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Sustainability Transition in EV Battery Life Cycle: A Multi-Level Perspective and Circular Economy Approach

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Abstract

Electric vehicle technology innovation can provide environmentally friendly and energy-efficient transportation solutions. However, there is a problem, namely batteries that have a limited lifespan. Therefore, researchers created a Multi-Level Perspective (MLP) model of electric vehicles. The model allows researchers to analyze the interaction between various levels, namely the socio-technical landscape at the macro level, the socio-technical regime at the meso level, and specific innovations at the micro level that will be used to analyze the sustainability transition. In addition, an electric vehicle battery life cycle model was created to plan a circular economy for electric vehicles. In the battery life cycle, batteries that have expired must go through a reuse, remanufacturing, and recycling process before being completely discarded. By creating a supply chain model with the implementation of a circular economy, it is hoped that it can help realize the use of more renewable energy, reduce the accumulation of electric vehicle battery waste, and maximize the value of recycled materials and ensure optimal performance in the supply chain. This research is expected to be a reference for future planning related to battery waste management.

Keywords
Waste Battery, Electric Vehicle, Circular Economy, Multi Level Perspective (MLP)

1. Introduction
The increasing use of motorized vehicles in Indonesia has resulted in higher fuel consumption, especially gasoline, with total ownership reaching 158,698,240 units, where motorcycles are the most dominant type of vehicle with 132,522,215 units (Korlantas Polri, 2023). The increase in the number of vehicles has raised concerns about the scarcity of fossil fuels (Prastyono et al., 2024). To address this issue, the government plans to commercialize electric vehicles as an environmentally friendly and cost-effective solution (Istiqomah et al., 2020, 2021). Electric vehicles

use batteries as the main energy source that can be recharged, offering a more sustainable energy life cycle and reducing emissions compared to fossil fuels (Richter, 2022). However, electric vehicle batteries have a limited lifespan and can increase battery waste as production and consumption increase (Siahaan et al., 2021). To address this issue, the application of the circular economy concept to batteries is important. The circular economy concept focuses on reducing waste through recycling and recovery, aiming to extend the product life cycle and reduce environmental impacts (Y. Chen et al., 2021). The Closed Loop Supply Chain (CLSC) plays a key role in supporting this concept by integrating recycling and material recovery into the entire product life cycle (Simonetto et al., 2022). Reverse logistics systems are critical to the success of CLSC, enabling the return of batteries to manufacturers for recycling and reuse (Mallick et al., 2023). This approach helps manage stock, handle used products, and reduce waste by repurposing battery waste as a resource. By maximizing the value of recycled materials, these systems contribute to resource efficiency in the supply chain (Ribeiro da Silva et al., 2023). Several studies have explored the implementation of the circular economy in various contexts (Istiqomah & Sutopo, n.d.). For example, blockchain technology is used to improve transparency in the electric vehicle battery supply chain (Ribeiro da Silva et al., 2023) and circular models seek to reduce global resource waste (Dragomir & Dumitru, 2022). In addition, feature-based circular economy e-business models have been proposed to improve environmental performance and sustainability (Fatimah et al., 2023). This study will develop a supply chain management model with the application of a circular economy to electric vehicles using the Multi-Level Perspective (MLP) method, which is expected to reduce battery waste and increase the value of recycled materials (Yudha et al., 2022). Therefore, this study aims to design a life cycle model of Nickel manganese cobalt (NMC) batteries in electric vehicles and to design a supply chain management model with the implementation of a circular economy in electric vehicle batteries using the Multi-Level Perspective (MLP) approach.

The increasing adoption of electric vehicles (EVs) as a solution to reduce carbon emissions has introduced new challenges in managing the EV battery life cycle. Inefficiencies in handling end-of-life (EoL) batteries pose environmental risks due to battery waste and excessive exploitation of natural resources. Conventional supply chain models have not fully integrated circular economy principles, such as recycling, remanufacturing, and repurposing, which could extend battery lifespan and minimize environmental impact. Therefore, a comprehensive approach is needed to support the sustainability transition in EV battery life cycle management. By incorporating the Multi-Level Perspective (MLP) framework and Circular Economy (CE) principles, this study aims to develop a sustainable supply chain management model to enhance resource efficiency, reduce waste, and accelerate the adoption of circular systems in the EV battery industry. This research will explore the challenges and opportunities in implementing a CE-based supply chain, as well as assess the environmental and economic impacts of the proposed approach.

2. Literature Review

A. Electric Vehicles

Electric vehicles are a type of vehicle that uses an electric motor as its driving force and a battery as its electrical energy storage that can be recharged or charged. In addition to environmental benefits, electric vehicles also reduce dependence on fossil fuels and increase energy efficiency, as well as provide economic benefits (Energy Agency, n.d.). Innovations in battery technology, such as Nickel manganese cobalt (NMC) batteries, contribute to the advancement of electric vehicles by offering good energy stability, high density, and lower risk compared to other types of batteries.

B. Circular Economy

Circular Economy that focuses on maximizing the value of using an item and its components repeatedly, prioritizing resource efficiency (Z. Chen et al., 2023; Kirchherr et al., 2017; Richter, 2022). Circular economy as a system that combines reducing, reusing, and recycling activities, which require systematic changes to increase economic value, environmental quality, and social justice, by involving the important roles of business models and consumers (Kirchherr et al., 2017). This model aims to extend the life cycle of products and resources so that they can be used as long as possible, focusing on reducing social and environmental damage arising from the traditional linear economic model . Thus, the circular economy aims to maintain the value of products and resources in the economy to achieve sustainable economic growth and minimize negative impacts on the environment and society.

C. Closed-Loop Supply Chain Management (CLSCM)

Closed-Loop Supply Chain Management (CLSCM) is a strategic approach that manages the entire product life cycle, including the recycling and reuse processes of products, to improve efficiency, sustainability, and profitability (Ma, 2022). CLSCM involves collaboration between manufacturers, distributors, and consumers to create a more sustainable product life cycle by integrating the return of used products into the supply chain for recycling or reuse, reducing environmental impacts, and opening up new opportunities for operational efficiency and economic value (Marcos et al., 2021; Tavana et al., 2022). The main principles of CLSCM include understanding the product life cycle, designing recyclable products, managing sustainable logistics, and reusing used products, which help reduce waste and maximize product value throughout its life cycle (Tavana et al., 2022). Implementing CLSCM offers benefits such as waste reduction, resource efficiency, and improving the company's image related to sustainability, although it faces challenges such as the complexity of logistics management and the need for supporting technology . With full support from various parties and continuous innovation, CLSCM has the potential to create a more sustainable and efficient supply chain.

D. Reserve Logistics

In supply chain management, reverse logistics refers to the process of moving products from consumers back to manufacturers for further management, including the collection, transportation, recovery, and recycling of used or waste goods (Fanani et al., 2022). The main goal of reverse logistics is to manage returned, returned, or waste goods in an efficient and sustainable manner. The process begins with the identification of returned goods to determine whether they can be resold, repaired, or recycled. The goods are then sent from the consumer to a processing facility where they may undergo repair, alteration, or recycling before being re-marketed or reused (Nanayakkara et al., 2022). The main activities in reverse logistics include collecting goods from customers, inspecting the products, and transporting them back to the recovery facility for remanufacturing, recycling, repair, or reuse, as shown in the basic concept of reverse logistics (Guo et al., 2017).

E. Multi-Level Perspective (MLP) Method

The Multi-Level Perspective (MLP) Method is a qualitative analysis approach designed to understand change in the context of a broader system, focusing on the interactions between multiple levels, such as individuals, organizations, and society (Osunmuyiwa et al., 2018). MLP views transitions as the result of dynamics and interactions between different levels, facilitating an understanding of how social, technological, and policy changes can occur simultaneously. In research using MLP, researchers collect data in depth and systematically to analyze how interactions between different levels affect transitions and social change (El Bilali, 2019). This approach also involves collaboration with stakeholders to identify and understand the factors that influence change at different levels of the system (Osunmuyiwa et al., 2018).

The literature review demonstrates familiarity with key concepts such as Closed-Loop Supply Chain Management (CLSCM), reverse logistics, and the circular economy (CE), highlighting their significance in managing the life cycle of EV batteries. While extensive research has been conducted on the benefits of CLSCM and CE, several critical gaps have been identified. Existing studies predominantly focus on technical and economic aspects, whereas a comprehensive analysis of socio-technical transitions influencing large-scale adoption remains limited. Additionally, although reverse logistics frameworks for battery recycling and repurposing have been widely discussed, challenges related to policy and regulatory constraints have not been sufficiently explored, thereby hindering the practical implementation of circular supply chains.

3. Methods

This research employs a systematic methodology that integrates a literature review, field study, and stakeholder analysis to develop a circular economy-based supply chain management model for EV batteries. The literature review identifies key concepts related to circular economy and supply chain management, while the field study, conducted through interviews and observations, gathers primary data from key stakeholders, including battery manufacturers, EV companies, policymakers, and recycling firms. A purposive sampling strategy is used to ensure that selected stakeholders represent diverse perspectives and that their insights can be generalized to broader industry applications. The collected data is analyzed using the Multi-Level Perspective (MLP) framework, which examines landscape trends, industry regimes, and niche innovations to understand the sustainability transition of EV battery management.

The research develops and compares three models: a conventional linear battery life cycle model, a traditional supply chain model, and a circular economy-based supply chain model. The rationale for integrating MLP with circular economy principles lies in MLP’s ability to contextualize system transitions, ensuring that CE practices align with industry structures and policy developments. The proposed model undergoes verification and validation through stakeholder feedback to assess feasibility and accuracy. Finally, the results are evaluated to draw conclusions, recommend improvements for circular supply chain adoption, and provide insights for future research.

4. Data Collection

A. Stakeholder

The researcher began data collection by implementing a series of methods for collecting direct information (primary data) and pre-existing information (secondary data). Direct data collection was carried out by the researcher by conducting interviews with five stakeholders. These stakeholders were selected to represent all stakeholders involved in this study. The five stakeholders will represent from suppliers to the final process of managing electric vehicle battery waste. Interviews were conducted to gather insights from expert opinions on the benefits that can be obtained from battery recycling management and the application of a circular economy to electric vehicles. The following is a list of stakeholders that will be explained in Table 1. To maintain the confidentiality of each stakeholder, the company name will be listed as "Stakeholder-X" and the participant's name will be anonymized.

Table 1. List of Stakeholder

Code	Stakeholder Profile	Information
Stakeholder 1	Stakeholder 1 is the CEO of a startup that provides lithium batteries and their derivatives. In addition, this company also implements an environmentally friendly production process.	The task of Stakeholder 1 is to make important decisions and manage the overall resources of the company and the production of lithium batteries.
Stakeholder 2	Stakeholder 2 is a CMO (Chief Marketing Officer) of a battery raw material supplier in Indonesia.	Stakeholder 2 is a battery raw material supplier whose job is to provide and supply quality raw materials needed for research and development at the company, ensure the availability of raw materials according to specifications, and ensure timely delivery to support the smooth operation of battery research and production.
Stakeholder 3	Stakeholder 3 is a professor at one of the universities in Indonesia.	Stakeholder 3 acts as an expert whose job is to provide technical advice and guidance related to battery technology to researchers and plays a role in bridging communication between researchers and other stakeholders.
Stakeholder 4 and 5	Stakeholder 4 consists of two researchers	Stakeholder 4 plays a role in verifying existing knowledge or developing theories and solutions for various research that is being conducted.

B. Batteries in Electric Vehicles

Electric vehicle batteries, such as NMC batteries, play a crucial role in providing power for electric motors and are a key component in electric vehicle energy storage systems. Although these batteries offer advantages such as high energy density and are environmentally friendly, the increasing production of electric vehicles has also led to significant battery waste problems. Batteries contain hazardous chemicals that can pollute water, soil, and air if not managed properly, posing a risk of pollution and health problems. Currently, Indonesia does not have a special facility for battery waste management, so it is necessary to apply the concept of a circular economy through the development of a battery life cycle model and supply chain management to handle battery waste effectively.

C. Bill of Material (BOM) NMC Battery

In the process of recycling batteries in electric vehicles, it is important to know the components of the battery so that the battery recycling process can be carried out optimally. The BOM of the battery will be described by the author in Table 2 below.

Table 2. Bill Of Material Battery

No	Material	NMC111
Cell Material		Kg
1	Active cathode material	0.287
2	Graphite	0.160
3	Carbon black	0.020
4	Binder (PVDF)	0.25
5	Copper	0.134
6	Aluminum	0.069
7	Electrolyte: Ethylene carbonate	0.018
8	Electrolyte: Dimethyl carbonate	0.050
9	Plastic: Polypropylene	0.012
10	Plastic: Polyethylene	0.003
Non-Cell Material		
11	Copper	0.003
12	Aluminum	0.184
13	Steel	0.007
14	PET	0.005
15	Electronics	0.037

Source: (Accardo et al., 2021)

The table includes the materials needed to make one battery cell. NMC battery materials are divided into two groups. First, cell materials, including the main materials for making battery cells and second, non-cell materials, namely all materials used to complete the battery pack. The cathode production process of NMC batteries begins by dissolving nickel, manganese, and cobalt substrates that react with hydroxides. After the substrates have been mixed and completely dissolved, sodium hydroxide and ammonium hydroxide are added to the solution. Then the reactor is heated by steam to 50 ◦C and kept warm for a long period of time. Next, the filtration, washing and drying processes are carried out to produce NMC precursors. The dry powder is then mixed with lithium carbonate to produce the desired oxide. The anode usually consists of graphite and PVDF binder. For non-cell materials, it consists of aluminum, steel, PET, and electronics.

5. Results and Discussion

Recyclable materials will go through several processes such as Pretreatment, pyrometallurgy and hydrometallurgy (Accardo et al., 2021). The following is an explanation of the battery material recycling process in electric vehicles (Figure 1).

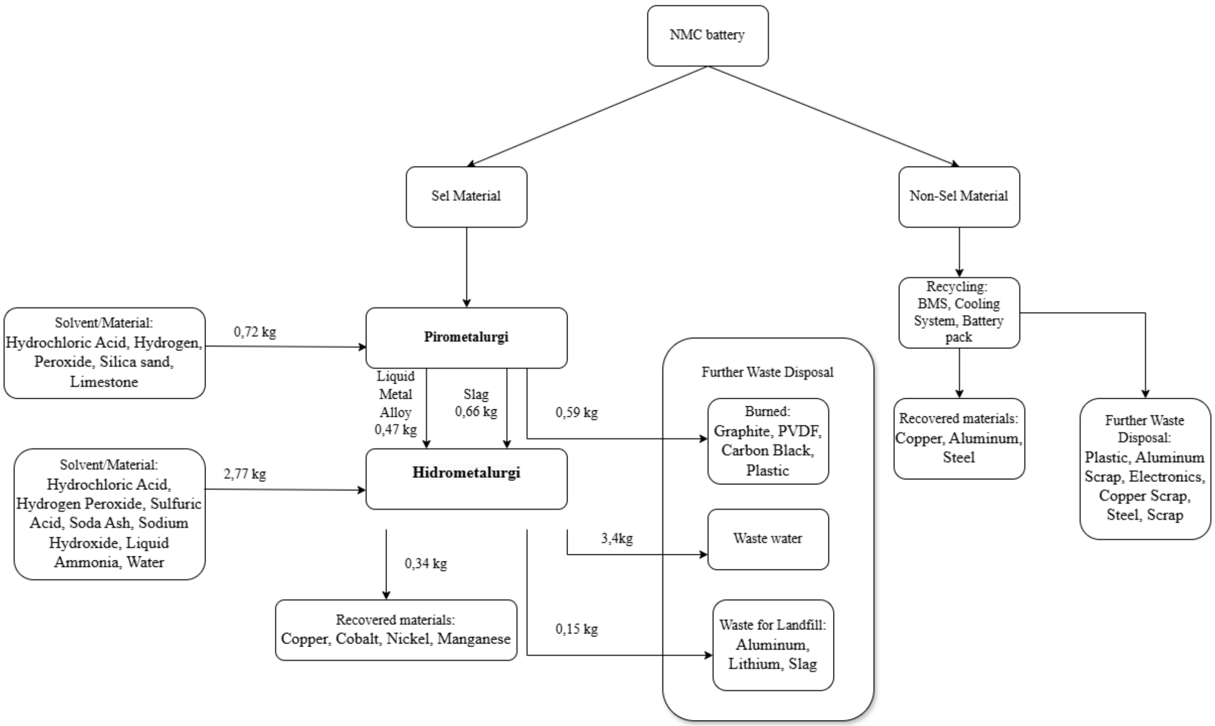

Figure 1. End of Life of Electric Vehicle Battery Components

1. Initial separation (Pretreatment) which begins with the battery in the electric vehicle being turned off and the remaining energy is removed, then the battery is opened and its components are separated, different components such as electrodes, electrolytes, and metal casings are separated.
2. Physical Separation, namely by separating the battery from other materials through physical means such as filtration or centrifugation.
3. The battery is processed to break down lithium-containing compounds into their separate elements, this process involves breaking down compounds containing materials such as nickel, manganese, cobalt, carbon, aluminum, and copper into their separate elements, which can then be separated and recovered.
4. Metal regeneration is carried out, metals such as nickel, manganese, cobalt, aluminum, and copper contained in the battery are restored through pyrometallurgy and hydrometallurgy processes. The process involves the use of oxalic acid to separate the metals and produce active materials that can be reused in the manufacture of new batteries.
5. Testing and purification are carried out, the solids produced from the recycling process are tested using FTIR (Fourier Transform Infrared Spectroscopy) and XRD (X-ray Diffraction) to ensure their quality, the solids are compared with solids produced from precursor materials to ensure that the material obtained has the same properties as the original material

A. Electric Vehicle Battery Waste Processing

The processing of electric vehicle battery waste that has reached the end of its life requires a special sorting process. The initial stage begins with the process of collecting batteries from various sources, such as recycling centers, electric vehicle battery manufacturers, consumers and battery waste disposal sites. Next, sorting is carried out based on type and condition to ensure proper handling and maximize recycling efficiency. Sorting grouping includes battery type, chemical type, and physical form, as well as based on battery condition (Accardo et al., 2021). The physical condition of the battery includes batteries that are still intact and undamaged separated from batteries that have experienced physical damage, such as leakage, swelling, or deformation. Furthermore, for the chemical condition of the battery, batteries that still have most of their energy capacity can be treated differently from batteries that are very depleted or have experienced severe degradation. The battery sorting process consists of several processes which will be illustrated in Figure 2.

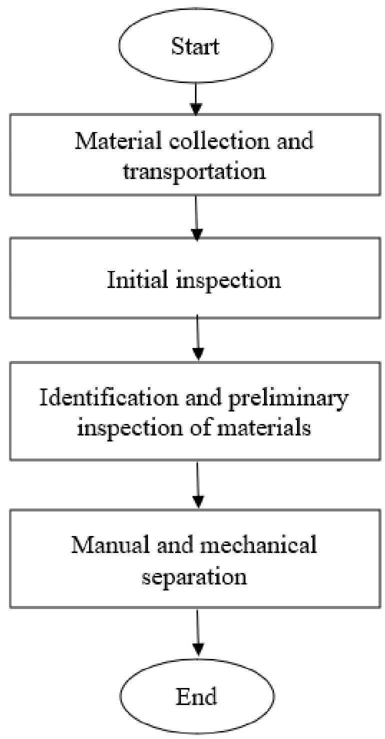

Figure 2. Battery Sorting Process Stages

1. Collection and transportation, which is the process by which used batteries are collected from various sources and transported to the appropriate recycling facility.
2. Initial inspection, which is the process carried out to identify physical damage and classify batteries by type and condition.
3. Identification and classification, which is the process that uses technology such as spectroscopy or X-ray analysis to identify the chemical composition and determine the type of cathode used in the battery.
4. Manual and mechanical separation, which is the manual separation process carried out to separate batteries based on physical form and visual condition. Mechanical separation can involve the use of conveyors, magnets, and other separation devices to further group batteries.

Furthermore, in the management of electric vehicle battery waste, the grouping of battery waste in electric vehicles is an important step to know the next steps that can be taken to handle the battery waste. After the battery that has reached the end of its first life is removed from the electric vehicle, the battery has three possible destinations, namely recycling facilities, second-life applications, or waste management facilities (Purwani et al., 2025). Batteries that are included in the recycling facility group, after the battery is removed from the electric vehicle, the battery will be processed to extract materials from the battery that can still be used. Furthermore, batteries that are included in the remanufacturing or reuse group, the battery will be supplied to a battery repair company. As stated by Stakeholder 1, the company will process the battery to make it suitable for second-life applications in stationary or static storage, such as improving grid performance and renewable energy integration, charging electric vehicles, used for powerwalls, generators and so on. Then the last battery that is included in the disposal group or waste management facility is a battery that can no longer be used or has been severely damaged. The battery will go to the landfill or other disposal facility without any residual value recovery. In the grouping of battery waste in electric vehicles, there are specifications that must be considered, these specifications are something that will be a benchmark in determining the group of battery waste (Purwani et al., 2025). Stakeholder 4 stated that to determine whether a battery is included in remanufacturing, reuse, recycle, and waste, it can be seen from the battery age, namely by looking at the State of Health (SoH) level in the battery. Table 3 will explain in more detail regarding these specifications.

Table 3. The State of Health (SoH) level in the battery.

Reuse	Recycling	Waste
• State of Health (SoH) level above 70-80%. • Has capacity degradation of less than 20-30%. • Shows no signs of overheating or thermal runaway • Has minor damage, such as scratches or small dents. • Has an internal resistance of no more than twice its original resistance. • Voltage variation between cells is no more than 0.1 volts (100 mV), ideally below 0.05 volts (50 mV) • The capacity difference between cells is not more than 5-10% of the nominal capacity. • The variation of internal resistance between cells is not more than 10-20% of the average internal resistance value.	• State of Health (SoH) below 70%. • Significant physical damage and leakage. • Excessive heating during charging or use. • Very high inter-cell voltage variation (greater than 0.1 volts). • Cell capacity within the battery pack varies by more than 10%.	• State of Health (SoH) below 50%. • Severe physical damage, such as dents or cracks. • Indicates electrolyte leakage. • Damaged or open casing or outer layer. • Internal damage, such as short circuits or burned cells inside. • Indicates very high voltage variations (more than 0.2 volts). • Having a very large cell capacity difference (more than 20%). • Internal resistance that increases more than three times from the initial value.

B. Electric Vehicle Battery Life Cycle Model

The average electric vehicle battery will last about ten years or more. As stated by Stakeholder 1, NMC batteries can be used for up to 1000 cycles or about 10 years. What determines the life of an electric vehicle battery before it experiences performance degradation is the number of charge cycles it goes through. Most batteries in electric vehicles will maintain their charge capacity through 1000 complete charge cycles, that is, from empty to 0% and recharge to 100%. Because electric vehicles have safety that prevents the battery from being completely drained and charged to 100% capacity. When the battery is damaged to the point that its range is reduced by about 30% of the expected range, the battery will be replaced. The battery will then be disposed of at a landfill .

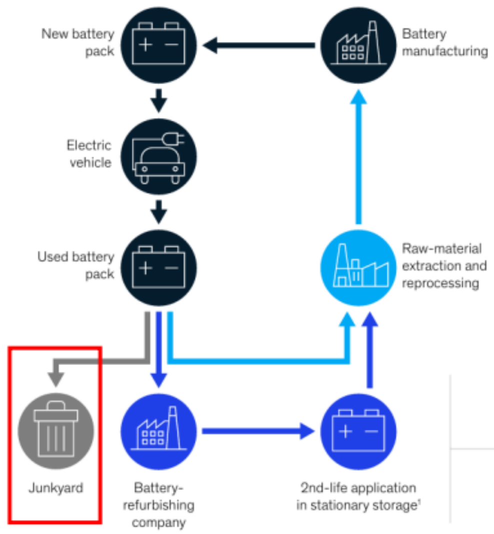

Figure 3. Current Electric Vehicle Battery Life Cycle Model Source. (Istiqomah & Sutopo, n.d., 2020)

Based on Figure 3, batteries that have expired will be thrown directly into the trash (red box). However, electric vehicle batteries that are damaged or have expired cannot be thrown away directly. Figure 4 will illustrate how the life cycle of an electric vehicle battery is by applying the concept of a circular economy. By implementing a circular economy, it will create a more sustainable battery life cycle.

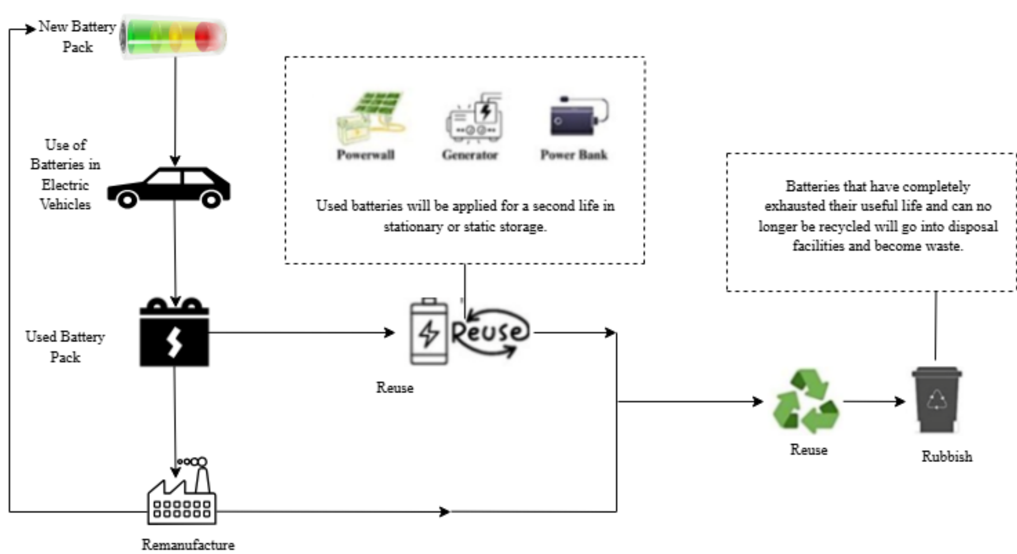

Figure 4. Electric Vehicle Battery Life Cycle Model with Application of Circular Economy Concept

Figure 4 explains that electric vehicle batteries that are no longer suitable for use in vehicles can be reused through several steps. First, the battery can be used for secondary applications such as stationary energy storage systems. After approximately 1,000 charge-discharge cycles, the battery still retains a significant portion of its capacity, making it suitable for static energy storage applications such as lighting in agricultural areas and residential energy backup systems. This step ensures that the battery's useful life is extended before further processing.

If possible, the battery can then undergo a remanufacturing process, which involves inspection and repair to restore its performance for potential reuse. If the battery cannot be reused or remanufactured, the next step is recycling, where valuable materials such as nickel and cobalt are extracted and recovered for the production of new batteries, thereby reducing the ecological impact. Currently, in Indonesia, battery recycling is still limited due to the low volume of used batteries available. Batteries that cannot be recycled will be processed at waste disposal facilities following appropriate environmental and safety procedures to prevent hazardous chemical waste accumulation. This multi-stage approach ensures that EV batteries do not become direct waste, minimizing their environmental footprint and maximizing material recovery.

C. Multi-Level Perspective (MLP) Model

The transition of conventional vehicles to electric vehicles from a multi-level perspective (MLP), which consists of three elements, namely the socio-technical landscape, socio-technical regime, and specific innovation. The transition of conventional vehicles to electric vehicles includes the old regime, or in this case conventional vehicles that use fossil fuels that still dominate the transportation sector in Indonesia. And the emergence of the potential for a new regime, or in this case electric vehicles that use renewable energy, namely NMC batteries. Figure 5 shows the MLP of fossil energy in conventional vehicles as the old regime, while Figure 6 illustrates the MLP of batteries in electric vehicles as the new regime.

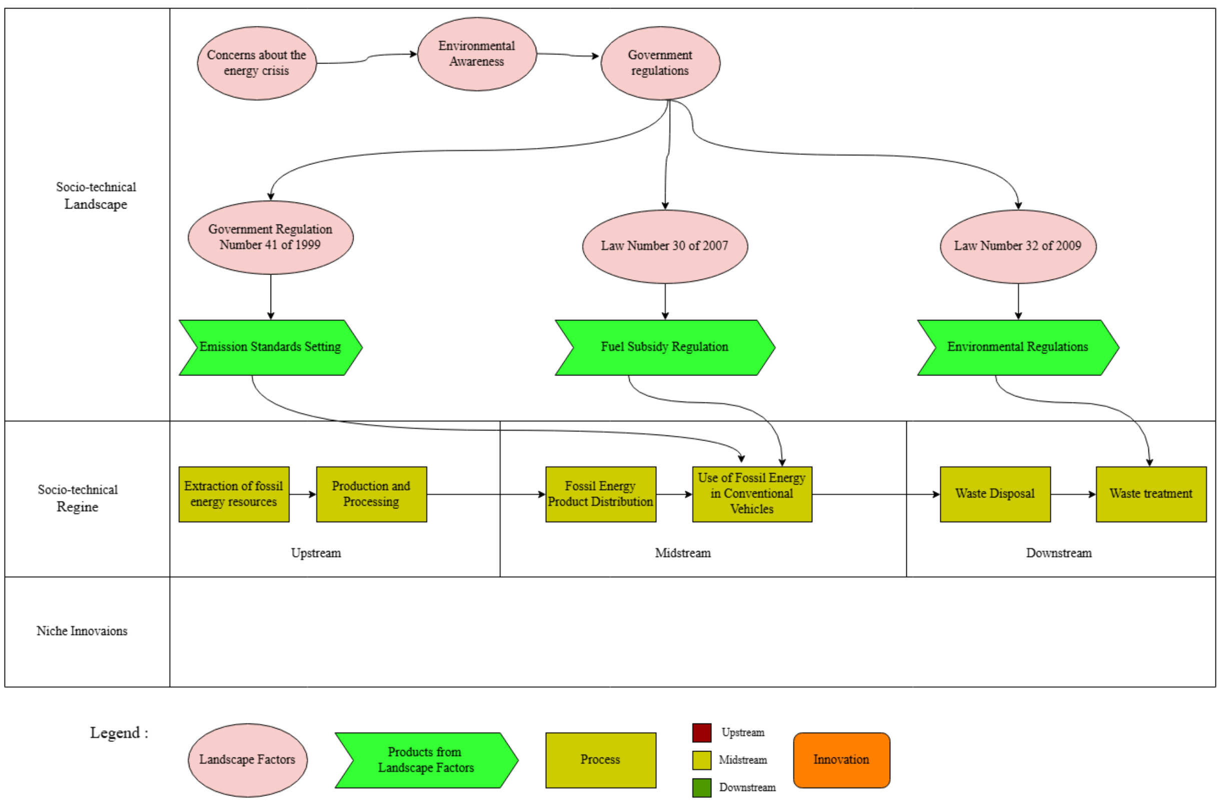

Figure 5. MLP Model for Fossil Energy in Conventional Vehicles as Old Regime

The MLP model of conventional vehicles as the old regime has been created in Figure 5. The MLP approach consists of three levels, namely the socio-technical landscape at the macro level, the socio-technical regime at the meso level, and specific innovations at the micro level (Energy Agency, n.d.).

a. Socio-Technical Landscape

At the macro level, the socio-technical landscape consists of several landscape factors (pink ellipses) that put pressure on the socio-technical regime and facilitate the transition from conventional vehicles to electric vehicles. These landscape factors are interrelated and can produce "landscape products". The landscape factor in the old regime consists of concerns about the energy crisis. This is based on the fact that as the number of motorized vehicles

increases, fuel consumption will also increase. It is feared that this will cause a shortage of fossil fuels and even an energy crisis [2].
Next is the environmental awareness factor, which is based on the statement of stakeholder 3, that it is important to have environmental awareness so that it can reduce the negative impacts of the environment. Then there are government regulations, namely Government Regulation Number 41 of 1999, Law Number 30 of 2007, and Law Number 32 of 2009. From several landscape factors, landscape products will be produced, namely emission standard regulations, fuel subsidy regulations, and environmental regulations. These landscape products will act as the main supporting factors for changing conventional vehicles that use fossil fuels to electric vehicles that use renewable energy.

b. Socio-Technical Regime

At the meso level, the socio-technical regime consists of a series of old regime supply chain processes. These proesses are classified into upstream, midstream, and downstream, symbolized by the yellow rectangle. The upstream process of fossil energy in conventional vehicles starts from the stage of extracting fossil energy resources by drilling wells on land or offshore to extract crude oil and natural gas from underground. After that, the next stage is the production and processing process. Then the middle part consists of the distribution process of fossil energy products and the use of fossil energy in conventional vehicles. Next is the downstream part, waste disposal and processing. In the old regime, the supply chain of conventional vehicles covering upstream, middle, and downstream was in a stable condition and needed to be broken, so that the transition from conventional vehicles to electric vehicles could occur. In addition, if the conditions in the old regime continue to be stable, it will eventually cause an energy crisis due to the continuous use of fossil energy as fuel for conventional vehicles.

c. Special Innovation

At the micro level, there is no special innovation in the old regime because a transition from conventional vehicles to electric vehicles is needed.

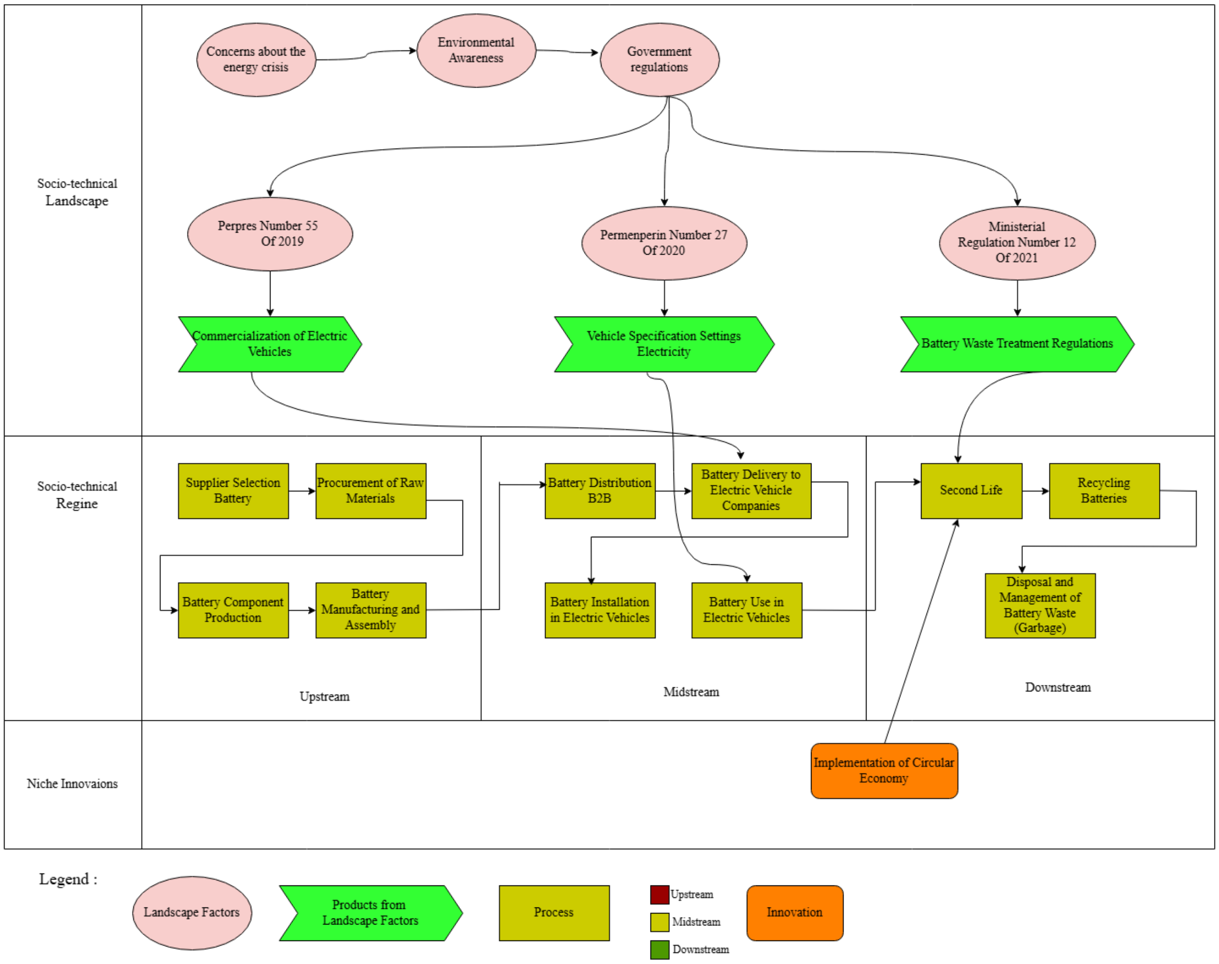

Figure 6. MLP Model of Electric Vehicle Battery as a New Regime

The MLP model of electric vehicles as a new regime has been created in the figure The MLP approach consists of three levels, namely the socio-technical landscape at the macro level, the socio-technical regime at the meso level, and specific innovations at the micro level (Yudha et al., 2022).

a.Socio-Technical Landscape

At the macro level, the socio-technical landscape consists of several landscape factors (pink ellipses) that put pressure on the socio-technical regime. The landscape factor in the new regime consists of concerns about the energy crisis. This is based on the fact that along with the increasing number of motor vehicles, fuel consumption will also increase. Later, it is feared that it will cause a shortage of fossil fuels and even an energy crisis (Prastyono et al., 2024). The next factor is environmental awareness, which is based on the statement of stakeholder 3, that it is important to have environmental awareness so that it can later reduce the negative impacts of the environment. Furthermore, there are government regulations consisting of Presidential Regulation No. 55 of 2019, Ministerial Regulation No. 27 of 2020, and Regulation of the Minister of Environment and Forestry (Permen LHK) No. 12 of 2021. Furthermore, these factors are interrelated with each other and can produce a "landscape product" that can act as the main supporting factor for changing conventional vehicles to electric vehicles. The resulting landscape product is the commercialization of electric vehicles, regulation of electric vehicle specifications and regulation of battery waste management.

b. Socio-Technical Regime

At the meso level, the socio-technical regime consists of a series of supply chain processes of the new regime. These processes are classified into upstream, midstream, and downstream, symbolized by the yellow rectangle. In this supply chain flow diagram, the upstream process of electric vehicles begins with the selection of battery suppliers, procurement of raw materials, production of battery components, and manufacturing and battery assembly processes. After that, the next stage is the battery distribution process. Then continued with the process of sending batteries to electric vehicle companies in Indonesia. Next, the battery is installed on the electric vehicle and the battery is used on the electric vehicle. Furthermore, the downstream part, namely, batteries that have expired will be reused (second life). After that, recycling is carried out and continued with the disposal and management of battery waste.

c. Special Innovation

At the micro level, a special innovation in the new regime is the application of a circular economy to electric vehicle batteries. The application of a circular economy to electric vehicle batteries is an innovation that has the potential to create opportunities for the transition of conventional vehicles to electric vehicles. In this study, the innovation will focus on how to extend the battery life cycle through the reuse, remanufacturing, and recycling processes. In this specific innovation, the author proposes implementing a circular economy in a loop. In the battery sorting process explained in Figure 2, close collaboration is expected between electric vehicle manufacturers and electric vehicle battery companies that are responsible for managing battery waste. This collaboration will allow battery manufacturers to work with electric vehicle battery companies. Thus, battery manufacturers can function as official collection points for electric vehicle batteries that are damaged or have reached the end of their useful life. Through this initiative, batteries that are no longer used can be returned to the manufacturer for further processing. Thus, this step not only reduces battery waste, but also strengthens the concept of a circular economy where resources are utilized optimally in the battery life cycle. This process creates added value for all parties involved, and supports environmental sustainability by reducing the negative impact of battery waste. In addition, a circular economy will be created with a looping process for batteries back to the manufacturer.

D. Verification and Validation

The results of interviews with various stakeholders regarding electric vehicle batteries revealed several important aspects related to the life cycle, use, and management of batteries. First, electric vehicle batteries have a cycle life of around 1000 cycles, with variations in characteristics depending on the type of battery used, such as FLP or NMC. These batteries must go through a reuse, remanufacturing, and recycling process before being completely disposed of, and this process is still in the development stage in Indonesia with challenges related to infrastructure and regulations. Batteries that can no longer be used for vehicles can be diverted to renewable energy applications such as powerwalls or powerbanks before being recycled. Battery waste management still faces constraints, but cooperation between government, industry, and the community is needed to increase recycling effectiveness and public awareness.

The battery life cycle model that has been developed and validated by stakeholders shows that the reuse, remanufacturing, and recycling processes are very important in the management of electric vehicle batteries. The model also supports the transition to electric vehicles by considering the technical and economic aspects of the battery. Verification and validation of the model were carried out through interviews with various competent parties, ensuring that the model is in accordance with current battery conditions and can support the development of a Closed Loop Supply Chain (CLSC) for more sustainable battery management.

6. Conclusion

Based on the research objectives and research results above, the following conclusions can be drawn:
This research has been conducted to analyze the sustainability transition in the electric vehicle (EV) battery life cycle by integrating the Multi-Level Perspective (MLP) framework and Circular Economy (CE) principles. It has been found that batteries cannot be immediately disposed of after reaching the end of their primary use. Instead, they must undergo reuse, remanufacturing, and recycling to optimize resource efficiency and minimize environmental impact. The life cycle of an EV battery has been identified to begin with raw material extraction, followed by component processing, assembly, and utilization in electric vehicles. Once the battery has been depleted beyond automotive use, it is redirected for secondary applications, such as stationary energy storage for agriculture and residential areas. If further degradation occurs, the battery is subjected to a remanufacturing process, where individual components are repaired or replaced. Only when the battery can no longer be reused or remanufactured is it processed through recycling, allowing for the recovery of materials such as nickel and cobalt. Batteries that cannot be recycled are then disposed of following strict waste management procedures.

The transition from fossil-fuel-based transportation to electric vehicles has been examined through two MLP models. The old regime has been identified as a linear and unsustainable fossil fuel supply chain, which contributes to high fuel consumption, environmental degradation, and energy crises. Meanwhile, the new regime, which is centered on

EV batteries, has been proposed as a more sustainable alternative. By shifting energy consumption from fossil fuels to electricity, it is expected that carbon emissions will be reduced, leading to long-term environmental sustainability. However, it has been observed that regulatory gaps, inadequate recycling infrastructure, and economic constraints remain significant barriers in Indonesia, delaying the adoption of circular economy principles compared to developed nations. Additionally, technological challenges in battery recycling processes, such as the efficiency and environmental impact of hydrometallurgy and pyrometallurgy, have been noted. To address these issues, alternative solutions, including bioleaching, have been suggested to enhance material recovery and reduce hazardous waste production. Moreover, it has been recommended that policy frameworks, such as Extended Producer Responsibility (EPR) and centralized recycling hubs, be strengthened to facilitate a smoother transition to sustainable battery management.

To ensure a more quantitative evaluation, it has been suggested that dynamic simulation models be incorporated into future research to assess the long-term impacts of circular economy practices on battery supply chains. Through the application of System Dynamics (SD) or Agent-Based Modeling (ABM), simulations could be conducted to measure the flow of used batteries, recycling rates, material recovery efficiency, and economic feasibility under various policy scenarios. By adopting this approach, a more realistic and measurable evaluation of sustainability strategies could be achieved, ensuring that proposed solutions are both practical and scalable for real-world implementation.

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