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Regulations and Policies on the Management of the End of the Life of Lithium-Ion Batteries in Electrical Vehicles

Jay N. Meegoda [1,*], Daniel Watts [2] and Udaysinh Patil [3]

[1] Civil and Environmental Engineering, New Jersey Institute of Technology, Newark, NJ 07102, USA
[2] Biology Department, Indiana University—Bloomington, Bloomington, IN 47405, USA; dajwatts@indiana.edu
[3] Mechanical and Industrial Engineering Department, New Jersey Institute of Technology, Newark, NJ 07102, USA; uup@njit.edu
* Correspondence: meegoda@njit.edu; Tel.: +1-973-596-2464

Abstract: Electrical vehicle (EV) batteries, particularly lithium-ion batteries, pose significant environmental challenges due to their hazardous components, the effects of initial building-material fabrication, and the difficulties of recycling and disposal. Policies and legislative strategies adopted by different governments to solve these issues are investigated in this manuscript, specifically based on circularity and resource use. Important steps are end-of-life management, safe disposal and transportation, avoidance of hazardous gas emissions, circularity, resource use, fire prevention, and expanded producer accountability. As of February 2024, New Jersey is the first and only state in the United States that has adopted a thorough legislative framework for EV battery management, therefore establishing a standard for other states. California passed major laws encouraging Zero-Emission Vehicle (ZEV) battery manufacture and recycling. Other states are likewise trying to show initiative by implementing and changing laws. Globally, the European Union is leading, while Canada, Australia, China, and others have created strong rules of regulation. This paper looks at and contrasts the environmental problems of lithium-ion electric vehicles with the legislative actions made by different nations and states to solve these problems. By means of a thorough examination of these policies, this paper seeks to present a whole picture of the current scene and the best techniques for lifetime management of EV batteries that can be embraced by different governments. In this manuscript, a comparison is made between two leading legislations, specifically that of the state of New Jersey and the European Union. To achieve the most beneficial outcome, it is the responsibility of stakeholders to promote rules; emphasize battery recycling, secure disposal, and extended producer accountability; promote innovation in sustainable battery technology; and try to build a pragmatic approach to battery management to mitigate environmental impacts based on a hybrid version of the legislations from the state of New Jersey and the European Union.

Keywords: end-of-life management; lithium-ion batteries; regulation and policies on EVs

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1. Introduction

Policy Implications of Restrictions and Incentives for Electric-Powered Vehicles

Primary Goal—Reduce Greenhouse Gas Emissions: The present global attention on growing the availability and use of electrically driven vehicles is mostly a result of many regulatory measures meant to reach goals leading to lowering of greenhouse gas emissions coming from the transportation of goods and people. Worldwide electric car sales in 2022—including plug-in hybrid cars and battery electric vehicles—rose to roughly 10 million [1] (IEA, 2023). The number of electric vehicles sold globally climbed ten times

higher than the previous years' units throughout the 2017–2022 time frame. With sales continuing to rise, there are now over 26 million electric cars on the road worldwide [1] (IEA, 2023).

In the United States, in 2022, electric car sales, including both battery electric vehicles and plug-in hybrid vehicles, were about 918,460, up from 195,680 in 2017 [2] (Argonne National Laboratory, 2023). The 2.23 million registered light-duty electric vehicles that were driven on American roads in 2021 grew with these sales [1]. The growing number of battery-powered and plug-in hybrid vehicles indicates that state and federal policies offer different types of initiatives to get more people to purchase EVs; actions, like stricter emission regulations and tax incentives, have had an impact on the percentage of EVs used in the US. Recent stats show that, in the second quarter of 2024, total EV sales in the US saw a 14% increase compared to the same time the previous year. Just like in the leading European markets, a big part of that increase can be attributed to the surge in hybrid sales, which saw a 28% jump compared to last year. On the flip side, ICE sales dropped by 4% during that time. So, the year-to-date electrified market share is now at 19%, which is the highest it has been since we began tracking electrified sales back in 2014. In the second quarter of 2024, BEV and hybrid market shares sat at 7% and 10%, while PHEVs trailed behind with just 2%.

France, Germany, Italy, Spain, and the UK: In the second quarter of 2024, the growth of electrified vehicles in the top five European markets really outpaced the overall vehicle market. So, EV sales went up by 11% compared to last year, while ICE sales dropped by 2%. So, it turns out that the total electric vehicle market share has nudged back above the 50% mark, bouncing back after missing it by 6% in the first quarter of 2024. Sales of full and mild hybrids saw a nice bump, growing by 21% in the second quarter of 2024 compared to the previous year's second quarter. It is interesting to see that hybrid sales growth really stood out in France with a 40% increase and in Spain with 27%. The hybrid market share in the top five EU countries is now at 32%. That means nearly one in three vehicles sold in that area are hybrids! In other European markets, Norway saw the biggest jump in full and mild hybrid sales, growing by 69% from the second quarter of 2023 to the second quarter of 2024. However, BEVs are still at the forefront, holding an impressive 87% market share. Switzerland topped the charts with a 33% hybrid market share, while The Netherlands followed closely behind at 29% [1].

As electric vehicles' popularity and need are making more sense, more automotive companies and environmental organizations are taking initiatives due to competition among companies and sales of EVs growing exponentially due to falling cost, technological advancements, and government support. Recent stats from 2022 show a 10% increase in sales of passenger vehicles compared to the last 5 years.

As electric vehicles come under alternate fuels or other fuels than petroleum and have less greenhouse gas emissions, many countries have already switched to EVs. Several countries are already making the switch to EVs at some pretty impressive rates. Norway leads the pack with a whopping 80% of passenger vehicle sales being all-electric in 2022. Following that, we have Iceland at 41%, Sweden at 32%, The Netherlands at 24%, and China at 22%. It is pretty interesting that China is on this list, especially since it is the largest car market globally. The other two largest car markets, the European Union and the United States, have lower EV sales right now, but they are seeing some rapid growth. To align with international climate goals that aim to keep global warming to 1.5 °C (2.7°F) and avoid serious consequences from climate change, it is essential for electric vehicles (EVs) to make up 75% to 95% of passenger vehicle sales worldwide by 2030, as highlighted in a high-ambition scenario from Climate Action Tracker. We can definitely hit this target, especially with the recent surge in EV sales. Over the last five years, the average annual

growth rate was 65%. Looking ahead, the world will only need an average annual growth rate of 31% for the next eight years. According to a survey, as EV sales reach 1%, the growth rate is accelerated [1].

Table 1 highlights some countries where EV sales hit 1% over the last five years, and it is interesting to see how they have been growing quicker than the global average. Norway in Europe and China in Asia are leading the way in electric vehicles. To hit those climate goals, we really need to ramp up EV sales at a pace similar to what China and Norway are doing [3].

Table 1. EVs as share of passenger vehicle sales in 2023.

Country	EV Sales Percentage
Norway	13.8
Germany	13.6
Finland	10.3
United Kingdom	11.6
Belgium	10.2
Spain	2.8
Portugal	3.1
Austria	6.4
Greece	2.7
Other European. Nations	4.8
United States	7.8
China	33.3
Israel	8.2
Australia	3.5
South Korea	2.1
Japan	3.3

Secondary Goal—Reduce Use of Fossil Fuels: Manufacturers of electric automobiles and governments are pushing them as the major technology to drastically reduce gasoline usage and fight global climate change everywhere. Climate change is a primary factor of EVs becoming more crucial to society. Both General Motors and Volvo were advised to stop selling new gasoline-powered cars and light trucks in the USA by 2035, so the two businesses will switch to battery-powered vehicles [4].

USA Initiatives to facilitate the use of EVs: The United States of America's efforts to promote at least 30 percent of Zero-Emission Medium- and Heavy-Duty Vehicle (ZE-MHDV) sales by 2030 and 100 percent of sales by 2040 depend on ensuring that electric-vehicle-charging stations and hydrogen-refueling stations are widely available and easily accessible throughout the nation's freight corridors, intermodal freight facilities, and high-usage ports. Additionally, by 2030, all Americans will be able to drive electric vehicles for both short- and long-distance travel thanks to the federal government's goal of creating a fair and practical network of 500,000 charging stations. It is anticipated that by that time, 50% of all new cars produced in the USA will be zero tailpipe emission.

Together, the 117th Congress and the Administration passed important laws that would keep the United States at the forefront of electric vehicle technology and preserve its position as a global leader in the automotive sector. Hundreds of millions of dollars have been spent in the electric vehicle industry by two landmark laws: the Infrastructure

Investment and Jobs Act and the Inflation Reduction Act; these acts were created to ensure that EV production will not be an issue. This will help supply chains and American manufacturing to facilitate the shift in the medium- and heavy-duty as well as light-duty sectors. The four main pillars that comprise the policy objectives are as follows:

- Purchase incentives

To stimulate market growth and signal a shift toward electric transportation, the United States has implemented tax credits for electric vehicles. The Section 30D tax credit for light-duty cars was extended by the Inflation Reduction Act, while the Bipartisan Infrastructure Law provided USD 2.5 billion to fund a Clean School Bus program. However, revisions are needed to improve compliance deadlines, increase the free-trade agreement nation requirement, and restrict funding to electric school buses.

- Charging infrastructure funding

In the Bipartisan Infrastructure Law, USD 5 billion is set aside for charging stations for electric vehicles (EVs) along roads, and USD 2.5 billion is set aside for competitive grants, with 50% going to low-income and rural areas. It was changed so that charging stations can work in both directions by the Inflation Reduction Act, which made the Section 30C Alternative Fuel Vehicle Refueling Property Credit last until 31 December 2032. But more programs are needed to meet the growing need for EV charging stations, such as putting electricity in rest stops and turning them into businesses along interstate roads.

- Federal fleet electrification funding

A good first step would be for the United States Postal Service and other federal agencies to switch to electric vehicles. Under Biden's administration, the goal is to have all newly purchased light-duty vehicles electrified by 2027 and all vehicles acquired by the federal government by 2035. An audacious distribution of funds for federal fleet electrification, including USPS fleet electrification, is supported by the EC, which also urges all agencies to monitor fleet electrification initiatives. Although USD 3 billion was allocated for the federal fleet under the Inflation Reduction Act, further funding is required to complete the fleet transfer and cover the initial upfront payments. For government fleet replacements, including non-tactical military vehicles, the EC backs the Total Cost of Owner (TCO) approach.

- EV manufacturing and supply chain funding and programs

The Inflation Reduction Act and the Bipartisan Infrastructure Law aim to strengthen the manufacturing and supply chain for clean vehicles in the United States. Key policies include allocating USD 6.135 billion for grants supporting battery material processing, manufacturing, and recycling; USD 10 billion for the Section 48C manufacturing tax credit; USD 3 billion for the Advanced Technology Vehicle Manufacturing program; and USD 2 billion for the Domestic Manufacturing Conversion Grant program. These measures highlight the US's commitment to advancing electric vehicle initiatives and fostering their development.

China is the global leader in EV sales, accounting for 4.4 million EVs sold in 2022, surpassing the rest of the world combined. China's early strategic investment in EVs aimed to reduce air pollution, decrease reliance on imported oil, and gain an edge in a new area of auto manufacturing.

Starting in 2009, China introduced financial subsidies and tax breaks for EV producers and consumers, first through pilot city programs and later expanded nationwide. Chinese companies, like BYD, have become major EV producers, with eight out of the top 10 EV models sold in China made domestically. China offers nearly 300 EV models, focusing on smaller, affordable cars, like the USD 4500 Wuling Hongguang Mini EV.

EV prices in China have dropped below those of gas vehicles, partly due to a price war spurred by Tesla's entry into the market. China also leads in charging infrastructure, with 760,000 fast charging and 1 million slow charging stations—more than the rest of the world combined. Additionally, non-monetary benefits, such as expedited license plate access for EV buyers in Beijing, further drive adoption [3].

Though US strategy is to be number one, China and Norway have become global leaders in EV adoption, due to three key factors. First, the government has provided significant financial incentives, including exemptions from high value-added and registration taxes, making EVs more affordable than gasoline cars. These incentives started in the 1990s to support a domestic EV brand but continued for environmental reasons. Second, China and Norway have invested in extensive EV charging infrastructure, boasting the highest number of fast chargers per capita globally. The government also ensures charging rights for apartment residents and offers grants for charger installations. Third, EV owners receive perks like reduced tolls, access to bus lanes, ferry discounts, and free parking. However, as EVs dominate the market, Norway is scaling back these benefits to avoid encouraging car use over public transport. The country aims to phase out internal combustion engine vehicles by 2025 [3].

In the US, the Electric Cars Act of 2021, also known as the Electric Credit Access Ready at Sale Act of 2021, focuses on promoting electric vehicle adoption through tax incentives and expanded access to credits: Key Provisions: Extension of EV Tax Credits: The legislation prolonged the tax credit for new eligible plug-in electric drive motor vehicles, making it available through 2031. This ensures a longer period of tax relief for EV buyers, incentivizing adoption over a decade. Credit Modifications: Removal of Manufacturer Cap: Previously, only a limited number of vehicles per manufacturer qualified for the credit. This limit was removed, allowing EV manufacturers to sell an unlimited number of vehicles with tax incentives, fostering competition and encouraging consumers to purchase EVs from various brands. Assigning Credits to Financing Entities: Taxpayers could assign the credit to a financing entity, simplifying the process for consumers by reducing upfront costs and incentivizing EV ownership. Carry Forward Unused Credits: Any unused tax credits could be carried forward for up to five years, providing flexibility for taxpayers and encouraging broader credit utilization. Other Tax Credit Extensions: Tax credits for alternative fuel-vehicle-refueling properties, such as charging stations and infrastructure and alternative motor vehicles were also extended through 2031, supporting the growth of EV infrastructure and alternative fuel vehicles. Related Legislation: Electric Vehicles for Underserved Communities Act of 2021: This bill mandates the Department of Energy to support the deployment of EV-charging infrastructure in underserved communities. It aims to ensure equitable access to EV infrastructure, addressing disparities in rural or economically disadvantaged regions that may lack sufficient charging options. By promoting infrastructure development in these areas, the bill encourages wider EV adoption and reduces the digital divide in sustainable transportation. Strategic EV Management Act of 2022: This bill requires the General Services Administration (GSA) to develop a strategic plan for the management of federal electric vehicle fleet batteries. It focuses on optimizing the lifecycle management of EV batteries used by the federal fleet, including recycling, reuse, and disposal, thus promoting sustainability in public sector operations and addressing environmental concerns related to battery disposal. President Biden's Investing in America initiative intends to have 50% of new vehicle sales go electric by 2030. The White House has committed to supporting this transition through the EV Acceleration Challenge, which aims to enhance domestic production, strengthen supply chains, increase competitiveness, and generate jobs. Biden's leadership and investments have resulted in a tripling of electric vehicle sales, with over three million EVs on the road

and over 135,000 public EV chargers nationwide. The Inflation Reduction Act increases tax breaks for EV sales, offers incentives to electrify heavy-duty vehicles, and promotes the building of charging infrastructure. Companies and non-profits are pledging to increase EV fleets, consumer education, and the availability of EV charging infrastructure. The United States government is collaborating with organizations, such as Generation180, Lucid, Avanza EV, Climate Power, Sierra Club, Electric Vehicle Association, Drive Clean Colorado, and Drive Clean Indiana to hold over 500 EV events in 2023. The EV Acceleration Challenge invites organizations to commit to EV adoption via a variety of strategies. Hertz is increasing electric vehicle rentals; Consumer Reports is offering expert advice on EV purchase incentives; Green Latinos, Hip Hop Caucus, Sierra Club, Clean Energy for America, Electric Transportation Community Development Corporation, National Religious Partnership for the Environment, Plug in America, Public Citizen, Union of Concerned Scientists, Coltura, and the Natural Resources Defense Council have launched Route Ze. The US is set to attract the most global investments in electric vehicle and battery manufacturing, surpassing China and closing in on Europe, according to a report by Atlas Public Policy. Companies have reported investments totaling USD 210 billion in the electric vehicle industry, an increase from slightly over USD 50 billion at the onset of President Biden's administration in 2021. This investment boom proves that zero-emission automobiles and strict clean car rules are a good idea. Manufacturers are also being enticed by the federal government's plans to implement requirements for clean cars and trucks. With an estimated USD 54 billion in planned investments, 37 EV battery production facilities will be built or expanded across the nation by 2030. This might allow for the electrification of around two-thirds of the passenger vehicle industry. Clean vehicle and truck norms, effective climate and infrastructure legislation, and supplementary state-level policy backing are all necessary for the long-term regulatory certainty necessary to turn these investments into real domestic projects [5,6].

Global initiatives to facilitate the use of EVs: Fifteen member nations have joined the International Energy Agency's Electric Vehicles Initiative. The aim was to encourage both public and commercial endeavors related to the electrification of vehicles. In 2012, over 90% of the global electric vehicle inventory (200,000 units, or 0.02% of the 1 billion passenger cars worldwide) resided in member countries. By 2020, the project's primary aim was to increase the total count of electric vehicles in the member nations to 20 million, or 2% of all passenger vehicles. Simultaneously with this endeavor, steps have been implemented to augment the number of electric-vehicle-charging points across the participating nations. In 2023, around 14 million new electric vehicles were registered worldwide, resulting in a cumulative total of 40 million vehicles on the road. This figure closely followed the sales estimate from the 2023 [1]. Electric vehicle sales rose 35% annually to 3.5 million in 2023. This is over six times higher than in 2018, five years ago. Over 250,000 new registrations were made per week in 2023—more than had been made in 2013 ten years earlier. About 18% of all cars sold in 2023 were electric vehicles, up from only 2% five years prior in 2018 and 14% in 2022. These patterns show that growth is still strong as the market for electric cars becomes older [1].

2. Environmental Implications of Movement Toward EV Transportation

While many people applaud the progress made toward reaching climate targets, it is also likely that some of the modifications brought about by the shifts in the vehicle mix will have an influence on sustainability or the environment that goes beyond any advantages in the field of climate change. A significant advantage of EVs compared to vehicles traditionally powered by combustion engines is the amount of energy they save. About 87% to 91% of an electric vehicle's power comes from its battery and regenerative

braking systems. At highway and city-driving averages, gasoline vehicles only manage to turn around 16–25% of the energy that goes into the fuel into usable motion (averaging highway and city driving) [6]. Environmental and social consequences are shifted rather than eradicated as a result of switching to electric vehicles from those powered by internal combustion engines (ICEs). Cleaner energy sources are essential because EVs lower tailpipe emissions but carry pollution upstream, particularly if the electrical grid is fueled by fossil fuels. The use of vital minerals like lithium, cobalt, and nickel in EV batteries causes environmental impact in the areas where mining takes place, frequently giving rise to moral questions regarding local ecological degradation and labor practices. Furthermore, because lithium-ion batteries require a lot of resources to develop and are challenging to recycle efficiently, EVs create new problems in battery production and disposal even while they reduce traditional vehicle emissions. Construction and energy distribution networks bear the brunt of the infrastructure needed for widespread EV use, such as charging stations and grid upgrades. Economically speaking, the shift may increase regional economic disparities by displacing people in the oil sector and generating opportunities in the battery and renewable energy industries. Furthermore, although EVs have greater initial production costs, their long-term effectiveness depends on using clean energy, which may eventually lessen their overall environmental impact. In summary, even while EVs have many advantages, they also transfer social and environmental costs to other sectors, necessitating careful regulation to avoid unforeseen effects [6,7]. Definitely, the shift to electrically powered vehicles and hybrid gasoline/electric vehicles will necessitate a greater use of lithium, cobalt, and other metals in the production of batteries. This will lead to the production of a sizable quantity of batteries that either reach the end of their useful lives or become surplus when the vehicle itself becomes unusable; although EVs may be environmentally friendly, the resources to produce these cars are also rare. Since lead–acid batteries are frequently found in gasoline-powered cars, regulations and procedures pertaining to the safe handling, disposal, and material recovery of these power storage devices have changed over time, potentially reducing harm to the environment and the general public. As we move forward with electrically driven vehicles, it is critical to understand that the primary battery for these vehicles differs significantly from the traditional lead–acid battery. EV batteries have more weight, volume, and monetary value. For a rather arbitrary instance, an average car lead–acid battery, according to Amazon.com, was offered for USD 342.30 and measured at $7 \times 12 \times 7$ inches. It weighed 56.2 pounds [8]. On the other hand, an EV's battery would typically weigh between 1000 and more pounds [9]. The GMC Hummer Edition 1 is said to feature a battery pack weighing 2923 pounds and an average advertised price of USD 20,000, making it possibly the highest-end model available right now [10]. The range of components and material amounts will vary based on the type of battery being investigated because different chemical processes are employed to store electrical energy in EV batteries. The following quantities of key metals were found in an average battery (e.g., the size of the battery in a Chevrolet Bolt): 77 lb. of aluminum, 64 lb. of nickel, 44 lb. of copper, 22 lb. of manganese, 18 lb. of cobalt, and 13 lb. of lithium [11]. The literature is not very explicit when it comes to how much an EV battery costs; however, some debates concerning the price of a reconditioned EV battery without labor fees suggest that a refurbished battery for a Tesla Model S can cost up to USD 12,000, while a Nissan Leaf battery can cost as little as USD 4500 [12]. Typically, 402 kW/hrs will be consumed for 1207 miles in an EV for a month, as electric cars usually travel three to four miles per kWh. According to the most recent household average estimate of 16.63 cents per kWh, charging an electric car at home would cost around USD67 per month. AAA says gas averages USD 3.08 per gallon. Filling a 12-gallon petrol tank costs USD 37. We all know that vehicles and trucks require various

amounts of gasoline, making things complicated. Say you drive a car that averages 30 miles per gallon on the interstate and in the city. With a 12-gallon tank, each fill-up provides 360 miles of driving range. Driving 1207 miles per month requires refueling three times and USD 111 (USD 37 × 3). Gas prices and fuel efficiency change; therefore, this is an estimate. Few vehicles and SUVs obtain 30 mpg combined, so our cautious number crunching shows that recharging will cost less than fueling. The budgetary difference narrowing with a fuel-efficient car yet remains. Electricity costs might vary depending on a number of factors, such as your location, the season, and even the time of day when peak charges are in effect. Late at night, power use and prices are often lowest. Even if consumers are concerned about the availability of public charging stations, it is important for them to understand that 90% of electric car charging occurs at home during the night. Almost often, charging your electric car overnight at home is the most cost-effective option. During the night, when their usage is at its lowest, some utilities provide discounted prices. The power bill is affected by the location. Compared to Utah, where the cost is roughly 12 cents per kWh, New Hampshire residents spend nearly 23 cents per kWh for energy consumption.

In August 2024, the average electricity rate is 16.63 cents/kWhr from the US Energy Information Administration [13]. The dynamics of recycling are considerably different for wasted (A wasted battery is a used or unused battery that is no longer useful and has been discarded) EV batteries because of their size and intrinsic worth (either for reuse or for recovering the constituent ingredients). Incentives for recycling are provided by the large majority of old EV batteries and the significant potential economic gain, in contrast to the previous lead–acid battery scenario. In circumstances like this, one of the main objectives of recycling policies is to not only encourage recycling but also to set up legal frameworks that facilitate efficient resource management in the most environmentally friendly manner.

The environment in which batteries are used to power electric vehicles is harsh; in a typical five-to-ten-year period, they experience over 1000 cycles of charging and discharging, a wide temperature range between 20 and 70 degrees Celsius, high depth of discharge (DOD), and high rate of charging and discharging (high power). An EV battery pack often signals the end of its automotive life when it can no longer meet the requirements for usage in EVs. The United States Advanced Battery Consortium (USABC) has set a 15-year calendar life target for battery packs in hybrid electric vehicles (HEVs) and a 10-year target for electric vehicles. According to the USABC, battery life diminishes due to factors like cycling, temperature extremes, and time, which lead to capacity loss and increased resistance. USABC established the popular retirement criterion in 1996, which stipulates that a battery pack should be replaced when 20% of its original capacity is lost [14]. Stated differently, a battery pack is retired at 80% of its metric state-of-health (SOH). However, it is not a requirement to retire at 80%. This threshold is still cited as the expected number, although its applicability to modern battery technology is coming under increasing scrutiny. On the one hand, both the maximum capacity and the maximum range of EV batteries have improved dramatically. The US Environmental Protection Agency (USEPA) has rated the Model S Long Range Plus, which Tesla recently unveiled, as the first electric vehicle with a range of 402 miles, more than quadrupling the maximum range of 20 years ago. Drivers can now tolerate a greater reduction in battery capacity, so retired batteries should still be able to satisfy consumer demands at this point. Furthermore, the threshold value ought to change according to the battery's chemistry [15]. However, this is dependent on vehicle size also since this affects a vehicle's resale value. One is more likely to replace a battery for larger, more expensive vehicles due to cost–benefit effects related to prolonging lifetime. The rest of the vehicle's condition and economic viability should be considered when determining the threshold value. Decisions on replacement batteries may be influenced, for instance, by the market's expectations for second-life battery performance

(frequency modulation, for instance, is far less demanding than peak shaving) and the possible financial gain of prematurely retiring batteries for second-life use. Table 2 provides a summary of popular US EVs from manufacture websites.

Table 2. Summary of popular US EVs.

Manufacturer	Model	Battery Warranty	Estimated Battery Lifespan	Starting Price (USD)	Battery Replacement Cost (USD)
Tesla	Model S	8 years/150,000 miles	10–20 years	USD 68,490	USD 12,000–USD 20,000
Tesla	Model 3	8 years/120,000 miles	10–20 years	USD 40,380	USD 10,000–USD 15,000
Tesla	Model X	8 years/150,000 miles	10–20 years	USD 79,990	USD 12,000–USD 20,000
Tesla	Model Y	8 years/120,000 miles	10–20 years	USD 47,490	USD 10,000–USD 18,000
Volkswagen	ID.4	8 years/100,000 miles	8–12 years	USD 46,385	USD 8000–USD 15,000
Kia	EV6	10 years/100,000 miles	8–12 years	USD 48,700	USD 7000–USD 13,000
Hyundai	IONIQ 5	10 years/100,000 miles	8–12 years	USD 41,450	USD 7500–USD 13,500
Ford	Mustang Mach-E	8 years/100,000 miles	8–12 years	USD 39,995	USD 11,000–USD 18,000
General Motors	Chevrolet Bolt EV	8 years/100,000 miles	8–12 years	USD 30,670	USD 9000–USD 16,000
General Motors	Chevrolet Silverado EV, 2024 Silverado 1500	8 years/100,000 miles	8–12 years	USD 44,795	USD 10,000–USD 17,000
Rivian	R1T	8 years/175,000 miles	Data not yet available	USD 71,700	USD 15,000–USD 22,000
Lucid Motors	Air	8 years/100,000 miles	Data not yet available	USD 71,400	USD 12,000–USD 24,000

Table 3 presents a comparison of the benefits and drawbacks of choices for recycling and reuse. The word 'Prevention' implies that lithium-ion batteries (LIBs) are engineered to utilize less-critical materials of significant economic value and yet susceptibility to scarcity, and that electric vehicles must be lighter with reduced battery sizes. 'Reuse' signifies that electric car batteries ought to be utilized for a secondary purpose. 'Recycling' denotes the process of reclaiming batteries to recover maximum material while maintaining structural integrity and quality, such as avoiding contamination. 'Recovery' refers to the utilization of certain battery materials as energy sources for processes like pyrometallurgy. Ultimately, 'disposal' signifies that no value is retrieved, and the waste is directed to a landfill.

Meegoda, Charbel, and Watts (2024) conducted a thorough examination of LIB management strategies and concluded that there are several different processes involved in the recycling of lithium batteries, including direct recycling, pyrometallurgy, hydrometallurgy, and foam flotation. Businesses that have successfully used hydro- and pyrometallurgy include Redwood Materials, ABTC, Ecobat, and Li-Cycle. These businesses have shown that these techniques are efficient and commercially viable, with some of the materials (e.g., cobalt, nickel, copper) attaining recovery rates of over 95% [16]. (While the overall recycling rate of a LIB might not reach 95%, advanced recycling techniques aim to recover a high percentage of valuable metals like nickel, copper, and cobalt from spent batteries). The first stage of battery transportation from the location of collection to the processing plant is an essential part of this recycling process. LIBs are categorized as hazardous products, so it is essential to adhere to strict regulations, such as the UN 38.3 Certification and the packaging specifications set forth by the US Department of Transportation (DOT). These guidelines play a crucial role in guaranteeing the safe management of these batteries, protecting the health of people and the environment alike. Different battery-recycling businesses in the USA operate differently, using different strategies based on their unique needs and capabilities. Methods include Hydro- and Pyrometallurgy, Thermal Reduction and Separation, and Direct Precursor Synthesis from Hydro to Cathode. Among the recyclers our study looked at, Redwood Materials stands out in particular because it currently has the highest yearly

processing capacity. As of April 2024, Redwood Materials' Nevada campus is processing 30,000 tons of end-of-life batteries and production scrap per year and is expected to reach a capacity of 60,000 tons by the end of the year. At full capacity, the facility could process enough material to create more than 5 million EV batteries each year [17].

Table 3. Advantages and disadvantages of reuse and recycling options.

Aspect	Recycling		Reuse	
	Advantages	**Disadvantages**	**Advantages**	**Disadvantages**
Resource Recovery	Efficient recovery of valuable materials like cobalt, lithium, and nickel.	Limited by current technologies in extracting all valuable materials efficiently.	Limited recovery of materials, focuses on extending battery's existing lifecycle.	Eventually, the batteries will still need to be recycled.
Environmental Impact	Reduces the need for raw material extraction, lessening environmental footprint.	Energy-intensive processes and potential for harmful emissions.	Reduces waste and the need for new battery production, lowering carbon footprint.	If not managed properly, it can lead to inefficient use and disposal challenges.
Economic Viability	Creates a supply chain for critical battery materials, potentially reducing costs.	High initial investment in technology and infrastructure.	Can be more cost-effective in the short term by extending battery life.	Limited market for repurposed batteries and potential costs in reconditioning.
Energy Efficiency	Potentially more energy-efficient in the long run as technologies improve.	Current recycling processes can be less energy efficient.	Reuse does not require the energy-intensive process of recycling.	The efficiency of repurposed batteries can decrease over time, requiring more energy.
Safety and Reliability	End products are raw materials that can be used to make new, reliable batteries.	Processes must be carefully managed to prevent environmental contamination.	Repurposed batteries may have less predictable performance and lifespan.	Potential safety risks if repurposed batteries are not properly evaluated.
Scalability	Scalable as battery use increases and recycling technologies improve.	Requires a steady and sufficient supply of spent batteries to be economically viable.	Limited by the availability of suitable batteries for repurposing.	May not be as scalable due to varying conditions of spent batteries.
Technological Development	Drives innovation in recycling technologies and materials science.	Dependent on advancements in technology for greater efficiency and recovery.	Encourages innovation in extending the life and use of lithium-ion batteries.	Limited by the current state of battery technology and degradation over time.

Redwood Materials is a company that recycles and refines battery materials to produce components for lithium-ion batteries. The company's hydrometallurgical process can recover up to 95% of the lithium, nickel, cobalt, and copper from end-of-life batteries. Redwood Materials also uses recycled and new feedstocks to produce cathode active materials and ultra-thin battery-grade copper foil [17].

The potential of battery recycling: As of 2020, approximately 200,000 metric tons of battery material were available for recycling globally [18]. By December 2023, China had established itself as the global leader in battery recycling capacity, surpassing 500,000 metric tons. In comparison, the US and Europe lagged behind, each with a capacity of around 200,000 metric tons [19]. With electric vehicle (EV) sales projected to soar in the coming decades and many existing batteries nearing the end of their lifecycle, the volume of battery materials available for recycling is expected to grow sevenfold by 2030. By 2040, this figure is anticipated to exceed seven million tons. The global revenue potential from battery reuse and recycling is forecast to reach USD 13 billion by 2030 [19,20].

Legislation driving capacity growth: To bridge the recycling capacity gap with China, the US and the EU have been working together. Expanding recycling capacities is the goal of recent legislative initiatives in both regions. The new battery regulations from the EU set aggressive recycling and recovery goals for the upcoming years and require a minimum percentage of recycled materials to be utilized in batteries [21]. To increase

domestic recycling capacity, the US has implemented battery-recycling subsidies under the Inflation Reduction Act.

Lifecycle assessment (LCA) studies are the greatest way to understand the wider environmental and economic benefits of these recycling processes, even though they have been proven to be efficient and commercially viable. Research like this not only shows how much money and energy recycling may save, but it also highlights how sustainable it is to reuse EV batteries for different things in the long run.

Findings and Implications of LCA Studies

Reusing and recycling battery components is crucial for beneficial effects, according to lifecycle assessment data. The production of EV batteries and resource management involve many different aspects. However, a study conducted in 2024 by Meegoda, Charbel, and Watts assessed life cycle impacts and costs and found that producing EV batteries from virgin material uses eight times more energy than producing them from recycled material [22]. In a similar vein, less damage is done to land, groundwater contamination, noise pollution, and thermal pollution when recycled materials are used to make EV batteries. According to the life cycle cost analysis, an equivalent EV battery made from recycled materials would cost significantly less than one made from virgin materials.

According to lifecycle assessment results, using EV batteries longer (for example, in solar power storage) is a sustainable practice. Meegoda, Charbel, and Watts (2024) have emphasized that keeping these batteries in use after they can no longer be used in cars (usually because the recharge time has degraded) allows for additional societal benefits at little cost to the environment or the economy before they are eventually recycled [22]. For instance, storage facilities for the on-demand usage of electricity generated by solar or wind power sources provide realistic long-term use. It should be mentioned that the quick evolution of battery chemistry and the current risk of fire make this application not without some technological difficulties. For more information on LCA, please refer to the study by Meegoda, Charbel, and Watts [16] on sustainable management of rechargeable batteries used in electric vehicles.

3. Current Policy Approaches for EV Battery Recycling

The growing popularity of electric vehicles has highlighted how important it is to manage their lithium-ion batteries well throughout their lives. These batteries are essential for the shift to more environmentally friendly transportation, but they also contain potentially dangerous substances that could harm the environment if not handled correctly. The existing policy approaches for EV battery recycling in the USA and several other countries are outlined in Table 4, and those are covered in more detail in the sections that follow. In addition to supporting sustainable recycling and reuse activities, Table 4 and the subsequent discussion seek to identify practical approaches and best practices for reducing the environmental impact of EV batteries. They also emphasize the significance of material recovery and responsible sourcing. It focuses on regulations pertaining to extended producer responsibility, end-of-life management, safe disposal, transportation, and the avoidance of hazardous gas emissions. Note that the discussion in this article is limited to lithium-ion batteries utilized in electric vehicles. It excludes applications not related to EVs and other battery types. The data presented here are based on industry practices and current legislation pertaining to lithium-ion electric vehicle battery lifecycle management.

Table 4. Summary of US States and Other Countries Addressing EV Battery Issues.

Category	Battery Issues	States Addressing It	Countries Addressing It
Safe disposal/Transportation	Addressing the fire risk in Solid Waste and Materials Facilities in Recycling Streams	CA [23], IL [24]	China [25,26]
	Preventing mixing with solid waste	WA [27], IL [28]	EU [29], Japan [30], Australia [31], Canada [32,33], UK [34], Mexico [35]
	Preventing hazardous gas emissions	ME [36]	EU [37], South Korea [38], Australia [39]
	Cannot be disposed of as solid waste	NJ [40,41]	Germany [42], Sweden [43]
	Preventing toxic materials release	CA [44]	Norway [45], Finland [46,47], The Netherlands [48]
End of life management	Removing hazardous waste classification	CA [44]	EU [49]
	Recycling/reuse requirements	CA [50], NJ [40]	Sweden [51], Germany [29,51], France [29,51], Canada [52], Australia [53], Mexico [35]
	Perform needs assessment to determine availability of recyclers/infrastructure	NJ [54]	Norway [45], The Netherlands [48]
	Submit report with final policy recommendations for collection/management	WA [27], NJ [54], CA [44], IL [28]	EU [29,37]
	Sale of recycled materials	NM [55], NJ [54]	South Korea [30]
	Development/incentives/regulation- Battery energy storage systems (BESS)	ME [56], MN [57], NM [58], NC [59], WI [60]	China [61]
	Decommissioning of *certain* Battery energy storage systems (BESS)	ME [62]	Australia [63]
Responsibility and ownership outlining accountable stakeholders at each stage of battery's life cycle	Extended producer/Manufacturer Responsibility/Producer take-back	NJ [54], IL [28], CA [64,65], MN [57], NH [66], WA [27]	Sweden [43], EU [29]
	Producers must create a battery management plan outlining how it will collect and manage its used batteries	NJ [54], IL [28]	China [67], EU [30]
	Shared Responsibility split among manufacturers, importers, distributors, retailers, customers, waste management	CA [64], NJ [68,69], WA [70]	Brazil [71]
	Retailers take back	NJ [54], CA [72], WA [27]	EU [73]
	Recycling entities must establish battery tracking system	NJ [54], WA [27], CA [44]	EU [29]
	Government agency responsibility	CA [44]	China [67]
	Core exchange and vehicle backstop	CA [44]	

Table 4. *Cont.*

Category	Battery Issues	States Addressing It	Countries Addressing It
Access to the Battery Information	Universal Diagnostic System	CA [44,74]	EU [29]
	Digital Identifier	CA [44,74]	EU [29]
	Physical Labeling/Notices	CA [44,74], NJ [54]	
Ensuring Compliance	Community Board Compliance with Notice and Annual Inspection Requirements		US [75], Canada [76], Germany [76]
Assessment and Reporting	Request for life cycle analysis	CA [44,74]	EU [77,78], US [79]
	Comprehensive study for the best EOL management of clean energy products	CA [44,74], NJ [54]	South Korea [76], EU [77,78]
Consumer/Stakeholder Education	Consumer/Stakeholder Education	IL [28], NJ [54], CA [65], WA [27]	EU [29,80]
	Providing educational materials to consumers	NJ [54], IL [28], CA [65], WA [27]	Germany [81], UK [82]
	Public Notice Requirements		
Material Extraction	Incentive for establishment of lithium mining operations, identifying extraction areas, and training workers	NM [55,58,83], NV [84–86]	Argentina [87], Bolivia [88,89], China [90,91], Mexico [92,93]
	Lithium Extraction Excise Tax	CA [94], WV [74], NV [95]	Chile [88,96], and Bolivia [88,89]
Sustainability and Ethics	Responsible sourcing of battery materials (responsible and conflict-free sources)	CA [97], NV [84,95]	Argentina [87], Chile [96], Bolivia [88] and EU [29]
	Environmental remediation reimbursement at sites of former battery recycling facilities	TX [98]	
Research and Development	Innovation in battery technology and materials to increase efficiency/sustainability	US [99]	US [99], EU [100]

3.1. US States Dealing with EV Battery Management Issues

In the US, both federal and state governments regulate EV lithium-ion battery policies. At the federal level, agencies like the EPA, DOE, and DOT set broad standards related to environmental safety, transportation, and recycling. For example, the EPA enforces hazardous waste laws, while the DOE promotes R&D for battery technology and recycling through grants and incentives, such as those in the Infrastructure Investment and Jobs Act (2021). States, however, can create more specific or stringent regulations, especially regarding battery disposal, recycling infrastructure, and Extended Producer Responsibility (EPR) programs. States like New Jersey and California lead with stricter recycling mandates and incentives for battery management. Overall, federal policies provide a framework, but states have the freedom to enforce their own policies to address local needs and environmental concerns.

3.1.1. New Jersey

With effect from 8 January 2024, the state of New Jersey has passed a comprehensive set of regulations to manage the lifecycle of EV batteries [40,54]. These rules are designed to protect the environment, encourage recycling, and make it easier to use EV batteries efficiently. They include specifications for disposal, labeling, needs assessment, and management plans. These prerequisites are listed as follows:

Electric Vehicle Battery Disposal Requirement

This law requires EV batteries to be disposed of (primarily refers to recycling, meaning they want to ensure EV batteries are not thrown away in landfills but instead collected and recycled properly through designated channels) properly in order to protect the environment. By establishing appropriate handling, shipping, and recycling norms, it seeks to reduce the potentially harmful effects of battery components on the environment.

Electric Vehicle Battery Labeling Requirement

The policy pertaining to labeling requirements guarantees that all EV batteries sold in New Jersey bear uniform and legible labels. These labels aid in safe handling and disposal by offering crucial details about the battery's chemistry, recycling guidelines, and safety alerts.

Electric Vehicle Battery Need Assessment

This legislation mandates that the state's present and future EV battery requirements be evaluated on a regular basis. It entails assessing the infrastructure needs, supply chain capacities, and demand necessary to support New Jersey's increasing use of electric vehicles.

Electric Vehicle Battery Management Plan

A complete strategy for managing EV batteries throughout their lifecycle must be developed and implemented by all stakeholders, including manufacturers, dealers, and recycling facilities, in accordance with the EV Battery Management Plan. Plans for gathering, recycling, and reusing used batteries are part of this, as are measures to ensure sustainable operations and cut waste.

3.1.2. California

In order to encourage the production and recycling of ZEV batteries, the state of California has passed a number of important laws that will help the market for electric vehicles expand and the environment remain sustainable [23]. These prerequisites are listed as follows:

ZEV Battery Manufacturing Grants

Funding is available for the production of ZEV batteries in the state through the California Energy Commission's (CEC) Power Forward Battery Manufacturing Grant Program. Program participants must be privately held, for-profit companies in California, and their initiatives must fit into one of the following categories to be eligible:

Category 1: The processing of precursor materials for cathodes for cells and batteries for ZEVs.

Category 2: The processing of end-of-life cells and batteries to recover critical battery materials for reuse in the production of new batteries for ZEVs.

Lithium-Ion Vehicle Battery Recycling Support

The Lithium-ion Car Battery Recycling Advisory Group was established by the California Environmental Protection Agency, the Department of Toxic Substances Control, and the Department for Resources Recycling and Recovery. This group was in charge of providing policy suggestions meant to see 100% of lithium-ion vehicle batteries recycled or used again in California. The suggestions covered best end-of-life practices, environmental management techniques, and opportunities and impediments to battery reuse as energy storage devices. They also served as a foundation for the creation of later laws pertaining to the recycling of EV batteries.

3.1.3. Illinois

To protect the environment and maintain public safety, the state of Illinois has implemented strict guidelines for the proper disposal and transportation of EV batteries [28]. Comprehensive end-of-life management strategies for ethical recycling and disposal must be created by manufacturers [28]. However, reading the Dan Watkins report does not make the limitation any clearer [70]. Furthermore, Illinois has put in place a thorough education program aimed at educating stakeholders and consumers about their respective roles in the EV-battery-recycling strategy [28]. Here is a list of the prerequisites:

Safe Disposal and Transport

In order to protect the environment and maintain public safety, manufacturers are required to make sure that EV batteries are transported and disposed of safely [24,28].

End-of-Life Management

To guarantee appropriate recycling and disposal, manufacturers must provide detailed strategies for handling batteries at the end of their useful lives [28].

Consumer Stakeholder Education Program

Illinois has put in place an education program to educate stakeholders and customers about their roles in the recycling of EV batteries.

3.1.4. Washington

To safeguard public safety and avoid environmental damage, EV battery producers in Washington state are required to provide safe disposal. Detailed end-of-life recycling strategies must be made by them. Batteries must be handled safely, have recycling plans established, and have their chemistry disclosed by the manufacturer [27]. Recycling facilities have to follow state standards when it comes to battery disassembly, material recovery, and disposal. Governmental organizations monitor adherence, impose rules, and encourage safe disposal and recycling by providing incentives and monitoring [27]. A list of these prerequisites is provided below:

Safe Disposal Practices

The safe disposal of EV batteries must be ensured by manufacturers in order to protect the environment and public safety.

End-of-Life Management

It is mandatory for manufacturers to develop and implement comprehensive strategies for the conscientious recycling and elimination of batteries at the conclusion of their lifespan.

Stakeholders Responsibilities

Washington lays out in detail the obligations of each party participating in the life cycle of an EV battery, where manufacturers are required to set up end-of-life recycling schemes; guarantee safe handling, storage, and transportation; and supply comprehensive information on battery chemistry.

Recycling Facilities: Take charge of properly disassembling batteries, recovering materials, and disposing of them in accordance with state laws. Government Organizations to monitor adherence to rules, uphold them, and encourage recycling and safe disposal via supervision and rewards.

3.1.5. Nevada

Through consumer education on maximizing battery life, comprehending warranties, and supporting responsible material extraction and recycling to reduce environmental effect, the state of Nevada has put measures in place to support sustainable EV battery practices [84,86,99,101,102]. A list of these prerequisites is as follows:

Consumer Education

Nevada offers resources to inform customers about the benefits and upkeep of electric vehicle batteries, such as how to extend battery life and comprehend warranty conditions (Nevada Energy Office, 2024) [101,102].

Material Extraction

Nevada promotes ethical mining techniques and the utilization of sustainable sources while addressing the moral and environmental ramifications of harvesting resources for electric vehicle batteries (Nevada Department of Environmental Protection, 2024) [84,86].

Sustainability Ethics

In order to lessen its impact on the environment and promote sustainable practices throughout the battery lifecycle, Nevada advocates for the recycling and appropriate disposal of electric vehicle batteries (Nevada Recycling Coalition, 2024, Reno, NV, USA) [102].

Consumer Education Initiatives

Initiatives were started to inform stakeholders and customers about their obligations in the recycling of EV batteries [84–86].

3.1.6. Compendium of Other US Approaches

Minnesota: Manufacturers would have to create a plan for the appropriate handling and recycling of electric vehicle batteries, which would include procedures for collecting, transportation, and recycling in addition to financial guarantees [57].

New Hampshire: The state of New Hampshire has put forth proposed regulations requiring manufacturers to create take-back programs, safe disposal procedures, and end-

of-life recycling plans. Additionally, the regulations require that all stakeholders have clear responsibilities and that consumer education initiatives be put in place [66].

Texas, New Mexico, and West Virginia: Texas has rules regarding environmental remediation reimbursement at locations of old battery-recycling factories [98], while the states of New Mexico [55,58,83] and West Virginia [74] have legislation pertaining to material extraction. Additionally, in order to improve sustainability and efficiency, US federal rules encourage innovation in battery technology and materials. In response to the problems with EV lithium-ion batteries, several states in the United States have begun to act proactively.

3.2. Other Countries Dealing with EV Battery Management Issues

3.2.1. Mexico

The RLGPGIR (Reglamento de la Ley General para la Prevención y Gestión Integral de los Residuos) and pertinent sections of the LGPGIR provide guidance for Mexico's approach to battery recycling. This approach entails a regulatory framework designed to guarantee the safe and environmentally responsible disposal of used EV batteries. Rules and Guidelines: With the goal of preventing hazardous materials from entering the trash stream, the Mexican government is developing regulations to guarantee the ethical recycling of EV batteries. These regulations support the creation of recycling facilities and the advancement of cutting-edge recycling-technology research.

Sectoral Initiatives: In Mexico, a number of businesses are investing in battery-recycling facilities. Ganfeng Lithium, Bacanora, Toyota, and LEOCH are organizations investing in Mexico. For instance, Ganfeng Lithium and Bacanora are collaborating to build a lithium-ion-battery-recycling facility in Sonora. This plant will enable a closed-loop system that minimizes the impact on the environment by continuously recycling and reusing materials in the creation of batteries [35,103,104]. The strategy consists of the following essential elements [92,105–107]:

Classification and Identification

Hazardous Waste Designation: Because of their chemical makeup, EV batteries are categorized as hazardous waste and need to be disposed of and handled carefully.

Safe Handling and Transportation

When handling and transporting old EV batteries, certain safety procedures must be adhered to in order to avoid contaminating the environment. To guarantee compliance and safety, personnel engaged in these activities must receive sufficient training in hazardous waste management.

Storage and Treatment

Used electric vehicle batteries need to be kept in places that are specifically made to keep out contaminants and other environmental entanglements.

Disposal and Recycling

In Mexico, the recycling of EV batteries, particularly lithium-ion types, is gaining momentum. The process starts with collecting and sorting used batteries, which are then disassembled to recover valuable materials like lithium, cobalt, and nickel. Through methods like mechanical shredding and chemical leaching, these metals are purified for reuse. The aim is to repurpose these materials for new batteries or other industrial uses, contributing to a more sustainable future.

3.2.2. Canada

In Canada, EV batteries navigate a layered regulatory framework. Federally, Environment and Climate Change Canada oversees their lifecycle under the Canadian Environmental Protection Act of 1999 and the Cross-border Movement of Hazardous Waste and Hazardous Recyclable Material Regulations (SOR/2021-25). Transport Canada ensures their safe transit through the Transportation of Dangerous Goods Act, 1992, and related regulations. Beyond the federal level, each province and territory crafts its own set of rules, adding a regional dimension to the handling of EV batteries and other hazardous materials, making compliance as diverse as Canada's landscapes [33,108,109]. A synopsis of the legislative measures implemented by the Canadian Provinces and Territories is provided below:

British Columbia (BC): British Columbia (BC) has set legislative standards for EV battery recycling schemes under the Environmental Management Act. By 2026, the province intends to have completed its phased recycling program. The government-approved battery collecting and recycling management program is called Call2Recycle. After being gathered at predetermined locations, batteries are brought to establishments like Retrieve Technologies in Trail, British Columbia, where they are disassembled, examined, and processed to separate materials like metals and lithium for use in other applications [110,111].

Ontario: The Resource Recovery and Circular Economy Act governs battery and electrical and electronic device recycling in Ontario. In charge of managing battery recycling, Call2Recycle is registered as a Producer Responsibility Organization (PRO). Battery collection from businesses and consumers is the first step in the process. After that, companies like Li-Cycle and Glencore disassemble and process the batteries. Recovered valuable materials are sold for reuse, such as nickel and cobalt. Glencore in Sudbury is a major contributor to the recovery of precious materials as Ontario increases its ability to handle and recycle EV batteries [112].

Quebec: Battery recycling in Quebec is controlled by government-approved stewardship schemes in accordance with the Environment Quality Act. Batteries are collected and recycled by Call2Recycle, which has drop-off stations all around the province. Batteries that have been collected are shipped to recycling centers, where priceless materials are extracted and used again [110].

Manitoba: To guarantee safe disposal, battery recycling is controlled by the Household Hazardous Material and Prescribed Material Stewardship Regulation of the WRAP Act. Battery collection and recycling are managed by Call2Recycle. Batteries are gathered from different locations for disposal, and valuable materials are recovered and recycled through processing [110].

Saskatchewan: To protect the environment, battery recycling is regulated by the Household Hazardous Waste Products Stewardship Regulations. Battery collection and recycling are overseen by Call2Recycle. At certain locations, batteries are gathered and processed to remove and reuse precious materials [113].

Nova Scotia: To guarantee appropriate disposal, battery recycling regulations are created under the Solid Waste-Resource Management Regulations. Battery collection and recycling are managed by Call2Recycle. Consumer batteries are gathered and then shipped to facilities for recycling in order to recover valuable materials [110,113].

The following provinces and territories have different degrees of battery recycling laws: Alberta, New Brunswick, Newfoundland, Northwest Territories, Nunavut, Prince Edward Island, and Yukon. These laws are frequently overseen by stewardship initiatives like Call2Recycle. The collecting of batteries from approved drop-off locations, transportation to recycling facilities, and processing to recover and recycle materials are additional implementation and operational steps [110,113]. Please be aware that the majority of the information

discussed above on Canadian policies, including the mentions of Call2Recycle, relates to the well-established program for lithium batteries used in non-EVs. Although Call2Recycle and the Canadian car industry are developing strategies for managing EV batteries, it does not appear to be well-established in either legislation or practice just yet.

3.2.3. The European Union

One of the first governmental bodies to establish uniform regulations for essential materials was the European Union (EU), which subsequently expanded them to include the battery industry. Aiming to guarantee that utilized resources remain inside the EU economy, the EU Commission has unveiled the new Circular Economy Action Plan, which is one of the measures towards achieving carbon neutrality by 2050 under the main priorities of the EU Green Deal [29,49,73,77,78]. The production of batteries and electric vehicles is one of the most resource-intensive industries that the Circular Economy Action Plan targets for its high potential for circularity. The commission suggested a new battery regulation structure as part of the strategy. It will change the battery management regulatory framework in the EU member states and broaden the Battery Directive, particularly by the following:

- Setting common rules for the battery segment across the EU,
- Proposing rules on recycled content in manufactured products to ensure the recovery of materials,
- Establishing requirements for sustainability and transparency of battery production and recycling, including the carbon footprint of battery manufacturing, ethical sourcing of raw materials and security of supply, and facilitating reuse, repurposing, and recycling.

The EU has a thorough regulatory framework. With effect from 18 February 2024, the new EU Batteries Regulation defines precise criteria for the whole battery lifecycle, including EV batteries [29]. It went into effect on 17 August 2023. These are the main tenets of the EU strategy:

Recycling Efficiency and Material Recovery Targets

The rule establishes ambitious targets for material recovery and recycling efficiency. For instance, in order to achieve high levels of recovery of vital raw materials like lithium, cobalt, and nickel, all collected waste batteries—including electric vehicle batteries—must be recycled. To guarantee that valuable components are reintegrated into the economy, minimize environmental effect, and lessen reliance on imported raw materials, specific recovery targets are set for these commodities.

Prohibition of Landfilling

The regulation continues to forbid disposing of used batteries in landfills. Regardless of their condition or place of origin, all batteries, including those from electric vehicles, must be gathered and recycled at no cost to the final consumer.

Producer Responsibility and Due Diligence

It is mandatory for manufacturers of EV batteries to establish and disseminate due diligence protocols that encompass detecting and minimizing social and environmental hazards across their supply networks. Beginning in August 2025, third parties must verify these policies.

Collection and Recycling Targets

For certain battery types, the regulation establishes gradual collection and recycling targets. For portable batteries, for instance, collection rates of 63% by 2027 and 73% by 2030 are outlined, with similarly challenging goals for other battery kinds.

Circular Economy and Carbon Footprint Reduction

By requiring batteries to use less hazardous materials and be made easier to recycle and reuse, the law seeks to reduce the carbon footprint of batteries. Batteries will need to adhere to strict carbon footprint and performance class criteria starting in 2025.

Information and Transparency

Batteries will be branded with comprehensive information that can be accessed by a QR code that links to a digital battery passport, in order to promote transparency and educated decision-making. This will give details about the composition, effect on the environment, and recyclability of the battery.

The timeline for implementation is as follows: 2024: the first prerequisites come into effect; 2025: due diligence requirements, complete recycling and material recovery targets, and more take effect; 2027: battery replaceability and removability requirements are enforced; 2030: assessing if it is feasible to gradually phase out non-rechargeable portable batteries; and 2050: to reach carbon neutrality.

Timeline for Material Recovery: The European Union has set specific quantitative targets for the recovery of materials from electric vehicle lithium-ion batteries as part of its new Battery Regulation. These targets aim to promote recycling, ensure the recovery of critical materials, and support a more circular economy for batteries. Here are the key recovery targets:

Material Recovery Rates: By December 2027, the second column of Table 5 shows that the EU has established the following critical mineral recovery rates from waste batteries.

Table 5. EU recommended material recovery rates and recycled contents.

Metal	Material Recovery Rates	Recycled Contents by 2031	Recycled Contents by 2036
Lithium	50%	6%	12%
Nickel	90%	6%	15%
Cobalt	90%	16%	26%
Copper	90%	6%	12%

These targets represent the minimum percentages of these materials that must be recovered from waste EV batteries.

Recycling Efficiency: The regulation also sets targets for overall recycling efficiency of lithium-based batteries: By December 2025: 65% recycling efficiency, and By December 2030: 70% recycling efficiency. This means that by 2030, at least 70% of the total weight of lithium-ion batteries must be recycled.

Recycled-Content Requirements: Starting in 2031, the third column of Table 5 shows that the new EV batteries placed on the EU market must contain minimum levels of recycled materials.

These percentages represent the minimum amount of each material that must come from non-virgin (recycled) sources.According to the new EU Battery Regulation, the recycled content targets for EV and energy storage batteries set to increase in 2036 are shown in the fourth column of Table 5.

These targets represent the minimum percentage of recycled materials that must be used in new EV and energy storage batteries placed on the EU market by 2036. It is impor-

tant to note that these targets are indeed more ambitious than the ones I initially mentioned. The EU aims to significantly increase the use of recycled materials in battery production over time, promoting a more circular economy for the battery industry. However, experts have raised concerns about the feasibility of meeting these targets, particularly due to the long lifespan of EV batteries and the potential scarcity of recycled materials in the short term. The success of these regulations will depend on factors such as the efficiency of collection systems, advancements in recycling technologies, and the overall growth of the EV market in Europe [29].

In addition to the European Union requirement, several European nations have proposed country specific requirements and are briefly described below.

I. Germany: The Battery Act (BattG), which oversees Germany's battery-recycling program and is compliant with the EU Battery Directive, consists of a vast network of collection locations and contemporary recycling facilities. Producers are tasked with collecting and recycling batteries with government backing. End-of-life management procedures facilitate second-life uses and guarantee safe disassembly. Campaigns for public awareness, unambiguous labeling, and merchant involvement inform customers about appropriate recycling procedures [42]. The recycling framework includes the following:

Legislation: governed by the Battery Act (BattG), which aligns with EU Battery Directive.

Collection Points: wide-ranging network of locations at merchants, government buildings, and vehicle dealerships for collection.

Recycling Facilities: establishments emphasizing pyrometallurgical and hydrometallurgical procedures.

Extended Producer Responsibility (EPR): battery recycling and collecting are the producers' responsibilities.

Government Incentives: funding for recycling programs and research and development for battery recycling technologies.

The end-of-life management includes the following:

Dismantling: EV batteries can be safely disassembled using established techniques.

Second-life Applications: encouragement of second life uses such as stationary energy storage.

Regulations: tight guidelines for handling and getting rid of dangerous substances.

Consumer education includes the following:

Public Awareness Campaigns: initiatives spearheaded by the government and business community to inform people about recycling batteries.

Labels and Instructions: batteries should have clear labels with information on recycling and disposal techniques.

Retailer Engagement: at the moment of sale and collection, retailers assist in educating customers.

II. France: The French Environmental Code and the EU Battery Directive serve as the foundation for France's electric-vehicle-battery-recycling program. France, devoted to upholding EU standards, encourages a circular economy by enforcing strict laws and initiating creative projects that emphasize recycling and reuse in order to cut down on waste and lessen reliance on raw resources [114,115].

The recycling framework consists of the following:

Legislation: France, being an EU member, supports the EU Battery Directive. It is guided by the French Environmental Code. Included in the end-of-life management is the following:

Recycling and reuse: In an effort to lessen waste and dependency on raw materials, France is promoting the recycling and reuse of electric vehicle batteries by enacting strict legislation and funding creative projects that advance a circular economy.

III. Norway: The Waste Regulation in Norway governs the recycling system for electric vehicle batteries and is in line with the EU Battery Directive. Norway imposes stringent environmental standards and evaluates recycling infrastructure performance in order to prevent the emission of harmful pollutants. This encourages sustainable recycling methods and guarantees high standards in the management of trash from EV batteries [45].

1. The framework for recycling comprises the following legal provisions:
   Waste regulation, which is following the EU Battery Directive.
2. End-of-life management

In addition to implementing stringent environmental standards, Norway is actively attempting to minimize the leakage of harmful compounds from EV batteries. Performance studies are being carried out to analyze the availability and effectiveness of recycling infrastructure. This guarantees that the nation upholds strict guidelines for handling the waste from EV batteries and encourages environmentally friendly recycling methods.

Efficiency of recycling infrastructure. This ensures that the country maintains high standards in managing EV battery waste and promotes sustainable recycling practices.

IV. The Netherlands: The Waste Electrical and Electronic Equipment (WEEE) Directive and the EU Battery Directive govern the recycling mechanism for EV batteries in The Netherlands. In line with EU policy, the nation has passed rules to stop the release of harmful materials and regularly assesses the availability and capacity of recycling infrastructure to ensure that hazardous waste is managed effectively [48].

1. Legislation: Legislation is managed under the EU Battery Directive and the Waste Electrical and Electronic Equipment (WEEE) Directive is part of the recycling system. The Netherlands, an EU member, is in favor of the EU's regulations regarding EV batteries. However, the nation has passed rules that specifically address the prevention of the discharge of hazardous chemicals and the need assessment process, which establishes the proper amount of recycling-infrastructure availability.

V. Finland: Finland has a recycling framework that conforms to both national waste legislation and the EU Battery Directive. By limiting hazardous substances, enforcing stringent collection and disposal standards, establishing extended producer responsibility, and regulating hazardous chemicals to safeguard human health and the environment, it focuses on reducing harm from toxic materials in EV batteries [46,47,115].

Finland's legal system, which is heavily impacted by national and EU legislation, aims to stop harmful substances in EV batteries from doing the following:

- Reducing the number of dangerous materials in battery composition.
- Enforcing stringent guidelines for disposal, recycling, and collecting.
- Enforcing extended producer responsibility for the whole lifecycle management of batteries.
- Putting strict hazardous waste management procedures into place.
- Controlling dangerous substances to safeguard both the environment and public health.

VI. Sweden: Sweden's EV-battery-recycling policy is based on the EU Battery Directive. In order to ensure that producers address the environmental implications, its Extended Producer Responsibility (EPR) programs mandate that manufacturers manage the full lifespan of their products, including collection, recycling, and disposal [43,115].

The EU Battery Directive is one piece of legislation that makes up the recycling framework. Sweden, being an EU member, abides by all EU norms and regulations.

VII. Comparison of Frameworks, with the European Union and Other European Union Nations

This is a targeted comparison of frameworks with the European Union and several member nations.

Legislation: While national implementations of the EU Battery Directive differ in terms of extra rules and degree of strictness, all countries comply with it.

Pickup Points: All of them have vast networks, and The Netherlands and Norway have tight integrations with the current waste management systems.

Comprehensive Recycling Technologies: Germany and The Netherlands are at the forefront of this field, with other countries gaining ground.

Robust Extended Producer Responsibility: Programs are prevalent; however, the extent of producer engagement and funding differs.

Government Incentives: Different financial and regulatory assistance levels, with notable incentives from Germany and France.

All nations have high levels of consumer education, but Norway and Finland stand out for their robust public awareness initiatives and merchant engagement. The specific recycling technology employed, the level of government assistance, and the integration of collection systems with the current waste management infrastructures are the main areas of variation amongst the nations. Furthermore, different nations take different approaches to consumer education; some prioritize public advertising, while others focus more on educational initiatives and shop involvement. While the EU sets the overarching framework for EV-battery-recycling policy, individual EU nations may have slightly different implementation details within that framework, with some potentially having stricter collection or recycling targets depending on their specific regulations and infrastructure, but all must adhere to the minimum standards set by the EU's "Battery Regulation", which mandates high recycling rates and recycled content requirements for new batteries across the bloc; essentially, there is a unified policy with some room for individual nation-level adaptation to suit local needs.

3.2.4. The United Kingdom

Following its exit from the European Union, the United Kingdom upheld the Batteries Directive and implemented supplementary policies, including the Extended Producer Responsibility (EPR) program. As per this plan [116]:

Producer Responsibility

EV battery manufacturers are in charge of providing funding for the gathering, processing, and recycling of their goods.

Compliance Schemes

Approved compliance schemes that handle the collection and recycling of batteries on behalf of producers are available for enrollment.

Collection and Recycling

Various battery types, including those used in electric vehicles, have distinct collection and recycling objectives specified for them.

Reporting and Monitoring

Under the supervision of the relevant authorities, producers or compliance schemes are required to report on their performance and adherence to the regulations.

Infrastructure Investment for Recycling

To construct domestic battery recycling facilities, the government is providing funding.

Battery Passport System

To improve battery traceability, the UK is introducing a battery passport system, much like the EU.

Standards and Laws

To facilitate the recycling of EV batteries, the UK is creating particular standards and laws.

Automotive Sector Deal

Developing a circular economy for EV batteries, including recycling, is one of the goals of the UK's Industrial Strategy.

3.2.5. China

China enacted the "Interim Measures for the Management of Recycling and Traceability of Power Batteries for New Energy Vehicles." This policy's important features include [117]:

Traceability System

To monitor EV batteries from manufacture to recycling or disposal, a traceability system has been set up.

Responsibility for Recycling

It is the duty of EV battery manufacturers to create and carry out a recycling strategy for their goods.

Recycling Procedures

It is the responsibility of manufacturers to guarantee that appropriate procedures are followed, such as disassembly, material recovery, and the elimination of any potentially dangerous parts.

Information Sharing

Manufacturers must provide pertinent stakeholders with information on the chemistry, content, and recycling procedures of batteries.

Monitoring and Enforcement

Appropriate authorities keep an eye on how the recycling plans are being carried out and have the authority to penalize non-compliance.

New Energy Vehicle Policy

With goals for recycling rates, China's regulations support the growth of an EV battery circular economy.

Tax Breaks and Subsidies

The government provides financial aid to businesses that recycle batteries.

Regulation Development

China is working hard to create battery-recycling policies that prioritize resource recovery and environmental protection.

3.2.6. South Korea

EV battery recycling is covered by the "Act on Resource Circulation of Electrical and Electronic Equipment and Vehicles" in South Korea. Important elements of this consist of the following [38,118–120]:

Producer Responsibility

EV battery producers are in charge of setting up and funding a recycling program for their goods.

Recycling Objectives

Separate objectives are established for various battery kinds, including EV batteries.

Collection and Transportation

To ensure that spent EV batteries are properly transported to recycling facilities, manufacturers must set up a national collection system. K-Eco and private companies have a program to collect, repurpose, and recycle EOL EV batteries.

Recycling Procedures

To salvage valuable materials and get rid of dangerous parts, the right recycling procedures must be followed.

Reporting and Monitoring

Producers must provide information about the effectiveness of their recycling initiatives, and the government keeps an eye on whether the rules are being followed.

Initiatives for the Circular Economy

In line with South Korea's Green Energy push, recent regulation adjustments permit the ecologically beneficial use of old EV batteries. This involves looking into used battery-based energy storage options and renting batteries for electric vehicle taxis.

Government Incentives

A USD 60.9 billion investment plan is included in the Green New Deal (2020), which is a component of South Korea's larger plan to move to a low-carbon economy. It seeks to create smart grids, stop supporting foreign coal plants, increase the number of green mobility vehicles, turn urban areas into smart green cities, and impose a carbon tax.

Industry Developments

Hyundai Glovis and KST Mobility are working together to recycle and manage used electric vehicle batteries, and Hyundai Motor Co. and LG Chem Ltd. are investigating the possibility of repurposing spent batteries for energy storage systems and other uses.

3.2.7. Japan

In Japan, the end-of-life (EOL) management strategy for EV lithium-ion batteries predominantly emphasizes a "cascaded usage" model, wherein batteries are initially repurposed for stationary energy storage applications prior to being recycled for the recovery of valuable materials. Prominent entities such as Sony and Sumitomo spearhead recycling initiatives employing a combination of pyrometallurgical and hydrometallurgical techniques, often in collaboration with automotive manufacturers like Nissan. This framework is significantly influenced by the "Act on the Promotion of Effective Utilization of Resources" and the principle of Extended Producer Responsibility (EPR) to promote effective collection and recycling practices [121–123]. Japan is promoting a circular economy through the 4th

Circular Society Plan (2018), which focuses on resource lifecycle management and waste processing. The plan was driven by the "Basic Law for Establishing the Recycling-based Society" that was passed in 2000. While government incentives like the Japan Energy Plan and Green Growth Strategy stimulate sustainable growth22, the Top Runner Program enforces energy efficiency standards [121–123].

Legislation

While there are no specific regulations solely for EV battery recycling, the "Act on the Promotion of Effective Utilization of Resources" encourages responsible management of waste batteries and promotes EPR principles. Japan's circular economy is founded on the "Basic Law for Establishing the Recycling-based Society", which was passed in 2000 and encourages green activities in the public, private, and government sectors.

Collection and Collection Points

Used EV batteries are collected from auto dealerships and specific collection locations by networks established by automakers and recycling businesses.

Recycling Process

a. Pre-processing: Batteries are disassembled to separate components like plastics and metals.
b. Pyrometallurgy: High-temperature processing to extract valuable metals like nickel, cobalt, and lithium.
c. Hydrometallurgy: Aqueous chemical processes to further purify and separate metals for reuse in new battery production.

Key Players in Recycling

Companies like Sony, Sumitomo, and J-Cycle are major players in battery recycling, often utilizing their expertise in battery manufacturing for efficient recycling processes.

Circular Economy Plans: The 4th Plan for Establishing a Circular Society (2018) Focuses on the following

a. Regional revitalization through a circularization of materials system.
b. Full circularizing throughout the life cycle of resources.
c. Appropriate processing of waste or regeneration of resources.

Circular Economy Initiatives

A highly acclaimed program called the Top Runner Program selects features associated with high-performing products and sets standards that other products in the same category must match or surpass in order to create new energy efficiency benchmarks. It encourages conformity with a combination of economic and command-and-control measures, such as the "name and shame" strategy.

Government Incentives

Through a variety of financial incentives and legal frameworks, Japan's policies and plans—such as the Japan Energy Plan and the Japan Green Growth Strategy—support sustainable growth and energy efficiency.

3.2.8. Chile

Chile is exploring policies to support battery recycling, given its significant lithium production [96].

3.2.9. Brazil

Brazil is developing regulations to manage the recycling of EV batteries, focusing on sustainability and environmental protection [71].

3.2.10. Argentina

Argentina is actively involved in the development of electric vehicle batteries through various initiatives. The country is focusing on boosting its lithium production, a key component for EV batteries, by investing in mining operations and establishing partnerships with international companies. Argentina aims to leverage its rich lithium reserves to become a major player in the global EV battery market while also working on local manufacturing and technological advancements to support the growing demand for electric vehicles [87].

3.3. Key Comparisons

Over time, philosophies have been changing, with some important variations in approach; the philosophies on Extended Producer Responsibility (EPR) for EV lithium-ion batteries are developing in the European Union and the United States.

3.3.1. European Union

A more extensive and well-established EPR framework for batteries, including electric vehicle lithium-ion batteries, is available in the European Union:

Mandatory EPR: The EU expects manufacturers to be accountable for batteries' whole lifetime, including collecting and recycling [124].

Ambitious targets: The European Union has established recycling efficacy targets for batteries with the objective of recovering a significant portion of the materials [124].

Eco-design focus: There is a strong emphasis on designing batteries for easier disassembly and recycling [125].

3.3.2. United States:

The US approach to EPR for EV lithium-ion batteries is less uniform and still evolving:

State-level initiatives: The primary implementation of EPR laws for batteries is at the state level, with varying requirements across various jurisdictions [126].

Growing momentum: EPR laws for batteries, including EV batteries, are being considered or implemented in an increasing number of states [126].

Voluntary programs: Some manufacturers are implementing voluntary take-back and recycling programs for EV batteries [127].

3.3.3. Key Differences

Regulatory approach: The EU has a more centralized, mandatory approach, while the US relies more on state-level initiatives and voluntary programs.

Scope: EU regulations cover a broader range of battery types and set more comprehensive targets, whereas US programs are often more limited in scope.

Recycling infrastructure: The EU is generally ahead in developing recycling infrastructure for EV batteries, driven by its more established EPR framework.

As the market for electric vehicles continues to expand, both areas are becoming aware of the necessity of more stringent EPR rules for lithium-ion batteries in order to address environmental issues and the lack of resources. A more sophisticated and standardized strategy is now being taken by the European Union in comparison to the United States, even though the trend is toward more producer responsibility.

3.3.4. End-of-Life Management

The responsibilities for end-of-life management of EV lithium-ion batteries are shifting in both the USA and EU, with a trend towards increased producer responsibility:

United States

In the past:

- Responsibility was primarily on consumers and local governments.
- Limited producer involvement in end-of-life management
- Current trends:
- Increasing state-level EPR laws for batteries, including EV batteries [127]
- Producers are becoming more responsible for collection and recycling.
- Some manufacturers are implementing voluntary take-back programs [127]

European Union

In the past:

- More established EPR framework compared to the US.
- Producers had some responsibility, but it was less comprehensive.

Current trends:

- Mandatory EPR for batteries, including EV lithium-ion batteries.
- Producers are responsible for the entire lifecycle, including collection and recycling [126]
- More ambitious recycling targets and eco-design requirements [124]

3.3.5. Key Changes

1. Shift in responsibility: Both regions are moving from consumer/government responsibility towards increased producer responsibility [124,127]
2. Scope expansion: EPR laws are expanding to cover more types of batteries and packaging materials [126,128]
3. Financial responsibility: Producers are increasingly required to fund collection and recycling programs [124,127]
4. Design considerations: There is a growing emphasis on designing products for easier disassembly and recycling, especially in the EU [124]
5. Recycling targets: Both regions are setting more ambitious recycling efficiency targets, with the EU generally having more comprehensive goals [124,126]

As the world moves toward a more circular economy, these changes show that producers are becoming more responsible for how their goods affect the environment throughout their whole lifecycle.

3.3.6. Glance at US

End-of-life management obligations for lithium-ion batteries used in electric vehicles are changing significantly in the US, especially since EPR regulations were implemented. Here is a summary of who is in charge of these batteries, the changes in accountability throughout time, and the most recent trends:

- Past Responsibilities

Consumers and Local Governments: In the past, customers and local governments were mostly in charge of handling end-of-life batteries. Batteries were frequently disposed of by consumers without explicit instructions, which resulted in inappropriate disposal techniques.

Limited Producer Accountability: Regarding the collecting or recycling of their products following customer usage, battery manufacturers have few responsibilities.

- Evolving Responsibilities

Producers: Manufacturers are being held more and more responsible for the full lifecycle of their batteries under the new EPR regulations. This comprises:

Collection and Recycling: Producers must establish systems for the collection and recycling of EV batteries.

Consumer Education: They are required to inform consumers about recycling options and proper disposal methods [129,130]

Management Plans: Producers must submit battery management plans to state environmental agencies for approval, detailing how they will handle end-of-life batteries [125]

- Recent Legislative Developments

New Jersey's EPR Law: New Jersey became the first state to pass an EPR law tailored especially for electric vehicles in January 2024. This rule requires battery manufacturers to develop management strategies and assume ownership of safe disposal and recycling [129,130].

Other States: Though they may not especially include EV batteries yet, several other states also instituted EPR rules addressing battery recycling. Although recently vetoed, California's planned law aimed at a thorough take-back scheme demonstrates continuous debates on producer obligations [130,131].

- Current Trends

Increased Producer Responsibility

Growing Momentum: There is a noticeable shift towards more robust EPR frameworks across various states in the US This includes:

State-Level Initiatives: States like California and Washington are developing their own EPR laws, which may expand to include EV batteries in the future.

Federal Guidance: The EPA has issued guidance recognizing lithium-ion batteries as hazardous waste at end-of-life, prompting states to consider stricter regulations [75]

- Future Directions

Core Exchange Programs: Some proposals suggest implementing core exchange programs where manufacturers would take back old batteries when selling new ones. This would ensure proper recycling and reuse of materials [132,133]

Recycling Infrastructure Development: As more EVs reach the end of their life cycles, there is an urgent need to develop a robust recycling infrastructure capable of handling large volumes of spent batteries [132]

The way that EPR is developing in the US is indicative of a larger movement toward environmental responsibility and sustainability, as manufacturers are being asked to assume greater accountability for their lifecycle. This change attempts to reduce environmental risks related to inappropriate battery disposal in addition to increasing recycling rates.

3.3.7. Difference in Philosophies

Extended producer responsibility for electric vehicle lithium-ion batteries is handled differently by the European Union and the United States. The EU's tighter system mandates manufacturers to control the lifetime of the battery, including eco-design and recycling. Using a distributed model, the US lets firms engage in voluntary initiatives at the state level. Both areas are approaching increasing producer accountability, comprehensive laws, and high recycling targets. The worldwide movement toward a circular economy highlights the need of stricter EPR rules.

3.3.8. Comparison of New Jersey and European Union

Based on the descriptions in Section 3.2, out of all regions and nations, it appears that EU and the State of New Jersey have the most comprehensive set of policies and regulations. Hence, Table 6 provide a companion.

Table 6. Key differences between the European Union and New Jersey.

Category	European Union	New Jersey
Regulatory Framework	The European Union has a thorough and consistent regulatory framework that applies to all member states according to the EU Battery Regulation [29] and the Battery Directive.	New Jersey follows a state-specific framework within the broader federal guidelines under the Electric and Hybrid Vehicle Battery Management Act. [40,54]
Producer Responsibility	Adopt EPR programs that mandate manufacturers handle batteries that have reached the end of their useful lives [54].	Adopt EPR programs that mandate manufacturers handle batteries that have reached the end of their useful lives [54].
Recycling Infrastructure	European Union guarantees that member states' recycling infrastructure is developed consistently [29].	The State of New Jersey focuses on state-specific infrastructure development, supported by federal norms [40,54].
Consumer Awareness	Promote public awareness initiatives and disseminate information on appropriate recycling and disposal practices [29,54]	Promote public awareness initiatives and disseminate information on appropriate recycling and disposal practices [29,54]
Financial Incentives	The European Union provides a substantial amount of financing for infrastructure development, innovation, and research. A EUR 2.9 billion assistance package for a pan-European research and innovation project along the full battery value chain was authorized by the European Commission in early 2021. The project specifically relates to raw and advanced materials, battery cells and systems, recycling, and sustainability [100]	The State of New Jersey provides incentives to consumers for returning batteries and grants and subsidies to increase recycling capacity [99].
Information and Transparency	The European Union has proposed a battery passport. The EU's battery passport, mandatory from 2027, is a digital system for EV and large industrial batteries. It uses QR codes to track each battery's lifecycle, composition, and performance. This initiative aims to improve sustainability, recycling, and transparency in the battery industry.	EV battery labels in New Jersey should include the battery's chemical composition, a recycling statement, and the brand name. The label must be visible and use contrasting colors. Manufacturers must also provide information on battery health, warranty terms, and safety procedures, though this does not necessarily need to be on the label itself. And recycling companies believe that battery passports would produce barriers to effective recycling and supply chain difficulties; battery passports mandate that battery producers create environmentally friendly and socially conscious batteries. To accomplish this shared goal, however, many things must first be in place, such as compatible technologies for data collection, processing, and sharing and a trained staff to document the data [134].

The EPR for electric vehicle EV lithium-ion batteries is developed differently in the EU and US. The EU has developed a thorough and obligatory EPR system whereby manufacturers must control the whole battery lifetime, including eco-design for simpler material recovery and disposal as well as collecting and recycling. Underline the EU's approach are ambitious recycling targets and a focus on sustainability. On the other hand, the US uses a distributed model whereby manufacturers' voluntary programs and state-level projects are implemented. While some states are progressively implementing similar policies, others such as New Jersey have pioneered particular EPR rules for electric batteries. Although customers and local governments have handled end-of-life batteries in the US, new trends show manufacturers taking on more responsibility, including consumer education, management strategies, and creation of recycling systems.

Important distinctions between the areas include the EU's centralized and more extensive regulatory authority as opposed to the US's diversified and restricted initiatives. Because of its developed EPR rules, the EU also leads in recycling infrastructure. Still, both areas are

moving toward more producer responsibility, broad legislation covering more battery kinds, and more ambitious recycling goals. Emerging US trends include ideas for central exchange programs and strong recycling systems to manage the increasing number of end-of-life electric vehicles. This worldwide shift toward a circular economy emphasizes the necessity of tougher EPR regulations to handle environmental issues and guarantee sustainability in handling EV battery lifetime. Hence, in this section, an attempt was made to compare policies and regulations of EU with the newly released NJ law. The comparison in Table 6 highlights improvements needed as well as over regulations that should not be adopted.

4. Recommendations for Effective Regulatory Approaches

To optimize sustainability contributions while highlighting the impact of climate change, the following features of an optimally successful EV battery management program would be anticipated:

- The program would address a complex matrix of ownership and responsibility for collection, repair, extended use, and ultimately recycling, based on the reality that the majority of end-of-life batteries will not be managed by consumers, but rather by repair facilities, auto dealers or manufacturers, or vehicle demolition facilities.
- The program would acknowledge the economic and environmental value of the end-of-life batteries and would facilitate collection, transportation, and recycling. When prolonged use has occurred, like in the case of electrical power storage, other parties may be involved in the end-of-life process. Thus, the management system ought to be adaptable enough to handle a range of circumstances while maintaining accountability.
- Legislative programs should acknowledge efforts that are ongoing to create novel battery chemistries, occasionally with the use of alternative building materials, in order to enhance the performance of EV batteries. This indicates that in order to prevent instances where sub-optimal material recovery occurs from new battery design, a management program should not be unduly specific in mandating or preferring technologies or recycling processes. Encouraging maximal material recovery and reuse, facilitating energy-efficient processing, and minimizing waste creation during processing all require appropriate regulatory incentives.
- The program needs to be designed with the understanding that gathering, storing, and transporting end-of-life batteries is an essential part of recycling EV batteries. Right now, there are worries about a potential fire brought on by a battery integrity issue. Because of this, a management strategy needs to deal with storage and transit concerns, perhaps in coordination with US DOT regulations. Noting that the delivery of a single ton of battery units requires energy consumption, recycling processing facilities should be located near appropriate travel distances of densely populated areas.
- The battery management program should be designed in a way that facilitates the extended use of EV batteries that are no longer suitable for efficient usage in vehicles, due to the sustainability benefits associated with this practice. This may necessitate, among other things, paying attention to assigning accountability for final recycling in order to ensure efficient progress toward ultimate recycling when prolonged usage becomes unfeasible.
- Although the market forces governing raw materials promote the use of recycled materials in the production of batteries, further incentives in favor of this practice could increase the strategy's acceptability. These incentives, including tax breaks, might be created and implemented at the state or federal levels, but they would probably be distinct from a battery management strategy.
- Effective regulatory approaches should include socioeconomic aspects for successful implementation.

5. Summary and Conclusions

With the explosive growth of the use of EVs, different countries and regions of the world are developing legislation and policies for the end-of-life management of LIBs in EVs. The end-of-life management of LIBs in EVs is needed to address issues such as resource recovery, safe disposal and transportation, avoidance of hazardous gas emissions, circularity, resource use, fire prevention, and expanded producer accountability. This manuscript summarizes and provides legislation and policies that are adopted by different countries and regions of the world for the end-of-life management of LIBs in EVs. Deeper analysis of legislation and policies of different countries and regions of the world showed that the EU and the State of New Jersey have the most comprehensive set of policies and regulations for the end-of-life management of LIBs in EVs. However, the thinking behind the EU's and the State of New Jersey's policies and regulations for the end-of-life management of LIBs in EVs are quite different because of the EPR for EV lithium-ion batteries. The manuscript suggests improvements to end-of-life management of LIBs in EVs based on comparison of policies and regulations of EU and the State of New Jersey policies. Effective regulatory approaches should include socioeconomic aspects for successful implementation.

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Abbreviations

EV	Electric Vehicle
ZEV	Zero Emission Vehicle
DOD	Depth Of Discharge
LIB	Lithium Ion Battery
LCA	Life Cycle Analysis
EOL	End Of Life
BESS	Battery Energy Storage System
EU	European Union
EPR	Extended Producer Responsibility
PHEV	Plug in Hybrid Eclectic Vehicle
USABC	United States Advanced Battery Consortium
AAA	American Automobile Association
IEA	International Energy Agency
EPR	Extended Producer Responsibility
ZE-MHDV	Zero-Emission Medium- and Heavy-Duty Vehicle
CEC	California Energy Commission

References

1. International Energy Agency. Global EV Outlook 2023: Catching up with Climate Ambitions. 2023. Available online: https://iea.blob.core.windows.net/assets/dacf14d2-eabc-498a-8263-9f97fd5dc327/GEVO2023.pdf (accessed on 26 August 2024).
2. Argonne National Laboratory; Carlier, M. Estimated Plug-In Electric Light Vehicle Sales in the United States from 2016 to 2022 (in 1000 units). Argonne National Laboratory. Available online: https://www.statista.com/statistics/665823/sales-of-plug-in-light-vehicles-in-the-us/ (accessed on 26 August 2024).
3. Renewable and Sustainable Energy Reviews. 191, 114176.111. Jaeger, J. These Countries Are Adopting Electric Vehicles the Fastest. World Resources Institute. Available online: https://www.wri.org/insights/countries-adopting-electric-vehicles-fastest (accessed on 30 October 2024).
4. Tabuchi, H.; Plumer, B. How Green Are Electric Vehicles? *New York Times*, 23 June 2021. Available online: https://www.nytimes.com/2021/03/02/climate/electric-vehicles-environment.html (accessed on 16 October 2024).
5. Biden-Harris. Administration Announces New Standards and Major Progress for a Made-in-America National Network of Electric Vehicle Chargers. The White House. 2023. Available online: https://www.whitehouse.gov/briefing-room/statements-releases/2023/02/15/fact-sheet-biden-harris-administration-announces-new-standards-and-major-progress-for-a-made-in-america-national-network-of-electric-vehicle-chargers (accessed on 26 August 2024).
6. America's Clean Future Fund Act, S.395, 117th Congress. Congress.gov. 2021. Available online: https://www.congress.gov/bill/117th-congress/senate-bill/395 (accessed on 30 October 2024).
7. Electric Vehicle Myths. U.S. Environmental Protection Agency. 2023. Available online: https://www.epa.gov/greenvehicles/electric-vehicle-myths#fn-2 (accessed on 30 October 2024).
8. Amazon. Motorcraft Battery—BAGM94RH7800. 2024. Available online: https://www.amazon.com/dp/B09GW7N7HT?linkCode=ogi&tag=pop-lift-20&ascsubtag= (accessed on 26 August 2024).
9. EVGAS. Bring the Power of EV Charging to Your Customers. 2024. Available online: https://getevgas.com/ (accessed on 26 August 2024).
10. Motavalli, J. Massive EV Batteries Deliver Big Range—And Tons of Curb Weight. *Autoweek*, 16 March 2022. Available online: https://www.autoweek.com/news/a39449944/problem-with-ev-battery-weight/ (accessed on 26 August 2024).
11. Elements 2024, "Visualizing the Supply Deficit of Battery Minerals (2024-2034P),". *Elements Newsletter*, 20 December 2024. Available online: https://elements.visualcapitalist.com/visualizing-the-supply-deficit-of-battery-minerals-2024-2034p/ (accessed on 20 December 2024).
12. Witt, J.; Najman, L. Electric Car Battery Replacement Costs. *Recurrent*, 3 December 2024. Available online: https://www.recurrentauto.com/research/costs-ev-battery-replacement (accessed on 26 August 2024).
13. Kurczewski, N. How Much Does It Cost to Charge an Electric Car? Kelley Blue Book. 2024. Available online: https://www.kbb.com/car-advice/how-much-does-it-cost-to-charge-an-electric-car/ (accessed on 26 August 2024).
14. Hunt, G. Electric Vehicle Battery Test Procedures Manual Revision 2. 1996. Available online: https://avt.inl.gov/sites/default/files/pdf/battery/usabc_manual_rev2.pdf (accessed on 26 August 2024).
15. Martinez-Laserna, E.; Gandiaga, I.; Sarasketa-Zabala, E.; Badeda, J.; Stroe, D.-I.; Swierczynski, M.; Goikoetxea, A. Battery second life: Hype, hope or reality? A critical review of the state of the art. *Renew. Sustain. Energy Rev.* **2018**, *93*, 701–718. [CrossRef]
16. Meegoda, J.; Charbel, G.; Watts, D. Sustainable Management of Rechargeable Batteries Used in Electric Vehicles. *Batteries* **2024**, *10*, 167. [CrossRef]
17. Sustainable Battery Materials Process. Redwood Materials. 2023. Available online: https://www.redwoodmaterials.com/news/sustainable-battery-materials-process/ (accessed on 13 November 2024).
18. Statista. Available Materials from Global Battery Recycling, by Material 2022. *Statista*. 2024. Available online: https://www.statista.com/statistics/1415338/battery-recycling-material-available-worldwide/ (accessed on 19 November 2024).
19. Worldwide EV Battery Recycling Capacity by Country. Statista. 2023. Available online: https://www.statista.com/statistics/1333941/worldwide-ev-battery-recycling-capacity-by-country/ (accessed on 13 November 2024).
20. Statista. Revenue Opportunity in Battery Reuse and Recycling by Country in 2021 and Projections to 2040. Statista. 2024. Available online: https://www.statista.com/statistics/1103253/revenue-opportunity-ruse-recycle-by-country/ (accessed on 19 November 2024).
21. Statista. EU Battery Directive: Mineral recovery targets for batteries in Europe by material (2025 and 2030). Statista. 2024. Available online: https://www.statista.com/statistics/1333043/eu-battery-directive-mineral-recovery-targets/ (accessed on 19 November 2024).
22. Meegoda, J.; Charbel, G.; Watts, D. Second Life of Used Lithium-Ion Batteries from Electric Vehicles in the USA. *Environments* **2024**, *11*, 97. [CrossRef]

23. California State Legislature, State of California. Battery Energy Storage Facilities: Emergency Response and Emergency Action Plans, Senate Bill 38. 2023. Available online: https://legiscan.com/CA/text/SB38/id/2832565#:~:text=California%20Senate%20Bill%2038&text=Bill%20Title:%20Battery%20energy%20storage,response%20and%20emergency%20action%20plans.&text=An%20act%20to%20amend%20Section,Utilities%20Code,%20relating%20to%25 (accessed on 26 August 2024).
24. Illinois General Assembly, State of Illinois. Environmental Protection Act, Senate Bill 3481. 2024. Available online: https://legiscan.com/IL/text/SB3481/id/2920420 (accessed on 26 August 2024).
25. Busch, J. New GB Standard GB 18384-2020 about Electric Vehicles Safety Requirements. MPR China Certification. 2024. Available online: https://www.china-certification.com/en/new-gb-standard-gb-18384-2020-about-electric-vehicles-safety-requirements/ (accessed on 26 August 2024).
26. Busch, J. Revision of GB 38031-2020: Safety Requirements for Power Batteries for Electric Vehicles. MPR China Certification. 2024. Available online: https://www.china-certification.com/en/revision-of-gb-38031-2020-safety-requirements-for-power-batteries-for-electric-vehicles/ (accessed on 26 August 2024).
27. Washington State Legislature, State of Washington. An Act Relating to Providing for Responsible Environmental Management of Batteries, Senate Bill 5144. 2023. Available online: https://lawfilesext.leg.wa.gov/biennium/2023-24/Pdf/Bill%20Reports/Senate/5144%20SBR%20WM%20TA%2023.pdf (accessed on 26 August 2024).
28. State of Illinois. Electronics-Lithium Batteries, SB3206. 2024. Available online: https://www.ilga.gov/default.asp (accessed on 26 August 2024).
29. The European Parliament and The Council of The European Union. Concerning Batteries and Waste Batteries, Amending Directive 2008/98/EC and Regulation (EU) 2019/1020 and Repealing Directive 2006/66/EC. *Off. J. Eur. Union* **2023**. Available online: https://eur-lex.europa.eu/eli/reg/2023/1542/oj/eng (accessed on 26 August 2024).
30. Popova, A. EV Battery Regulations Around the World: What You Need to Know. MINESPIDER. 2022. Available online: https://www.minespider.com/blog/ev-battery-regulations-around-the-world-what-you-need-to-know (accessed on 26 August 2024).
31. Australian Government, Department of Industry Science and Resources. Priority 4: Sustainability, ESG and Circular Economy. National Battery Strategy. Available online: https://www.industry.gov.au/publications/national-battery-strategy/priority-4-sustainability-esg-and-circular-economy#:~:text=The%20National%20Waste%20Policy%20Action%20Plan%20outlines%20how,batteries%20and%20e-waste%20materials%20in%20landfill%20by%202024 (accessed on 26 August 2024).
32. Canadian Centre for Occupational Health and Safety. Transportation of Dangerous Goods (TDG)—Overview (Road). Canadian Centre for Occupational Health and Safety. 2024. Available online: https://www.ccohs.ca/oshanswers/legisl/tdg/tdg_overview.html (accessed on 26 August 2024).
33. Ministry of Justice, Government of Canada. Transportation of Dangerous Goods Act. Justice Laws Website. 2024. Available online: https://laws-lois.justice.gc.ca/PDF/T-19.01.pdf (accessed on 26 August 2024).
34. Environment Agency. Waste Batteries: Producer Responsibility. Business and the Environment. Available online: https://www.gov.uk/guidance/waste-batteries-producer-responsibility#vehicle-and-automotive-battery-producer-register (accessed on 26 August 2024).
35. Mobility Foresight. Mexico EV Battery Recycling Market. 2024. Available online: https://mobilityforesights.com/product/mexico-ev-battery-recycling-market/ (accessed on 26 August 2024).
36. State of Maine. An Act to Transition State and Local Motor Vehicle Fleets to 100 Percent Zero-Emission Vehicles, S.P. 456.0. 2021. Available online: https://legislature.maine.gov/legis/bills/display_ps.asp?LD=1579&snum=130 (accessed on 26 August 2024).
37. The European Union. Batteries: Ensuring That Batteries Placed on the EU Market Are Sustainable and Circular Throughout Their Whole Life Cycle. An official EU website. Available online: https://environment.ec.europa.eu/topics/waste-and-recycling/batteries_en (accessed on 26 August 2024).
38. South Korean Ministry of Environment. Act on Resource Circulation of Electrical and Electronic Equipment and Vehicles (EEEV Act). 2019. Available online: https://www.iea.org/policies/16960-act-on-resource-circulation-of-electrical-and-electronic-equipment-and-vehicles-eeev-act (accessed on 26 August 2024).
39. Australian Battery Stewardship Council. B-Cycle Positive Charge. 2023. Available online: https://bcycle.com.au/wp-content/uploads/2023/12/B-cycle-Positive-Charge-Report-20231207.pdf (accessed on 26 August 2024).
40. State of New Jersey. Electric and Hybrid Vehicle Battery Management Act, Bill S3723 ScaAaSa (3R). 2024. Available online: https://www.njleg.state.nj.us/bill-search/2022/S3723 (accessed on 26 August 2024).
41. Garden, L. New Jersey Has Made It Illegal to Discard EV Batteries in Landfills. TRELLIS. 2024. Available online: https://trellis.net/article/new-jersey-has-made-it-illegal-discard-ev-batteries-landfills (accessed on 26 August 2024).
42. Gesetz Über Das Inverkehrbringen. Die Rücknahme Und Die Umweltverträgliche Entsorgung von Batterien Und Akkumulatoren (Batteriegesetz-BattG). Available online: https://www.gesetze-im-internet.de/ (accessed on 26 August 2024).
43. Bestämmelser, Ö. Första Avdelningen. Available online: https://faolex.fao.org/docs/pdf/swe50970.pdf (accessed on 26 August 2024).

44. State of California, California Lithium-Ion Battery Recycling Advisory Group Act. Assembly Bill 2832, (California State Legislature, 2018). Available online: https://leginfo.legislature.ca.gov/faces/codes_displaySection.xhtml?sectionNum=42450.5&lawCode=PRC (accessed on 26 August 2024).
45. The National. How Norway Is Turning Used Car Batteries into Black Gold. Business Technology. 2023. Available online: https://www.thenationalnews.com/business/technology/2023/07/06/how-norway-is-turning-used-car-batteries-into-black-gold/#:~:text=But%20this%20black%20gold%20%E2%80%93%20a,,%20cobalt,%20lithium%20and%20graphite (accessed on 26 August 2024).
46. Ministry of the Environment. Translation from Finnish Legally Binding Only in Finnish and Swedish. Available online: https://www.finlex.fi/fi/laki/kaannokset/2011/en20110646_20220494.pdf., (accessed on 26 August 2024).
47. Paristokierratys. Producer Responsibility in Legislation. Available online: https://www.paristokierratys.fi/en/for-producers/producer-responsibility-in-legislation/ (accessed on 26 August 2024).
48. Shoshan, A.; Gervasi, E.; Kes, J.; Plaisier, F.; Wagemaker, M. Circular Batteries Charging the Future. Colophon. Available online: https://english.rvo.nl/sites/default/files/2023-11/HCH-Circular-Batteries-Charging-the-Future-Brochure.pdf (accessed on 26 August 2024).
49. The European Commission. Delivering the European Green Deal. Legal documents on Delivering the European Green Deal. 2023. Available online: https://commission.europa.eu/publications/legal-documents-delivering-european-green-deal_en (accessed on 26 August 2024).
50. State of California. Vehicle Traction Batteries, Senate Bill 615. California Legislature. 2024. Available online: https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=202320240SB615 (accessed on 26 August 2024).
51. Farmer, A.; Watkins, E. Managing Waste Batteries from Electric Vehicles the Case of the European Union and Japan. 2023. Available online: https://ieep.eu/wp-content/uploads/2023/05/Managing-waste-batteries-from-EVs-JP-and-EU-May-2023.pdf (accessed on 26 August 2024).
52. National Research Council Canada. Advanced Clean Energy Program: Battery Energy Storage. Research and Collaboration Program. 2023. Available online: https://nrc.canada.ca/en/research-development/research-collaboration/programs/advanced-clean-energy-program-battery-energy-storage (accessed on 26 August 2024).
53. Guthire, S. What Happens to Old Electric Car Batteries? DRIVE. 2024. Available online: https://www.drive.com.au/caradvice/what-happens-to-old-electric-car-batteries/#comments (accessed on 26 August 2024).
54. State of New Jersey. Electric and Hybrid Vehicle Battery Management Act, Bill A5365 AcaAa (2R). 2024. Available online: https://www.njleg.state.nj.us/bill-search/2022/A5365 (accessed on 26 August 2024).
55. State of New Mexico. Trade Practices and Regulations Article 30—Sale of Recycled Metals. Battery Policies and Incentives. Available online: https://www.energy.gov/eere/vehicles/battery-policies-and-incentives-search#/?jurisdiction=NM (accessed on 26 August 2024).
56. State of Maine, Maine Economic Development and Energy Programs. Battery Policies and Incentives. 2021. Available online: https://www.energy.gov/eere/vehicles/battery-policies-and-incentives-search#/?show=result&id=120 (accessed on 26 August 2024).
57. State of Minnesota, Minnesota Economic Development and Energy Programs. Batteries Policies and Incentives. 2021. Available online: https://www.energy.gov/eere/vehicles/battery-policies-and-incentives-search#/?show=result&id=117 (accessed on 26 August 2024).
58. State of New Mexico, New Mexico Economic Development and Energy Programs. Battery Policies and Incentives. 2021. Available online: https://www.energy.gov/eere/vehicles/battery-policies-and-incentives-search#/?show=result&id=89 (accessed on 26 August 2024).
59. State of North Carolina. North Carolina Economic Development and Energy Programs. Battery Policies and Incentives. Available online: https://www.energy.gov/eere/vehicles/battery-policies-and-incentives-search#/?show=result&id=84 (accessed on 26 August 2024).
60. State of Wisconsin, Wisconsin Public Service Commission's Office of Energy Innovation (OEI). Renewable Energy and Energy Storage Grant Program. Battery Policies and Incentives. Available online: https://www.energy.gov/eere/vehicles/battery-policies-and-incentives-search#/?show=result&id=177 (accessed on 26 August 2024).
61. Brodie, S. The China Battery Energy Storage System (BESS) Market. New Energy for A New Era. Cushman and Wakefield. 2024. Available online: https://www.cushmanwakefield.com/en/greater-china/insights/china-battery-energy-storage-system-report-2024 (accessed on 26 August 2024).
62. State of Maine. Battery Storage System Decommissioning Plan Requirements. Battery Policies and Incentives, United States of America. 2024. Available online: https://www.energy.gov/eere/vehicles/battery-policies-and-incentives-search#/?show=result&id=304 (accessed on 26 August 2024).
63. Battery Stewardship Council Australia. Electric Vehicle Battery Stewardship Discussion Paper under Waste Reduction and Recycling Act 2020. 2023. Available online: https://bcycle.com.au/wp-content/uploads/2023/04/BSC_FCAI_MTAA-EVB-Stewardship-Discussion-Paper-20230402.pdf (accessed on 26 August 2024).

64. LaMotte, R.; Clare, J. California Passes Two New Laws to Overhaul State's Battery Extended Producer Responsibility Program and Broadly Expand State's E-Waste Program. Beveridge & Diamond. 2022. Available online: https://www.bdlaw.com/publications/california-passes-two-new-laws-to-overhaul-states-battery-extended-producer-responsibility-program-and-broadly-expand-states-e-waste-program/ (accessed on 26 August 2024).
65. State of California, California State Legislature. Responsible Battery Recycling Act of 2022, AB 2440. 2022. Available online: https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=202120220AB2440 (accessed on 26 August 2024).
66. State of New Hampshire. Establishing a Committee to Study Extended Producer Responsibility, House Bill 253. 2023. Available online: https://www.energy.gov/eere/vehicles/battery-policies-and-incentives-search#/?show=result&id=289 (accessed on 26 August 2024).
67. The State Council, Ministry of Industry and Information Technology. English.Gov.Cn. 2024. Available online: https://english.www.gov.cn/state_council/2014/08/23/content_281474983035940.htm (accessed on 26 August 2024).
68. Gorjala, M.; More, J.R. New Jersey Enacts Extended Producer Responsibility Law for Electric Vehicle Batteries. Environmental Update. 2024. Available online: https://natlawreview.com/article/new-jersey-enacts-extended-producer-responsibility-law-electric-vehicle-batteries (accessed on 26 August 2024).
69. Gorjala, M.; More, J.R. New Jersey Enacts Extended Producer Responsibility Law for Electric Vehicle Batteries. ArentFox Schiff. 2024. Available online: https://www.afslaw.com/perspectives/environmental-law-advisor/new-jersey-enacts-extended-producer-responsibility-law (accessed on 26 August 2024).
70. Wilkins, D.; Kuna, J. State Policymakers and EV Battery Recycling. 2023. Available online: https://www.isri.org/docs/default-source/state-program/summit-fact-sheet_policymakers.pdf (accessed on 26 August 2024).
71. Brazilian NR. Brazilian Environmental Legislation. Brazilian National Policy on Solid Waste. 2010. Available online: https://braziliannr.com/brazilian-environmental-legislation/law-no-12305-brazilian-national-policy-solid-waste/ (accessed on 26 August 2024).
72. State of California, California State Legislature. Vehicle Code: Infractions. 2023. Available online: https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=202320240AB1125 (accessed on 26 August 2024).
73. Stone, M. EU's Bold Move: Revolutionizing EV Battery Recycling. Grist. 2023. Available online: https://ethicalhour.com/environment-sustainability/eus-bold-move-revolutionizing-ev-battery-recycling/#:~:text=The%20EU%20is%20now%20following,back%20all%20batteries%20for%20rec (accessed on 26 August 2024).
74. State of Virginia. Imposition of Tax on Privilege of Severing Other Natural Resources. Available online: https://casetext.com/statute/west-virginia-code/chapter-11-taxation/article-13a-severance-and-business-privilege-tax-act/section-11-13a-3c-imposition-of-tax-on-privilege-of-severing-other-natural-resources (accessed on 26 August 2024).
75. Boxerman, S.B.; Langan, D.U.S. EPA Memo Offers Direction on Lithium Battery Recycling—Essential to the Future Supply Chain for Battery Electric Vehicles. SIDLEY. 2023. Available online: https://environmentalenergybrief.sidley.com/2023/08/16/u-s-epa-memo-offers-direction-on-lithium-battery-recycling-essential-to-the-future-supply-chain-for-electric-vehicle-batteries/ (accessed on 26 August 2024).
76. UL Solutions. EV Battery Regulatory Compliance Testing. UL Solutions.com. Available online: https://www.ul.com/services/ev-battery-testing-compliance-regulatory-requirements-and-standards (accessed on 26 August 2024).
77. European Commission Website. European Platform on LCA | EPLCA. Available online: https://eplca.jrc.ec.europa.eu/ (accessed on 26 August 2024).
78. Hill, N.; Raugei, M.; Pons, A.; Vasileiadis, N.; Ong, H.; Casullo, L. Environmental Challenges Through the Life Cycle of Battery Electric Vehicles. 2024. Available online: https://www.europarl.europa.eu/RegData/etudes/STUD/2023/733112/IPOL_STU(2023)733112_EN.pdf (accessed on 26 August 2024).
79. EPA. Application of Life-Cycle Assessment to Nanoscale Technology: Lithium-Ion Batteries for Electric Vehicles. 24 April 2013. Available online: https://19january2017snapshot.epa.gov/sites/production/files/2015-04/documents/lithium_batteries_ch1.pdf (accessed on 26 August 2024).
80. Directorate-General for Climate Action. 5 Things You Should Know About Electric Cars. European Commission. 2024. Available online: https://climate.ec.europa.eu/news-your-voice/news/5-things-you-should-know-about-electric-cars-2024-05-14_en (accessed on 26 August 2024).
81. Balzer, M. The Ultimate Guide to EV Incentives in Germany. Evolve Stories to Drive Change by Wall Box. 2020. Available online: https://wallbox.com/en_nz/ev-incentives-in-germany (accessed on 26 August 2024).
82. Office for Zero Emission Vehicles. Electric Vehicle Charge Point and Infrastructure Grant Guidance for Installers. gov.uk. 2024. Available online: https://www.gov.uk/guidance/electric-vehicle-chargepoint-and-infrastucture-grant-guidance-for-installers (accessed on 26 August 2024).
83. Official Legal Publisher of State Of New Mexico. Mineral Resource Research and Development. Battery Policies and Incentives. 1991. Available online: https://www.energy.gov/eere/vehicles/battery-policies-and-incentives-search#/?show=result&id=151 (accessed on 26 August 2024).

84. Williams, A. State of Nevada: Sustainable Materials Management Plan Aligning Solid Waste, Hazardous Waste, and Other Materials Management Processes with Sustainable Practices Expansion of and Revision to the 2017 State Solid Waste Management Plan. 2022. Available online: https://innovation.luskin.ucla.edu/wp-content/uploads/2022/09/Lithium-Extraction-Policy-in-the-Salton-Sea-and-Thacker-Pass.pdf (accessed on 26 August 2024).
85. Goed Nevada Governor's Office of Economic Development. Business incentives. 2024. Available online: https://goed.nv.gov/incentives/ (accessed on 26 August 2024).
86. State of Nevada. Clean Energy Study, Nevada Revised Statutes 218E. Battery Policies and Incentives. 2019. Available online: https://www.energy.gov/eere/vehicles/battery-policies-and-incentives-search#/?show=result&id=145 (accessed on 26 August 2024).
87. Baskaran, G.; Yu, F. Leveraging Argentina's Mineral Resources for Economic Growth. CSIS | Energy Security and Climate Change Program. 2024. Available online: https://www.csis.org/analysis/leveraging-argentinas-mineral-resources-economic-growth (accessed on 26 August 2024).
88. Law No 928: Law of the National Strategic Public Company for Bolivian Lithium Deposits—YLB. lea50. 2022. Available online: https://www.iea.org/policies/16654-law-no-928-law-of-the-national-strategic-public-company-for-bolivian-lithium-deposits-ylb, (accessed on 26 August 2024).
89. Único, A.I. Ley N° 928 Ley de 27 de Abril de 2017 evo Morales Ayma Presidente Constitucional del Estado Plurinacional de Bolivia por Cuanto. La Asamblea Legislativa Plurinacional, Ha Sancionado la Siguiente Ley: La Asamblea Legislativa Plurinacional, Decreta: Ley de la Empresa Pública Nacional Estratégica de Yacimientos de Litio Bolivianos-Ylb. 2017. Available online: https://mineria.gob.bo/juridica/20170427-13-12-42.pdf (accessed on 26 August 2024).
90. Sanchez, W.A. China's Win-Win in Zimbabwe: Lithium for Regime Legitimacy. Geopolitical Monitor. 2023. Available online: https://www.geopoliticalmonitor.com/chinas-win-win-in-zimbabwe-lithium-for-regime-legitimacy/ (accessed on 26 August 2024).
91. Li, H.; Zhu, T.; Chen, X.; Liu, H.; He, G. Improving China's Global Lithium Resource Development Capacity. *Front. Environ. Sci.* **2022**, *10*, 938534. [CrossRef]
92. de Diputados, C.; Congreso De, D.H.; Unión, L.A.; Reforma, Ú. Reglamento de la Ley General Para la Prevención y Gestión Integral de Los Residuos. 2014. Available online: https://www.diputados.gob.mx/LeyesBiblio/regley/Reg_LGPGIR_311014.pdf (accessed on 26 August 2024).
93. Lema, K. Litio 2040: Sustainably Developing Mexico's Lithium from Ground to Grid. Ecological Security Fellowship Briefer Series. 2024. Available online: https://councilonstrategicrisks.org/2024/06/11/litio-2040-sustainably-developing-mexicos-lithium-from-ground-to-grid/#:~:text=Since%20nationalizing%20lithium%20resources%20in,policymakers%20should%20hope%20to%20emulate. (accessed on 26 August 2024).
94. Research and Statistics Section CDTFA. California Lithium Extraction Tax Study, Senate Bill 125, Statutes of 2022. 2023. Available online: https://www.cdtfa.ca.gov/taxes-and-fees/LithiumTaxStudy.pdf (accessed on 26 August 2024).
95. State of Nevada. Economic Development Tax Incentives. Battery Incentive and Policies. 2021. Available online: https://www.energy.gov/eere/vehicles/battery-policies-and-incentives-search#/?show=result&id=144 (accessed on 26 August 2024).
96. Ministerio de Minería. Decree Law 2886. Reserve Lithium in Favour of the State. lea50. 2022. Available online: https://www.bcn.cl/leychile/navegar?idNorma=7029&idVersion=1979-11-14&idParte= (accessed on 26 August 2024).
97. Governor Gavin Newsom. New Report Highlights the Promise of Lithium Valley. ca.gov.com. 2023. Available online: https://www.gov.ca.gov/2023/11/28/new-report-highlights-the-promise-of-lithium-valley/ (accessed on 26 August 2024).
98. State of Texas, Texas Legislature. Relating to the Use of Certain Fees Deposited to the Hazardous and Solid Waste Remediation Fee Account for Reimbursement of Environmental Remediation at Certain Former Battery Recycling Facility Sites, HB 2708. 2021. Available online: https://legiscan.com/TX/text/HB2708/id/2405372 (accessed on 26 August 2024).
99. Vehicle Technologies Office. US Federal Policies, Battery Policies and Incentives Search. energy.gov. Available online: https://www.energy.gov/eere/vehicles/battery-policies-and-incentives-search#/ (accessed on 26 August 2024).
100. Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs. European Battery Alliance. 2024. Available online: https://single-market-economy.ec.europa.eu/industry/industrial-alliances/european-battery-alliance_en (accessed on 26 August 2024).
101. NV Energy. Electric Vehicle Programs: Clean Energy Future. Power Shift by NV Energy. 2023. Available online: https://www.nvenergy.com/cleanenergy/electric-vehicles (accessed on 26 August 2024).
102. Nevada Battery Coalition. Available online: https://nevadabatterycoalition.com/our-members/ (accessed on 26 August 2024).
103. President of Mexico Nationalizes Lithium. Green Car Congress. 2023. Available online: https://www.greencarcongress.com/2023/02/20230220-mexico.html (accessed on 26 August 2024).
104. BioAge Group, LLC. Mexico Forms State-Run Company to Mine Lithium: Litio Para. Green Car Congress. 2022. Available online: https://www.greencarcongress.com/2022/08/20220826-litiomx.html (accessed on 26 August 2024).
105. Occupational Knowledge International. Exporting Hazards: U.S. Shipments of Used Lead Batteries to Mexico Take Advantage of Lax environmental and Worker Health Regulations. 2011. Available online: https://www.ohchr.org/sites/default/files/Documents/Issues/ToxicWaste/RightToInformation/OccupationalKnowledgeInternational2.pdf (accessed on 26 August 2024).

106. Martine, J.A.T.; Vázquez, K. Electric Vehicle Regulation and Law in Mexico. CMS. 2018. Available online: https://cms.law/en/int/expert-guides/cms-expert-guide-to-electric-vehicles/mexico (accessed on 26 August 2024).
107. Hernández, V.L.; Hilbert, I.; Castillero, L.G.; Manhart, A.; García, D.; Nkongdem, B.; Dumitrescu, R.; Sucre, C.; Herrera, C.F. Recycling and Reuse of Lithium Batteries in Latin America and the Caribbean Analytical Review of Global and Regional Practices. 2024. Available online: https://publications.iadb.org/en/recycling-and-reuse-lithium-batteries-latin-america-and-caribbean-analytical-review-global-and (accessed on 26 August 2024).
108. Ministry of Justice Canada. Canadian Environmental Protection Act, 1999 (S.C. 1999, c. 33). Justice Laws Website. Available online: https://lois-laws.justice.gc.ca/PDF/C-15.31.pdf (accessed on 26 August 2024).
109. Ministry of Justice Canada. Cross-Border Movement of Hazardous Waste and Hazardous Recyclable Material Regulations (SOR/2021-25). Justice Laws Website. 2024. Available online: https://laws-lois.justice.gc.ca/PDF/SOR-2021-25.pdf (accessed on 26 August 2024).
110. Canadian Region. Call2Recycle: Leading the Charge for Recycling. Available online: https://www.call2recycle.ca/ (accessed on 26 August 2024).
111. McSheffrey, E. New report Urges B.C. to Become the Region's Leader in Recycling Electric Vehicle Batteries. *Global News*, 7 December 2021. Available online: https://globalnews.ca/news/8432601/bc-electric-vehicle-battery-recycling/ (accessed on 26 August 2024).
112. Basen, N. Can Ontario Boost EV Battery Recycling Before It's Too Late? Tvotoday. 2021. Available online: https://www.tvo.org/article/can-ontario-boost-ev-battery-recycling-before-its-too-late (accessed on 26 August 2024).
113. Call2Recycle Canadian Region. Provincial Recycling Regulations. Call2Recycle—Leading the Charge for Recycling. Available online: https://www.call2recycle.ca/provincial-recycling-regulations/ (accessed on 26 August 2024).
114. Mathieu, L. France's Eco-Bonus Shows How We Can Promote Cleaner Made-in-Europe EVs. *T&E*, 14 December 2023. Available online: https://www.transportenvironment.org/articles/frances-eco-bonus-shows-how-we-can-promote-cleaner-made-in-europe-evs (accessed on 26 August 2024).
115. Rizos, V.; Urban, P. Implementing the EU Digital Battery Passport. 2024. Available online: https://circulareconomy.europa.eu/platform/en/knowledge/implementing-eu-digital-battery-passport-opportunities-and-challenges-battery-circularity (accessed on 26 August 2024).
116. PWC. Update on Extended Producer Responsibility Changes in the UK. Available online: https://www.pwc.co.uk/services/legal/insights/update-on-extended-producer-responsibility-changes-in-uk.html. (accessed on 26 August 2024).
117. Wei, L.; Wang, C.; Li, Y. Governance strategies for end-of-life electric vehicle battery recycling in China: A tripartite evolutionary game analysis. *Front. Environ. Sci.* **2022**, *10*, 1071688. [CrossRef]
118. United Nations University Institute for Integrated Management of Material Fluxes and of Resources (UNU-FLORES). NABATE Transfer Workshop on the Sustainable Management of End-of-Life Batteries in South Korea. Available online: https://unu.edu/flores/workshop/nabate-transfer-workshop-sustainable-management-end-life-batteries-south-korea (accessed on 13 November 2024).
119. Sung, S.-H. Korea to Keep Track of EV Battery Life Cycles for Recycling. *Batteries*. 10 July 2024. Available online: https://www.kedglobal.com/batteries/newsView/ked202407100017 (accessed on 13 November 2024).
120. Choi, Y.; Rhee, S.-W. Current status and perspectives on recycling of end-of-life batteries of electric vehicles in Korea (Republic of). *Waste Manag.* **2021**, *125*, 91–104. [CrossRef] [PubMed]
121. Cui, Y.; Teah, H.Y.; Dou, Y.; Kanematsu, Y.; Yamaki, A.; Yonetsuka, T.; Chang, I.-S.; Wu, J.; Kikuchi, Y. Design and assessment of sustainable spent automobile lithium-ion battery industries in Japan: A system dynamic business model approach. *J. Clean. Prod.* **2020**, *273*, 122898. [CrossRef]
122. Chen, M.; Ma, X.; Chen, B.; Arsenault, R.; Karlson, P.; Simon, N.; Wang, Y. Recycling end-of-life electric vehicle lithium-ion batteries. *Nat. Sustain.* **2019**, *2*, 195–202. [CrossRef]
123. Krabberød, F.; Ho, A. End of Life Strategies for Electric Vehicle Lithium-Ion Batteries. HSSMI. Available online: https://autorecyclingworld.com/wp-content/uploads/2020/07/EoL-Strategies-for-EV-LIBs-2020-HSSMI.pdf (accessed on 26 August 2024).
124. Indeed Innovation. Unpacking EPR: A Look at US and EU Packaging Laws. The Mensch. Available online: https://www.indeed-innovation.com/the-mensch/unpacking-epr-a-look-at-us-and-eu-packaging-laws/ (accessed on 20 November 2024).
125. EUROPEN. Extended Producer Responsibility. EUROPEN: The European Organization for Packaging and the Environment. Available online: https://www.europen-packaging.eu/policy-area/extended-producer-responsibility/ (accessed on 20 November 2024).
126. Hunter Jeffry, L.; Shiigi Kaela Perkins Coie, L.L.P. Extended Producer Responsibility Packaging Laws in the United States. Perkins Coie. Available online: https://perkinscoie.com/insights/update/extended-producer-responsibility-packaging-laws-united-states (accessed on 20 November 2024).

127. Adam, H.; Jacob, M.-R.; Tax Foundation. Extended Producer Responsibility (EPR). Tax Foundation. Available online: https://taxfoundation.org/research/all/state/extended-producer-responsibility-epr/ (accessed on 20 November 2024).
128. Source Intelligence. Packaging EPR Laws in the US. Source Intelligence Blog. Available online: https://blog.sourceintelligence.com/packaging-epr-laws-in-the-us (accessed on 20 November 2024).
129. Quinn, M. New Jersey Governor Signs EPR Law for Electric Vehicle Batteries. Waste Dive. Available online: https://www.wastedive.com/news/electric-vehicle-battery-epr-law-new-jersey-murphy/704220/ (accessed on 20 November 2024).
130. Haskins, E.; Wooten, N.E. Grappling with Safe Battery Handling and End-of-Life Concerns in the EV Revolution. *Baker Donelson*, 18 October 2024. Available online: https://www.bakerdonelson.com/grappling-with-safe-battery-handling-and-end-of-life-concerns-in-the-ev-revolution (accessed on 20 November 2024).
131. My Compliance. Full EPR Service in the USA. My Compliance. Available online: https://www.my-compliance.eu/news/usa-full-epr-service-in-the-usa/ (accessed on 20 November 2024).
132. Tankou, A.; Hall, D. Will the U.S. EV Battery Recycling Industry be Ready for Millions of End-of-Life Batteries? *The International Council on Clean Transportation Blog*, 29 September 2023. Available online: https://theicct.org/us-ev-battery-recycling-end-of-life-batteries-sept23/ (accessed on 20 November 2024).
133. Alliance for Automotive Innovation. Lithium-Ion EV Battery Recycling Policy Framework. Alliance for Automotive Innovation. Available online: https://www.autosinnovate.org/about/advocacy/Lithium-Ion%20EV%20Battery%20Recycling%20Policy%20Framework.pdf (accessed on 20 November 2024).
134. Jannesar Niri, A.; Poelzer, G.A.; Zhang, S.E.; Rosenkranz, J.; Pettersson, M.; Ghorbani, Y. Sustainability Challenges Throughout the Electric Vehicle Battery Value Chain. 2024. Available online: https://www.sciencedirect.com/science/article/pii/S1364032123010341#:~:text=Besides,%20another%20initiative%20is%20the,data%20documentation)%20[95] (accessed on 26 August 2024).

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