquisition and distribution. Energy input is still required in the EV production phase. Only using more renewable energy sources will reduce the carbon footprint and GHG emissions, because EV production requires more energy than ICEV. That is due to the highly energy-intensive processes of extraction and processing of the materials used to manufacture the drive components and batteries.

On the other hand, during the use phase, electric vehicles show significantly lower GHG emissions when compared to ICEVs. At the point of use, EVs do not emit compounds and are therefore referred to as 'non-emitting.' However, mains electricity is used when charging the battery. However, when charging the EV battery, the energy from the energy networks is used.

Recycling batteries and their second life is also an important environmental issue. The possibility of reusing materials that are also 'costly' in ecological terms, and the ongoing development of recycling technologies and methods in this area, raises hopes. In this specific issue, directives adopted by the EU imposing mass recovery and recycling rates for end-of-life vehicle waste prove to be particularly helpful. The overview of battery reusability provided in the article depends on the degree of battery wear and the reason (e.g., accident) for the EV recall. It is estimated that most of the batteries from the recalled EVs will have an SoH (state of health) rating over 75%, making it a great opportunity for reuse.

The continuous increase EVs in the vehicle stock is a challenge for the LiBs recycling sector and the opportunity to obtain low-cost energy storage in second-life LiBs applications. It is expected that the recycling of LiBs and their second life will be an important direction for further research in the near future. Existing industrial recycling methods do not allow lithium recovery, the resources of which will be exhausted in the future. Limited resources of rare earth metals can increase the production price of new LiBs and the sales price of EVs. The use of direct recycling on an industrial scale is an important direction for further research and offers great opportunities in the recycling of LiBs. An incorrect approach to batteries after the first life and the lack of a rational SoH assessment (taking into account, e.g., daily routines) in the near future may lead to an irrational management of used LiBs, which will be recycled (necessity of energy consumption) or stored (exposure to leaks or fire—additional environmental hazard). The overview of battery reusability provided for in the article depends on the degree of battery wear and the reason (e.g., accident) for the EV recall. The unification of LiBs (chemical composition, dimensions) used by EV manufacturers is an important challenge, which may consequently help in the development of second-life applications. Meeting this challenge is difficult as vehicle manufacturers strive to develop new LiBs with better performance characteristics. Taking into account the market competitiveness of vehicle manufacturers, we should expect the production of new batteries with a different chemical composition even without the use of lithium.

The authors have chosen to concentrate on the EU because of regional considerations influenced by specific challenges and developments in the context of electric vehicles. Beyond the EU, major contributors to the production of EVs and electric drive components include China, Japan, and the USA. Evaluating the environmental impact of EVs in different countries necessitates a comprehensive analysis spanning the entire vehicle life cycle. Regional disparities in energy sources, manufacturing processes, and governmental policies significantly influence the overall sustainability of electric mobility in each country [120–123]. A pivotal factor in this assessment is the environmental impact of battery production. The sustainable manufacturing and recycling of batteries are paramount in mitigating the overall environmental footprint of EVs. China's prominence as a key player in battery manufacturing underscores the critical importance of adopting sustainable production practices.

This part largely summarizes the environmental aspects associated with the life cycle of an electric vehicle. Part 2 of this article presents infrastructure issues, mainly the availability of charging stations, affecting the so-called range anxiety, and safety of use including fire hazards.

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