Environ. Eng. Res. 2024; 29(3): 230351
https://doi.org/10.4491/eer.2023.351

pISSN 1226-1025
eISSN 2005-968X

Research

Revisiting actors' role in circular economy governance: A case of electric vehicle waste batteries in South Korea

Youhyun Lee[1†], Minjeong Kim[2], Kyoungmin Kim[3†]

[1]*Ajou University, Department of Public Administration, 206 Worldcup-ro, Yeongtong-gu, Suwon, Gyeonggi-do 16499, Republic of Korea*
[2]*Ajou University, Social Science Research Institute, 206 Worldcup-ro, Yeongtong-gu, Suwon, Gyeonggi-do 16499, Republic of Korea*
[3]*National Assembly Research Service, 1 Uisadang-ro, Yeongdeungpo-gu Seoul 07233, Republic of Korea*

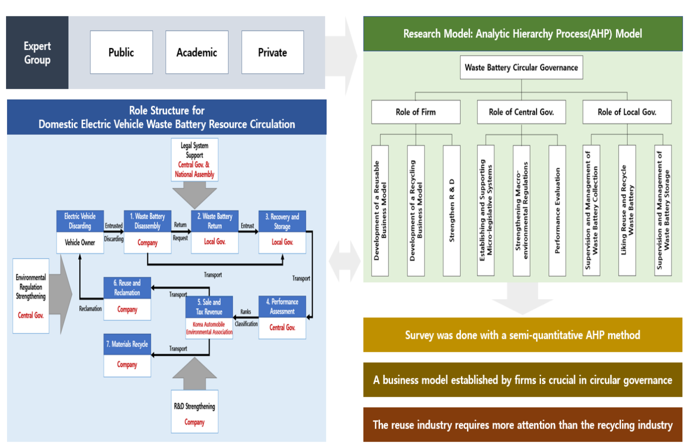
Received June 12, 2023 **Revised** August 4, 2023 **Accepted** September 6, 2023

ABSTRACT

An increase in the number of electric vehicle (EV) waste batteries has driven the growth of the waste battery market. In the EV battery industry, South Korea has demonstrated excellent output in battery production but poor output in waste battery reuse and recycling. To determine appropriate waste battery use, primary governance actors should establish their role and lead the early stage of the industrial ecosystem. Herein, we elucidated the appropriate role of each circular governance actor in EV waste batteries using the South Korean case. We used the analytic hierarchy process, a semiquantitative method, and included 37 circular economy experts. For the first class, the firm is the most important actor in the circular governance of waste batteries, with a weight of 0.404, followed by the central (0.375) and local (0.221) governments. For the second class, the reuse industry (0.167) requires more attention than the recycling industry (0.133). Because many countries worldwide interested in the waste battery market have yet to begin the implementation stage, analyzing South Korea's case can offer practical insights for countries aiming to expand their waste battery market with a clear policy orientation towards carbon neutrality or net-zero emissions and strong policy actor leadership.

Keywords: Circular economy, Electric vehicles, Governance, Waste batteries

Graphical Abstract



† Corresponding author
E-mail: kmkim@assembly.go.kr (K.K.), youhyun@ajou.ac.kr (Y.L.)
Tel: +82-6788-4732 (K.K.), +82-31-219-2751 (Y.L.)
ORCID: 0000-0002-4729-032X (K.K.), 0000-0001-9345-1094 (Y.L.)

1. Introduction

The escalation of the global climate crisis and implementation of carbon neutral policies have accelerated the transition to new and renewable energy sources, thereby increasing the supply of electric vehicles (EVs) [1, 2]. Recently, owing to the rapid transition to EVs, EV waste battery treatment has emerged as a critical public policy issue [3, 4]. Providing waste batteries, a second life could be beneficial for the environment and economy [5]. However, to date, environmental and transport policies have not prioritized value creation from EV lithium-ion battery (LIB) waste; therefore, the circular economy remains unachieved. This failure is primarily attributable to uncertain governance. Therefore, concrete governance is warranted in EV waste battery policies.

First, owing to the absence of proper management, an increase in the number of EV waste batteries [6] has raised concerns [7-9]. Despite the rapid growth of the EV battery market, policies directed toward their treatment are lacking. Second, waste battery policies can be a new driver for the economic growth of the nation. A sudden increase in the cost of raw materials for secondary batteries used in EVs has been stimulating the waste battery market [10, 11]. For example, in the global market, the average price of lithium, a major raw material for secondary batteries, has increased by 410% in 2022 compared with 2020 [12]. Furthermore, there has been an increase in the supply prices of cobalt and nickel [12]. Third, fierce competition to secure supply chains has triggered the waste battery market. Competition has been intensifying owing to the entry of new European companies, including Northvolt. Notably, the growing demand for producers to internalize battery production has facilitated the growth of the waste battery market.

The key drivers in the battery industry include structured cooperation among the government, companies, and stakeholders and a strong policy [13, 14]. This has been proven by the industrial models of China and Japan. However, the experience of South Korea in the EV battery industry has been like a double-edged sword: an excellent output in battery production but poor output in waste battery reuse and recycling. Therefore, infrastructural and societal needs for waste batteries have been established in South Korea; however, institutions and governance systems fail to meet these demands.

As South Korea is a leading country in EV technology, case studies concerning EV waste batteries from South Korea are emerging in international journals. Choi and Rhee [15] explained the recycling management and technology of end-of-life EV batteries in Korea. In addition, Chen et al. [16] compared next-generation vehicles in China, Japan, and South Korea and suggested developmental strategies and policy trends for vehicle batteries. Furthermore, Herrador et al. [17] compared circular economy policies on battery issues in Korea and Japan. However, these recent studies have failed to apply proper methodologies and have relied on reviews. In addition, previous studies have only explained Korean policies in general and not focused on governance systems. Therefore, we aimed to overcome the methodological limitations of previous studies by including an actual survey, i.e., the analytic hierarchy process (AHP), for policy experts in South Korea. Our primary objective was to determine which actor's role should be prioritized in waste battery governance, ultimately facilitating the circular economy. Because many countries interested in the waste battery market are not yet in the implementation stage, analyzing South Korea's situation can offer practical insights for countries aiming to expand their waste battery market with a clear policy orientation towards carbon neutrality or net-zero emissions and strong leadership of policy actors.

2. EV Waste Battery Policies in the European Union, Japan, China, and Korea

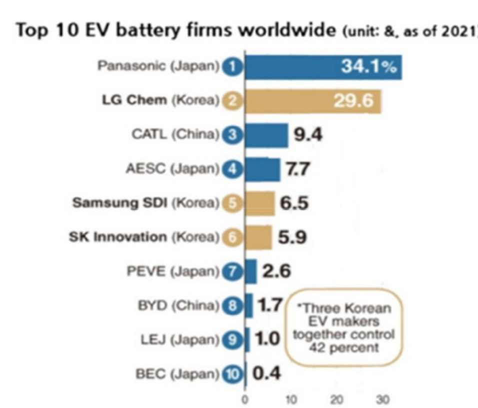
After the adoption of the Paris Climate Agreement in 2015, the supply of EVs has expanded and is expected to continue increasing. Although Asian countries such as China, Japan, and South Korea dominate the market and revenue share (Fig. 1), the European Union (EU) has implemented the leading institutions and legal frameworks [18, 19].

In the EU, it is expected that by the year 2040, 70% of the vehicles sold will be EVs because economic feasibility will improve with the development of EV manufacturing technology, resulting in regulations on fossil fuel vehicles. Furthermore, the recent EU battery and waste battery regulation (draft) law, which will revise

Electric Vehicle Battery Recycling Market Share (By Region, 2021, %)

Regions	Revenue Share in 2021
North America	25%
Asia Pacific	51%
Europe	18%
Latin America	4%
MEA	2%

▲ Source : https://www.precedenceresearch.com/electric-vehicle-battery-recycling-market



▶ Source : https://m.koreaherald.com/view.php?ud=20200401000377

Fig. 1. Battery and battery recycling market.

Table 1. Comparison of the recycling and reuse of waste batteries [12]

	Recycling of waste batteries	Reuse of waste batteries
Definition	After disassembling the waste batteries at the cell level, the rare metals are extracted and recycled	Using waste batteries at the module or pack level as an energy storage system (ESS)[1] or uninterruptible power supply (UPS)[2]
Main target batteries	Small waste batteries from IT instruments	Medium- or large-sized batteries such as electric vehicle batteries
Necessary facilities and requirements	A waste battery discharge system is warranted. Secure technologies for recovering the structure materials are needed.	A waste battery diagnostic and analysis facility are warranted. Possessing expertise in ESS manufacturing and operation is an advantage.
Expected effects	Saving raw material expenses owing to the replacement of raw material import. For recycling 24 kWh NCM[3] battery packs, sales of \$600–\$900 per pack are expected from selling metals.	Because modules and cells need not be disassembled, the disassembly process is safe, without much additional expenses.
Business model	Companies specializing in waste battery recycling, including Umicore in Belgium or SungEel HiTech in Korea, are doing business.	Examined as a new business model by automakers and battery makers.

Note 1: A system that saves electric power in storage devices and supplies the electric power when needed later.
Note 2: A facility that supplies emergency power at the time of power failure.
Note 3: A ternary battery that uses nickel, cobalt, and manganese as cathode materials.

the battery directive, has stated that an increase in battery usage will be a major factor influencing the transition to a climate neutral economy. Notably, the manufacture of new batteries may decrease owing to the increased use of recycled batteries, thereby decreasing the use of natural raw materials.

The Japanese government has predicted that by the year 2050, >500,000 EVs will be supplied as next-generation vehicles, with the generation of batteries after their use. Notably, Nissan Motor and Sumitomo Shoji established “Fore Energy Company” in September 2010 to review the reuse business of lithium-ion battery separators in EVs supplying electricity. In addition, “Vehicle to Home,” a conceptual diagram of the solution, aims to use the large-capacity batteries of EVs as a power supply device.

China has the world’s largest EV market share [20], and the Chinese government has presented a roadmap to supply 5 million new EVs by 2020. Furthermore, it has been promoting support policies, including vehicle purchase subsidies and exemption from acquisition tax [21]. The Chinese government has also implemented regulations to strengthen the management of the recycling of new energy vehicle batteries, standardize industrial development, protect the environment and human health, ensure safety, and promote comprehensive resource utilization and the development of the new EV industry. However, studies on the recycling of EV batteries are lacking [22].

In South Korea, 25,593 EVs were distributed (cumulative) in 2017, representing an average annual growth rate of approximately 85% (2011–2017). In addition, based on the fine dust management plan in Korea, the South Korean government planned to supply 350,000 EVs by 2022. Furthermore, the South Korean EV battery market is expected to grow to 1,243 GWh by 2025, with an annual average growth rate of 46.7%. Notably, EV batteries are generally discarded after 5–10 years of use, and the initial EV market was established in 2011; therefore, the number of waste batteries may increase after 2020 [23].

3. Recycling and Reuse of Waste Battery

The EV waste battery business is divided into recycling and reuse methods (Table 1). Notably, EV batteries can no longer be used if their charging decreases to <70% of the initial capacity owing to decreased mileage and charging/discharging speed due to the operational reasons. Therefore, batteries with a charging capacity of 70% are warranted for replacement, necessitating recycling and reuse.

The recycling method involves disassembling the batteries and extracting and recycling their core materials, including cobalt and lithium. Therefore, facilities such as a waste battery discharge system are required for the recycling industry. Furthermore, it is important to secure process technologies that can minimize constituent materials. Recycling waste batteries can replace the import of raw materials and decrease costs associated with battery raw materials. Companies such as Belgium’s Umicore, which specializes in battery recycling, are successful business models [12].

In the reuse method, the condition of waste batteries is first evaluated, followed by changing them to energy storage systems (ESS) and uninterruptible power systems. Notably, domestic and foreign automakers are actively researching and developing new reuse methods. The reuse industry requires facilities to diagnose and analyze the remaining performance of waste batteries. Furthermore, technical expertise in ESS manufacturing and operation is warranted. Reusing waste batteries as ESS may establish new economic value. Although a successful model for the commercialization of ESS remains undeveloped, vehicle manu-

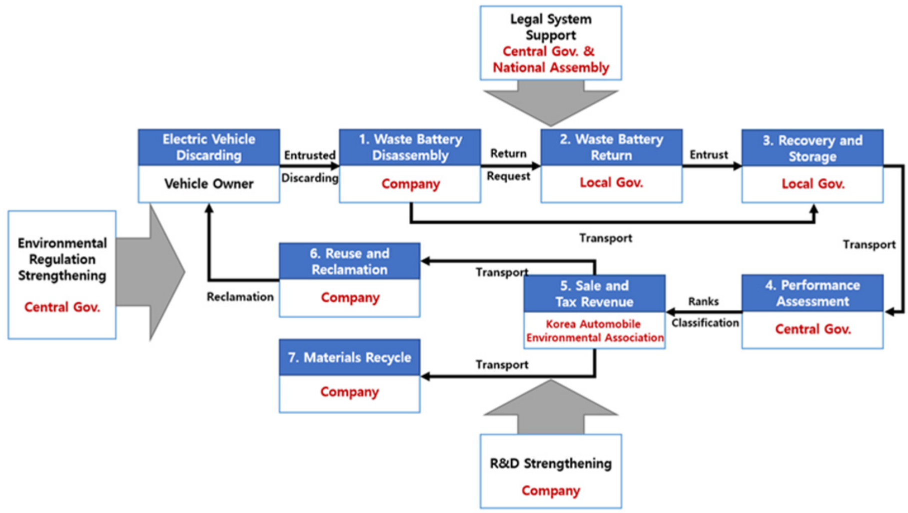


Fig. 2. Role structure of different actors in the resource circulation of domestic electric vehicle waste batteries.

facturers are reviewing it as a new business model owing to its potential [12].

4. South Korean Electric Vehicle Waste Battery Governance and the Role of Actors

Governance in public policy can be defined as the process of decision-making by core policy actors [24-26]. Notably, policies are an outcome of interactions among policy actors; therefore, identifying the core actors and their roles has been the primary concerns of studies on energy and environmental policies [27-31].

Fig. 2 demonstrates that the primary policy actors in the domestic waste battery circulation system are the central government, parliament, corporations, and local governments. In addition, vehicle owners and automobile environmental associations play vital roles. First, the central government or parliament supports legal systems related to battery reuse and recycling. Next, the waste batteries are segregated at the company level, and the local government collects and stores returned waste batteries. Thereafter, the central government evaluates and classifies the performance of the stored waste batteries. Subsequently, the Automobile Environmental Association sells the waste batteries to companies for recycling or reusing as ESS. Furthermore, the companies develop business models and strengthen research and development (R&D) in the reuse and recycling processes. Lastly, the central government strengthens macroenvironmental regulations related to the circular economy and influences the entire cycle of waste batteries.

5. Materials and Methods

5.1. Research Models and Methods

In the present study, expert opinion regarding domestic EV battery waste policy was gathered to establish a governance system to promote the resource circulation of EV waste batteries. Thereafter, AHP was implemented to determine the issues that should be prioritized in establishing governance. AHP, proposed by Saaty [32], facilitates effective decision-making by systematically ranking several alternative or multi-criteria elements and comparing and analyzing their weights [32, 33]. It is a decision-making method that systematically evaluates mutually exclusive alternatives to derive priorities [34, 35]. This method is based on the principle that when a problem is complex and has multiple evaluation criteria, the human brain uses a stepwise or hierarchical analysis process for decision-making [36]. This methodology has several advantages because it can help simply and quantitatively represent an otherwise unquantifiable human judgment [36, 37]. Furthermore, AHP is useful for generating quantitative results by measuring relative importance or preference on a ratio scale [38]. This method is widely used in environmental policy studies to help prioritize integrated policies [34-42]. Because we aimed to identify the actors that play the most important role in waste battery governance, AHP is the most appropriate methodology.

In AHP, issues are structured and hierarchically decomposed [43, 44]. Accordingly, structuring was performed by dividing the parties involved into the central government, local government, and enterprise based on who will play a major role in establishing governance to promote the resource circulation of EV waste batteries. Hierarchical decomposition comprised the essential roles each participant may play. Using this model, a desirable role was determined for policy actors in the future, including strategies for developing related policies. Fig. 3 presents the resulting AHP model.

In the AHP model used in this study, the first layer represented policy actors, comprising corporations, central governments, and local governments. The second layer described the role of each policy actor, which is as follows: corporations are mostly responsible for developing a reuse and recycling business model and improving R&D; the central government establishes and supports micro-laws and systems, strengthens macroenvironmental regu-

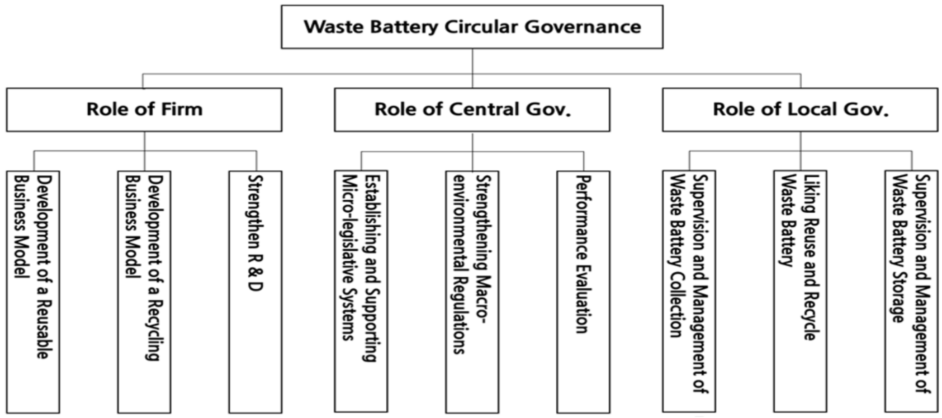


Fig. 3. Analytic hierarchy process (AHP) model of the circular governance of waste batteries.

lations, and evaluates performance; and local governments manage and supervise waste battery collection and storage and link the reuse and recycle of waste batteries. The priorities of these roles were analyzed using pairwise comparisons for each item.

5.2. Research Questions

To achieve the objectives of the present study, the main research questions comprised the weight of each actor's role: firms, central government, and local government. The actual questionnaires are indicated in the supplementary materials (Fig. S1).

Question 1. Whose role should be prioritized in the circular governance of waste batteries?

Three expert groups were analyzed in this study: public, academic, and private (corporations and associations) sectors. The experts' opinions on which policy actors' roles should be emphasized the most in governance to promote the resource circulation of EV waste batteries and whether each expert group emphasizes different policy actors or roles were examined. Accordingly, the following questions were proposed:

Question 2-1. Expert groups (public/academic/private) will have different opinions on which role criterion of the firm is the most important.

Question 2-2. Expert groups (public/academic/private) will have different opinions on which role criterion of the central government is the most important.

Questions 2-3. Expert groups (public/academic/private) will have different opinions on which role criterion of the local government is the most important.

We verified these questions by conducting an AHP survey in the three expert groups. Thereafter, the differences in responses among the groups were compared and analyzed. Lastly, the response results of the entire expert group were analyzed to determine the priorities of the factors optimal for the governance of the resource circulation of waste batteries.

5.3. Data Collection and Analysis

This study aimed to determine the priorities for the roles necessary for establishing governance to promote the resource circulation of EV waste batteries using the AHP method. Based on the study hypotheses, the expert group was classified into three sectors: public, academic (research institutions and universities), and private (corporations and associations). These groups were asked to fill out a questionnaire, followed by analysis of the results. Direct surveys, a primary data collection method, were completed by 10 public, 15 academic, and 12 private sector respondents. Furthermore, the data comprised public sector surveys of individuals working at central ministries, local governments, and public institutions; academic surveys of individuals employed at government-funded research institutes and universities (professors of related majors); and private sector surveys of individuals at companies, corporations, associations, and cooperatives.

Data collection was performed between September 6 and October 13, 2022. Overall, 37 experts on EV waste batteries participated in this study. Because quantitative and qualitative factors can be integrated based on the characteristics of AHP analysis, the questionnaire was organized such that both factors were considered [33] and sought to obtain a relevant expert opinion. Therefore, the AHP method was used as a qualitative research method, and expert opinions were supplemented as a quantitative research method.

Based on the AHP method proposed by Saaty [32], items of pairwise comparison become appropriate for human perception when they comprise two or three hierarchical layers that can be compared and answered. In this stratified comparison, the views of the decision-makers were considered reasonably integrated. As previously demonstrated in Figure 3, this study comprised two hierarchies—the actors and their roles—required in developing a model for the resource circulation of EV waste batteries.

6. Results and Discussion

6.1. Demographic Characteristics of the Study Sample

The AHP sample was classified into three groups based on the affiliated institutions of each expert: public, academic, and private. Table 2 presents the demographic characteristics of the study sample. In total, 37 respondents (32 males, 86.5%; 5 females, 13.5%)

Table 2. Demographic characteristics of the analytic hierarchy process sample

No.	Affiliation	Working periods (years)	Ages (years)	Sex	Sector
1	National Assembly	~15s	50s	Female	PUBLIC
2	Korea Environment Corporation	~10s	50s	Male	
3	Korea Environment Corporation	~10s	40s	Male	
4	Korea Evaluation Institute of Industrial Technology	~10s	30s	Male	
5	Ministry of Trade, Industry and Energy	10–15s	40s	Male	
6	Ministry of Trade, Industry and Energy	10–15s	40s	Male	
7	Ministry of Trade, Industry and Energy	~15s	40s	Male	
8	Ministry of Environment	~15s	40s	Male	
9	Local Government	~30s	50s	Male	
10	Korea Productivity Center	10–15s	40s	Male	
11	Korea Institute of Industrial Technology	~10s	30s	Female	ACADEMIA
12	Korea Environment Institute	10–15s	40s	Female	
13	Korea Electrotechnology Research Institute	~15s	50s	Male	
14	Korea Institute of Geoscience and Mineral Resources	~10s	30s	Female	
15	Korea Institute of Geoscience and Mineral Resources	~10s	30s	Male	
16	Korea Transport Institute	~15s	50s	Male	
17	Korea Institute of Science and Technology	~15s	40s	Male	
18	Korea Institute of Science and Technology	10–15s	40s	Male	
19	Korea Institute of Science and Technology	10–15s	40s	Male	
20	Korea Institute of Civil Engineering and Building Technology	~30s	60s	Male	
21	University	~15s	50s	Male	
22	University	~15s	40s	Female	
23	University	~15s	60s	Male	
24	University	~15s	60s	Male	
25	University	~15s	60s	Male	
26	Korea ESS Industry Development Association	~15s	50s	Male	PRIVATE
27	Korea Battery Industry Association	~10s	50s	Male	
28	Korea Electric Vehicle Association	~10s	50s	Male	
29	Korea Automotive Recyclers Association	10–15s	50s	Male	
30	Korea Electronics Recycling Cooperative	~15s	50s	Male	
31	Corporation	~10s	50s	Male	
32	Corporation	~10s	40s	Male	
33	Corporation	~15s	40s	Male	
34	Corporation	~15s	50s	Male	
35	Corporation	10–15s	40s	Male	
36	Corporation	~15s	60s	Male	
37	Corporation	~30s	60s	Male	

participated in this survey, with a disproportionate number of male respondents. Four individuals were in their 30s (10.8%), 14 were in their 40s (37.8%), 13 were in their 50s (35.1%), and 6 were ≥60 (16.2%); therefore, the majority of the sample comprised individuals in their 40s and 50s. The working years of the individuals were as follows: 1 to <5 years: 2 respondents (5.4%); 5 to <10 years: 8 respondents (21.6%); 10 to <15 years: 8 respondents (21.6%); and >15 years: 19 respondents (51.4%); therefore, the group with working years of >15 years had the largest proportion. Organizational types were classified into the public, academic, and private sectors based on the affiliated organizations of the respondents; >10 individuals under each type participated in the survey.

6.2. Confirmation of the Results and Analysis of the First Class

In the AHP model, the geometric mean was calculated after coding the collected questionnaires as primary data. Priority was elucidated using the Expert Choice 11.5 program. The reliability of the AHP model was verified using the consistency index (CI), with a value of ≤0.10 indicating good reliability [32]. The CI formula is as follows:

$$CI = (\lambda\_max \cdot n)/(n - 1) \tag{1}$$

Notably, most items verified in this study had values of <0.10, confirming their reliability. Furthermore, the CI was ≥0.10 when the group was separately analyzed, excluding the questions for public sector experts regarding the priority of the roles of the local governments; however, it was within the generally accepted range of 0.1–0.15 [32, 34, 35].

The results of the AHP analysis on the importance of the roles for the governance of the resource circulation of EV waste batteries revealed that priorities were in the following order: corporate (0.404), central government (0.375), and local government (0.221). The CI was 0.03, which is acceptable based on Saaty's study [32]. Additionally, the weight difference between the role criterion of the corporate sector and central government was 0.03 and that between the role criterion of the corporate sector and local government was 0.18; this indicates that the role of the companies is emphasized the most and that of the local government is less emphasized. A study on current EU and UK waste battery management frameworks and policies has suggested the limitations of not solving technological innovations in terms of LIB recycling supporting the circular economy of EV batteries [45]. In this regard, it is possible to realize the importance of technological innovations in the circular economy of waste batteries and the context in which the role of the private sector is emphasized.

6.3. Analysis of the Second Class

Fig. 4 presents the results of the AHP analysis of the second class. In this figure, n1 represents the overall weight of the second class, including the three expert categories (public, academic, and private sectors). In n1, the weight of developing a reusable business model ranked first (0.167), followed by the establishment and support of micro-legislative systems (0.155); the development of a recycling business model ranked third (0.133). Furthermore, strengthening R&D ranked fourth (0.126), followed by strengthening macroenvironmental regulations (0.117) and supervising and managing the collection of waste batteries, which ranked sixth (0.091). Lastly, linking reuse and recycle waste batteries ranked seventh (0.086), followed by evaluating performance (0.070) and supervising and managing the storage of waste batteries, which ranked eighth and ninth, respectively.

As shown in n2, experts in the public sector, primarily public servants working for the ministry of the environment, the ministry of trade, industry, and energy, and the national assembly, presented the same results as n1. However, academic experts emphasized

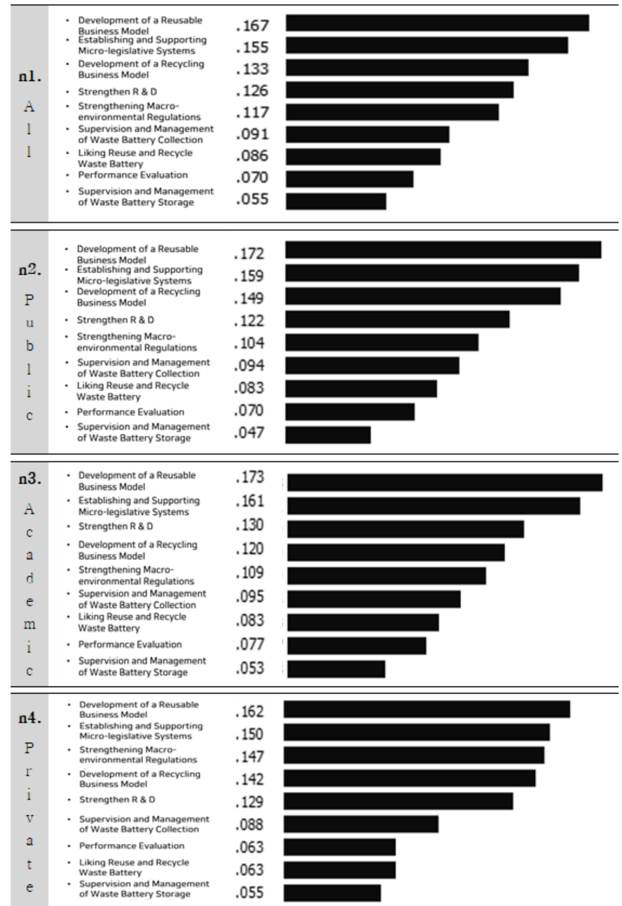


Fig. 4. Comprehensive analytic hierarchy process (AHP) results. Detailed indicators of waste battery governance. R&D, research and development.

strengthening R&D, which was ranked third, instead of developing a recycling business model. However, private sector experts had a different priority: strengthening macroenvironmental regulations instead of developing a recycling business model. Based on this perspective, the private sector is more sensitive to government regulations than other sectors. Nevertheless, the sensitivity of the private sector to government regulations or policy measures is not limited to Korea and can be observed in cases of EV waste batteries in China and other countries [46].

6.4. Results of the Analysis of Individual Expert Groups: Public, Academic, and Private Sectors

The results of the priority analysis of the detailed indicators are as follows: Analysis of the role of the firm revealed that developing a reusable business model was the first priority, with a weight of 0.393, followed by developing a recycling business model (0.312, second) and strengthening R&D (0.296, third). The CI was 0.00763, which is acceptable. The differences in weights among the three indicators were not large; therefore, they were all considered important.

Experts in the public and private sectors shared similar weights for indicators of the role of the firm, thereby representing the overall ranking. However, academic experts considered developing a reusable business model (0.409) more vital than the public (0.388) and private (0.374) sector experts. Furthermore, among academic experts, there were different rankings for developing a recycling business model and strengthening R&D. The CI of the public, academic, and private sectors was set at 0.00001, 0.04, and 0.00029, respectively.

For the roles of the central government, establishing and supporting micro-legislative systems was the first priority, with a weight of 0.455, followed by strengthening macroenvironmental regulations (0.341, second) and evaluating performance (0.204, third). The difference in weights among the three sectors was evident; therefore, prioritization is apparent for the role of the central government. The CI was 0.00111, which is acceptable. In this study, the micro-legislative system does not necessarily imply the size of the policy; rather, it implies that more detailed and precise regulations are warranted to promote the ecosystem of EV waste batteries.

All three expert groups shared the same order regarding the role of the central government. However, the private sector provided a very low weight to establishing and supporting micro-legislative systems (0.174). This is because the experts in the private sector, primarily the firm, give considerable importance to national-scale regulations for a greener and circular society. The CI of the public, academic, and private sectors was set at 0.03, 0.00235, and 0.00024, respectively, which are all acceptable.

Lastly, for the role of the local government, supervising and managing waste battery collection was the first priority, with a weight of 0.392, followed by linking reuse and recycle waste batteries (0.372, second) and supervising and managing waste battery storage (0.236, third). The differences in weight between the first and second priorities were not large; therefore, they were considered important. The CI was set at 0.00311, which is acceptable.

All three expert groups shared the same order. The differences in weight were not as apparent as that for the roles of the central government and firm. The CI of the public, academic, and private sectors was set at 0.12, 0.00472, and 0.00006, respectively.

6.5. Discussion and Confirmation of the Questions & Limitations

Based on the results of AHP analysis, four questions were answered. For question 1, "Whose role should be prioritized in the circular governance of waste battery?," the firm should be the most important actor, followed by the central and local governments. However, considering the current situation in South Korea, where the primary responsibility of waste batteries belongs to the local government, this prioritization is controversial. For example, Article 58(5) of the "Air Environment Protection Act" and Article 79(4)(3) of the "Enforcement Rules of the Act" specify that owners of EVs who have received purchase subsidies must return the batteries to the governor of their local governments if they wish to cancel their vehicle registration for scrapping by December 31, 2020.

EV waste batteries contain valuable rare metals and can be reused as energy storage devices; therefore, battery recycling and reuse are essential for conserving and recycling these materials [15]. However, it is difficult for local governments to efficiently perform the technology-intensive reuse and recycling of batteries. Based on the findings of the present study, we hypothesize that the powers and roles currently assigned to local governments should be transferred to private companies or that public–private partnerships (e.g., between firms and local governments and firms and central governments) should be reorganized to efficiently manage waste batteries.

Therefore, at least in the early stage of the circular ecosystem, waste batteries should be managed by firms and the central government, but not the local government.

The second question (2-1), "Expert groups (public/academic/private) will have different opinions on which role criterion of a firm is the most important," was confirmed via AHP analysis. For example, academic experts provided different ranks for developing a recycling business model and strengthening R&D. Furthermore, they had a long-term perspective of the circular economy and prioritized R&D over the recycling business model, which has already been developed in the case of Korea.

The third question (2-2), "Expert groups (public/academic/private) will have different opinions on which role criterion of the central government is the most important," was partially confirmed via AHP analysis. Although the overall ranking order was not different, the weighted values of private sector experts were visibly different from those of public and academic sector experts.

Lastly, the fourth question (2-3), "Expert groups (public/academic/private) will have different opinions on which role criterion of the local government is the most important," was not confirmed via AHP analysis. Nevertheless, the overall ranking order and distribution of each weight were similar.

Nevertheless, the present study has two major limitations. First, because AHP analysis does not consider empirical confirmation, the sampling and subjectivity of the interpretation are potentially biased. Furthermore, sample bias should be considered. Although we attempted to include as many different expert groups as possible, the sample size may have contributed to biased results. Therefore, additional in-depth interviews, cost–benefit analysis, and other empirical evidence using a larger sample size are warranted to support the study results. Second, in this study, we identified companies, the central government, and the local government as the main governance actors; therefore, the importance of the roles of other key policy actors was not determined. For example, the role of citizens may be important in the advanced stage of the waste battery policy, which was not included in the study. Therefore, additional studies on the role of new actors after the establishment of the waste battery policy are warranted.

7. Conclusions

The EV market is rapidly growing toward green transportation and the global target of carbon neutrality. However, the after-effects of EV components, particularly waste battery treatment, remain unclear. To elucidate the correct use of waste batteries, the appropriate roles of primary governance actors should be identified and they should lead to the early stage of the industrial ecosystem. In the present study, we determined the appropriate role of each circular governance actors in EV waste batteries using the case of South Korea. To achieve this, we performed AHP analysis, a semiquantitative method, of 37 experts in the circular economy. This study derived several insights and policy implications as follows.

Point 1. More authority and resources to firms and the central government.

First, more authority and resources should be designated to firms and the central government. In South Korea, the local government is primarily responsible for waste battery management. However, in the early stage of the circular ecosystem of waste batteries, the responsibility should be given to firms (by developing a business model) and the central government (by reinforcing the detailed regulations), and not to local governments.

Point 2. Reuse industry requires more attention.

Second, the reuse industry requires more attention than the recycling industry, which has already been established and does not require advanced technology. However, because the reuse industry is in the beginner stage, it is vital to invest more in technology and put additional efforts into developing the reuse industrial value chain.

Point 3. Confirming consistent prioritization for significant issues.

Third, South Korean experts in different sectors mostly had similar opinions on circular governance. Excluding several detailed factors, the public, academic, and private sector experts exhibited comparatively consistent prioritization for significant issues, including the urgency of developing a business model for reuse and recycling and implementing regulations for waste batteries.

Point 4. Korean case as guideline for EV waste battery governance.

Lastly, additional case studies should be conducted in other countries to confirm the results of the present study, enabling their generalizability. Nevertheless, the case discussed in this study is meaningful because South Korea occupies a large portion of the global EV and battery market in terms of production and consumption. Our study results can offer some guidelines for conforming the governance of EV waste batteries in latecomer countries in EV technology. This can ultimately facilitate the growth of the EV market toward sustainable and more ecological transportation in global society.

Acknowledgments

This work was supported by Korea CCUS Association(K-CCUS) grant funded by the Korea Government (MOE, MOTIE) (KCCUS20220001, Human Resources Program for Reduction of greenhouse gases).

Conflict of Interest Statement

The authors declare that they have no conflict of interest.

Author Contributions

Y. L. (Professor), the first and corresponding author, designed the framework, constructed the survey, and completed the write-up and funding; K. K. (Ph. D.), as the corresponding author, organized the research project and survey; M. K. (Research Professor), as the second author, conducted the analysis.

References

1. Akimoto K, Sano F, Nakano Y. Assessment of comprehensive energy systems for achieving carbon neutrality in road transport. *Transp. Res. D.* 2022;112:103487. https://doi.org/10.1016/j.trd.2022.103487
2. Hossain MS, Fang YR, Ma T, et al. Narrowing fossil fuel consumption in the Indian road transport sector towards reaching carbon neutrality. *Energy Policy* 2023;172:113330. https://doi.org/10.1016/j.enpol.2022.113330
3. Baum ZJ, Bird RE, Yu X, Ma J. Lithium-ion battery recycling—overview of techniques and trends. *ACS Energy Lett*. 2022;7:712-719. https://doi.org/10.1021/acsenergylett.1c02602
4. Nurdiawati A, Agrawal TK. Creating a circular EV battery value chain: End-of-life strategies and future perspective. *Resour. Conserv. Recy*. 2022;185:106484. https://doi.org/10.1016/j.resconrec.2022.106484
5. Shahjalal M, Roy PK, Shams T, et al. A review on second-life of Li-ion batteries: Prospects, challenges, and issues. *Energy* 2022;241:122881. https://doi.org/10.1016/j.energy.2021.122881
6. Hu Y, Cheng H, Tao S. Retired electric vehicle (EV) batteries: Integrated waste management and research needs. *Environ. Sci. Technol*. 2017;51:10927-10929. https://doi.org/10.1021/acs.est.7b04207
7. Harper G, Sommerville R, Kendrick E, et al. Recycling lithium-ion batteries from electric vehicles. *Nature* 2019;575:75-86. https://doi.org/10.1038/s41586-019-1682-5
8. Awasthi AK, Cheela VRS, D'Adamo I, et al. Zero waste approach towards a sustainable waste management. *Resour. Environ. Sustain*. 2021;3:100014. https://doi.org/10.1016/j.resenv.2021.100014
9. Jiang S, Zhang L, Hua H, Liu X, Wu H, Yuan Z. Assessment of end-of-life electric vehicle batteries in China: Future scenarios and economic benefits. *Waste Manag*. 2021;135:70-78. https://doi.org/10.1016/j.wasman.2021.08.031
10. Bird R, Baum ZJ, Yu X, Ma J. The regulatory environment for lithium-ion battery recycling. *ACS Energy Lett*. 2022;7:736-740. https://doi.org/10.1021/acsenergylett.1c02724
11. Ziemann S, Müller DB, Schebek L, Weil M. Modeling the potential impact of lithium recycling from EV batteries on lithium demand: A dynamic MFA approach. *Resour. Conserv. Recy*. 2018;133:76-85. https://doi.org/10.1016/j.resconrec.2018.01.031
12. KPMG. Synthesis of Media Reports. Restructuring by KPMG Samjeong Economic Research Institute. 2022.
13. Gebhardt M, Beck J, Kopyto M, Spieske A. Determining requirements and challenges for a sustainable and circular electric vehicle battery supply chain: A mixed-methods approach.

Sustain. Prod. Consum. 2022;33:203-217. https://doi.org/10.1016/j.spc.2022.06.024

14. Kosai S, Hanqing L, Zhang Z, Matsubae K, Yamasue E. Multi-regional land disturbances induced by mineral use in a product-based approach: A case study of gasoline, hybrid, battery electric and fuel cell vehicle production in Japan. *Resour. Conserv. Recy.* 2022;178:106093. https://doi.org/10.1016/j.resconrec.2021.106093
15. Choi Y, Rhee SW. Current status and perspectives on recycling of end-of-life battery of electric vehicle in Korea (Republic of). *Waste Manage.* 2020;106:261-270 https://doi.org/10.1016/j.wasman.2020.03.015
16. Chen H, Yu J, Liu X. Development strategies and policy trends of the next-generation vehicles battery: Focusing on the international comparison of China, Japan and South Korea. *Sustainability* 2022;14:12087. https://doi.org/10.3390/su141912087
17. Herrador M, de Jong W, Nasu K, Granrath L. Circular economy and zero-carbon strategies between Japan and South Korea: A comparative study. *Sci. Total Environ.* 2022;820:153274 https://doi.org/10.1016/j.scitotenv.2022.153274
18. Michelini E, Höschele P, Ratz F, et al. Potential and most promising second-life applications for automotive lithium-ion batteries considering technical, economic and legal aspects. *Energies* 2023;16:2830. https://doi.org/10.3390/en16062830
19. Torjesen S, Isaksen A. Rethinking the role of landscape in the multi-level perspective: The case of electric vehicle battery production in Europe and China. Available at SSRN 4357817. http://dx.doi.org/10.2139/ssrn.4357817
20. Wang S, Yu J. A comparative life cycle assessment on lithium-ion battery: Case study on electric vehicle battery in China considering battery evolution. *Waste Manag. Res.* 2021;39:156-164. https://doi.org/10.1177/0734242X2096663
21. EPA Victoria. Reusing and recycling water [Internet]. Carlton: EPA Victoria; c2009 [cited 20 November 2009]. Available from: http://www.epa.vic.gov.au/water/reuse/default.asp.
22. Zhu L, Chen M. Research on spent LiFePO4 electric vehicle battery disposal and its life cycle inventory collection in China. *Int. J. Environ. Res. Public Health* 2020;17:8828. https://doi.org/10.3390/ijerph17238828
23. Kim B. Korean EV batteries capture 40% global market share. Korea Herald: Business, 2020, April, 19.
24. Howlett M, Lindquist E. Policy analysis and governance: Analytical and policy styles in Canada. *J. Comp. Policy Anal. Res. Pract.* 2004;6:225-249. https://doi.org/10.1080/1387698042000305194
25. Howlett M. Analyzing multi-actor, multi-round public policy decision-making processes in government: Findings from five Canadian cases. *Can. J. Pol. Sci.* 2007;40:659-684. https://doi.org/10.1017/S0008423907070746
26. Treib O, Bähr H, Falkner G. Modes of governance: Towards a conceptual clarification. *J. Eur. Public Policy* 2007;14:1-20. https://doi.org/10.1080/135017606061071406
27. Chou MH, Jungblut J, Ravinet P, Vukasovic M. Higher education governance and policy: An introduction to multi-issue, multi-level and multi-actor dynamics. *Policy Soc.* 2017;36:1-15. https://doi.org/10.1080/14494035.2017.1287999
28. Dagnachew AG, Hof AF, Roelfsema MR, van Vuuren DP. Actors and governance in the transition toward universal electricity access in Sub-Saharan Africa. *Energy Policy* 2020;143:111572. https://doi.org/10.1016/j.enpol.2020.111572
29. Lemos MC, Agrawal A. Environmental governance. *Annu. Rev. Environ. Resour.* 2006;31:297-325. https://doi.org/10.1146/annurev.energy.31.042605.135621
30. Urwin K, Jordan A. Do es public policy support or undermine climate change adaptation? Exploring policy interplay across different scales of governance. *Glob. Environ. Change* 2008;18:180-191. https://doi.org/10.1016/j.gloenvcha.2007.08.002
31. Vignola R, McDaniels TL, Scholz RW. Governance structures for ecosystem-based adaptation: Using policy-network analysis to identify key organizations for bridging information across scales and policy areas. *Environ. Sci. Policy* 2013;31:71-84. https://doi.org/10.1016/j.envsci.2013.03.004
32. Saaty TL. The Analytic Hierarchy Process. New York: McGraw-Hill; 1980.
33. Kim MJ, Park SM. Study on improving performance evaluation systems of Korea NPO: Focusing on examining the validity of performance and meta evaluations. *Korean Public Admin. Rev.* 2014;48:463-497. [Written in Korean].
34. Lee Y, Song H, Jeong S. Prioritizing environmental justice in the port hinterland policy: Case of Busan New Port. *Res. Transp. Bus. Manag.* 2021;41:100672. https://doi.org/10.1016/j.rtbm.2021.100672
35. Lee Y, Kim YJ, Lee MC.Improving public acceptance of H2 stations: SWOT-AHP analysis of South Korea. *Int. J. Hydrog. Energy* 2021;46:17597-17607. https://doi.org/10.1016/ j.ijhydene.2021.02.182
36. Li S, Li JZ. Hybridising human judgment, AHP, simulation and a fuzzy expert system for strategy formulation under uncertainty. *Expert Syst. Appl.* 2009;36:5557-5564. https://doi.org/10.1016/j.eswa.2008.06.095
37. Lee S. Determination of priority weights under multiattribute decision-making situations: AHP versus fuzzy AHP. *J. Constr. Eng. Manag.* 2015;141:05014015. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000897
38. Lee Y, Jung J, Song H. Public acceptance of hydrogen buses through policy instrument: Local government perceptions in Changwon city. *Int. J. Hydrog. Energy* 2023;48:13377-13389. https://doi.org/10.1016/j.ijhydene.2022.11.270
39. Khan D, Samadder SR. A simplified multi-criteria evaluation model for landfill site ranking and selection based on AHP and GIS. *J. Environ. Eng. Landsc.* 2015;23:267-278. https://doi.org/10.3846/16486897.2015.1056741
40. Reisi M, Afzali A, Aye L. Applications of analytical hierarchy process (AHP) and analytical network process (ANP) for industrial site selections in Isfahan, Iran. *Environ. Earth Sci.* 2018;77:1-13. https://doi.org/10.1007/s12665-018-7702-1
41. Kharat MG, Raut RD, Kamble SS, Kamble SJ. The application of Delphi and AHP method in environmentally conscious solid waste treatment and disposal technology selection. *Manag. Environ. Qual.* 2016;27:427-440. https://doi.org/10.1108/MEQ-09-2014-0133
42. Xi H, Li Z, Han J, et al. Evaluating the capability of municipal solid waste separation in China based on AHP-EWM and BP

neural network. *Waste Manage.* 2022;139:208-216. https://doi.org/10.1016/j.wasman.2021.12.015
43. Lee Y, Kim YJ, Lee MC. Improving public acceptance of H2 stations: SWOT-AHP analysis of South Korea. *Int. J. Hydrog. Energy* 2021;46:17597-17607. https://doi.org/10.1016/ j.ijhydene.2021.02.182
44. Lee Y, Jung J, Song H. Public acceptance of hydrogen buses through policy instrument: Local government perceptions in Changwon city. *Int. J. Hydrog. Energy* 2023;48:13377-13389. https://doi.org/10.1016/j.ijhydene.2022.11.270
45. Malinauskaite J, Anguilano L, Schmidt Rivera X. Circular waste management of electric vehicle batteries: Legal and technical perspectives from the EU and the UK post Brexit. *Int. J. Thermofluids* 2021;10:100078. https://doi.org/10.1016/j.ijft.2021.100078
46. Hao H, Wenxian X, Fangfang W, Chuanliang W, Zhaoran X. Reward–penalty vs. deposit–refund: Government incentive mechanisms for EV battery recycling. *Energies* 2022;15:6885 https://doi.org/ 10.3390/en15196885