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Article

Exploring public charging infrastructure development strategies with BBWM-mV integrated multi-viewpoint perspective

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Abstract: To achieve the electrification of private vehicles, it is urgent to develop public charging infrastructure. However, choosing the most beneficial type of public charging infrastructure for the development of a country or region remains challenging. The municipal decision's implementation requires considering various perspectives. An important aspect of energy development involves effectively integrating and evaluating public charging infrastructure. While car charging facilities have been thoroughly studied, motorcycle charging facilities have been neglected despite motorcycles being a vital mode of transportation in many countries. The study created a hybrid decision-making model to evaluate electric motorcycle charging infrastructure. Firstly, a framework for evaluating electric motorcycle charging infrastructure was effectively constructed through a literature survey and expert experience. Secondly, decision-makers' opinions were gathered and integrated using Bayesian BWM to reach a group consensus. Thirdly, the performance of the alternative solutions was evaluated by exploring the gaps between them and the aspiration level through modified VIKOR. An empirical analysis was conducted using examples of regions/countries with very high rates of motorcycle ownership worldwide. Finally, comparative and sensitivity analyses were conducted to demonstrate the practicality of the proposed model. The study's findings will aid in addressing municipal issues and achieving low-carbon development objectives in the area.

Keywords: private vehicles; electrification; public charging infrastructure; electric motorcycles; Bayesian BWM; modified VIKOR

1. Introduction

In recent years, governments and industries have realized the importance of clean energy transportation and its impacts and benefits on the world environment (Huang and Ge, 2019). In most countries around the world, urbanization has led to an increase in the demand for commuting and mobility, and these demands have created a great demand for private vehicles, even in cities where mass transit is well-developed (Eccarius and Lu, 2020). Therefore, the electrification of private transport has been globally recognized as one of the most important policy objectives for national/regional governments to implement low-carbon development (Sonar and Kulkarni, 2021).

Risso et al. (2021) pointed out that the key factor in choosing electric vehicles is the mileage of the battery. Ibanez et al. (2019) extensively discussed methods to improve the battery run time of vehicles. Campana and Inga (2023) proposed a model for creating fast-charging station infrastructures based on accessible data from

OpenStreetMap, which can reduce the possible charging peak. Raqabi and Li (2023) developed a framework through scenario analysis that aims to minimize the costs involved in establishing charging networks. But judging from the existing technology, there are still many technologies that need to be overcome. Therefore, some research has focused on how to effectively charge electric vehicles. The convenience and popularity of electric vehicle charging technology and charging infrastructure have become key factors in promoting the electrification of vehicles (Mouli et al., 2017). It affects consumers' willingness to purchase electric vehicles (Huang et al., 2018). It can be seen that the construction of charging infrastructure needs to fully consider the charging habits and preferences of users in order to truly and effectively maximize the efficiency of charging infrastructure (Hardman et al., 2018).

Hardman et al. (2018) examined the charging duration and location configurations of charging infrastructure for various power charging modes and compiled literature about the following five consumer-oriented aspects: the significance of charging infrastructure, accessibility, access cost, grid impact, and management. The three common methods for charging infrastructure technology are the conductive charging method (CCM), inductive charging method (ICM), and battery swapping technique (BST) (Ahmad et al., 2018). One of the most common methods is CCM, which has a less convenient charging infrastructure, risk of accidental electrocution, and poor battery capacity. The low cost of hardware construction for electric vehicles outweighs any inconvenience it may cause during usage (Yogesh and Radhakrishna, 2021). ICM can be classified into static and dynamic charging models, which use electromagnetic induction to charge the battery. This charging technology is suitable for all weather conditions and does not involve direct connections, thus eliminating the risks of electrical arcs or shocks.

However, the health risks associated with radiation pose the biggest challenge to the widespread use of this technology. Charging stations must consider the biosecurity of the surrounding area and the potential for heat generation when foreign objects are exposed (Sandhya and Nisha, 2022). Similar to gas stations, in a BST station a depleted battery can be rapidly and conveniently replaced with a partially or fully charged one within a few minutes. Although fast and convenient, there remain five significant challenges: interchangeability, feasibility, infrastructure, battery degradation, and battery ownership. Each charging technology possesses distinct characteristics and suitability, so the type of infrastructure chosen will affect a country's charging efficiency, which, in turn, influences the utilization rate of electric vehicles and the environment's sustainable development.

Most of the past studies related to charging infrastructure and charging technologies have focused on electric cars, discussing the market trends, charging strategies, and grid integration in recent years (Das et al., 2020). Funke et al. (2019) reviewed the past literature to compare and discuss the demand for charging infrastructure in an international context. Gnann et al. (2018) focused on fast-charging infrastructure for electric cars. In addition, Schroeder and Traber (2012) provided a relevant assessment of fast-charging infrastructure from the perspective of economic efficiency. Previous studies have focused on charging infrastructure at home and workplace (Funke et al., 2019; Hardman et al., 2018), while the discussion on public charging infrastructure was rather limited. The discussed transportation modes are mainly cars. However, the motorcycle is another most common private means of transportation worldwide, and it is still the most numerous private vehicle in many countries, especially in Southeast Asian countries or other tropical and subtropical regions (Eccarius and Lu, 2020). There is a research gap regarding what charging infrastructure should be used for the promotion of electric motorcycles. Therefore, the objective of this study is to evaluate the public charging infrastructure for electric motorcycles, which can be used in a more effective way to promote the electrification of vehicles to reduce pollution and achieve the goal of sustainability. The charging devices for electric cars and electric motorcycles differ significantly. Besides the difference in power requirements and charging time, the most substantial difference is the space needed. An electric car requires at least one parking space, while an electric motorcycle may only need a small corner. Additionally, for charging methods, motorcycles can opt for quick battery swapping, which is mostly not feasible for electric cars currently.

However, the establishment of public charging infrastructure for electric motorcycles is an important energy policy issue for local governments, which will affect a country's overall energy planning. The construction and planning of these facilities have a strong connection with residents. Cong et al. (2021) pointed out that the "Not In My Back Yard" perspective is one of the keys to the failure of charging station site selection. For the planning of such policies, how to fully consider different voices and opinions to make final decisions will affect the construction of public charging infrastructure. In addition to fully considering the opinions of different stakeholders, the selection decision of this infrastructure must also consider factors such as technological development, resource investment, regulatory standards, and economic benefits. Therefore, the construction of charging infrastructure is a complex multi-criteria decision-making evaluation issue. Sadrani et al. (2023) used multi-criteria decision-making fuzzy BWM to discuss the charging strategy selection of electric buses. This model can effectively reduce the number of pairwise comparisons in the decision-making process and obtain better consistency. Similar models use arithmetic mean or geometric mean to integrate the suggestions of multiple decision-makers, but that can easily cause the loss of information (Deveci et al., 2023). Mohammadi and Reza (2020) introduced Bayesian BWM, a novel model based on BWM that incorporates the notion of probability and accounts for the influence of each decision-maker, ultimately achieving decision-maker consensus. This methodology is appropriate for accommodating input from multiple stakeholders. Thus, the present study, Bayesian BWM, synthesizes the viewpoints of various decision-makers and addresses the evaluation system's significance.

Dong and Yang (2021) used VIKOR to select from three alternative public charging infrastructures. This model uses the distance from the ideal solution to conduct a gap analysis. The selection of the solution is based on the final utility obtained by the two distance concepts. This method is better than other compromise ranking solutions. However, this method can easily lead to the problem of "selecting the less rotten apples from rotten apples" due to insufficient alternatives, but it is not conducive to improving the fundamental problem. Huang et al. (2021) used the modified VIKOR to improve the quality of the national health system. The modified VIKOR method is different from the traditional VIKOR method. In addition to ranking the alternatives, it can also find the aspiration level, allowing decision-makers to find the goals and directions for continuous improvement. Due to the change in the target baseline, it fully implements the management philosophy of "keeping on getting better" and optimizes the decision-making model originally applied to selection. Therefore, this study uses modified VIKOR for charging infrastructure selection and target improvement.

Summarizing the above, the objectives of this study include developing a multi-attribute hybrid decision-making model, proposing a new evaluation framework from five perspectives of policy, society, economy, technology, and environment, exploring national strategies for the development of public charging infrastructures for electric motorcycles, and evaluating three types of public charging infrastructures. Although there have been many discussions on charging infrastructure in the past, most of the studies focus on the issues of hardware equipment, technical barriers, and future trends, and few studies focus on the selection of energy charging modes, especially for electric motorcycles. Therefore, the main contributions of this study are as follows:

1) Based on the unique features of electric motorcycles, this research builds an evaluation framework appropriate for selecting energy charging modes for electric motorcycles. Such a framework would enhance the accessibility of charging infrastructure and offer recommendations for the electrification of vehicles.
2) Given that the government, manufacturers of electric motorcycles, and consumers likely hold dissimilar views regarding the energy charging modes, Bayesian BWM proves successful in integrating the divergent opinions of decision-makers and rectifying the inadequacies of standard averaging techniques.
3) The weights obtained in this study provide objective evaluation criteria that can effectively aid government departments in prioritizing resource allocation.
4) This study utilizes multi-criteria decision analysis to objectively examine the advantages and disadvantages of the three major energy charging modes available on the market, and determine the optimal investment option.

The rest of the paper is organized as follows: Section 2 presents a review of the literature; Section 3 describes the research methodology: BWM and VIKOR; Section 4 describes the empirical process of evaluating the energy charging model for electric motorcycles/scooters and conducts a sensitivity analysis to test the stability of the research methodology proposed in this study; and finally, the conclusions are presented in Section 6.

2. Literature review

Narrow streets and relatively high population densities are features that characterize cities in many Asian countries, making motorcycles or scooters the most convenient way to move around. They are an essential means of transportation in Asia (Guerra, 2019). In addition to their greater mobility compared to other modes of transportation, scooters are lighter and more efficient in terms of the space needed (Yeung et al., 2015). The relatively low costs of acquisition and maintenance also make them affordable for almost every household. Despite these advantages, heavy reliance on scooters also has some disadvantages, especially environmental pollution. Greenstone et al. (2015) showed that airborne particulate emissions from transportation can seriously affect the health of the population, and the impact of motorcycles on environmental problems in Asia is significant due to the large number of such vehicles and their relatively high emission rates (Jones et al., 2013). The advantages of EMs over conventional fuel vehicles are reduced emissions, less urban noise pollution, and reduced fuel consumption (Agency, 2009). With the increased urgency of environmental sustainability and the growing popularity of EM technology, many countries have incorporated the development and promotion of EMs into their policies. For example, at least 10 postal agencies word-wide have switched from gasoline powered to electric powered delivery vehicles, and they have plans to expand to other regions and cities (Kim et al., 2021). Paris has actively developed EM sharing rental services to solve the problems of heavy traffic and difficult parking in large cities (Christoforou et al., 2021). Electric motorbikes can also improve the environmental protection-related performance of the transportation sector (Trappey et al., 2012).

The benefits and advantages of EMs are clear, but one of the most important questions in marketing practices is how to change consumer perceptions and encourage consumers to switch to electric vehicles. Most of the previous studies on EMs have thus focused on consumer acceptance and on the incentives and subsidies that should be provided by the government. For example, Chiu and Tzeng (1999) conducted an interview survey and used a stated preference modeling approach to investigate the acceptance and potential market for EMs in Taiwan; Chiou et al. (2009) used fuel prices as an indicator of consumer acceptance; Zhu et al. (2019) applied the conditional valuation method to investigate the willingness of consumers to buy EMs in Macau. In addition to consumer acceptance, Huang et al. (2018) explored the impact of government incentives, vehicle emission standards, fuel prices, and battery costs on consumers' purchase of EMs through a quantitative model.

In terms of practical use, the biggest difference between electric and conventional fuel-powered motorbikes lies in the method of powering them. There are three main types of energy charging models currently in use: CCM, BST, and HCB. The convenience of charging is one of the core elements of the development of electric powered scooters and for promoting the development of the EM industry (Zhu et al., 2019). The lack of convenient and efficient charging infrastructure will significantly reduce the incentive for consumers to purchase EMs because of their limited riding range (Kannan et al., 2021; Ribeiro et al., 2019). One of the most important decisions when planning and constructing EM charging stations is finding the optimal locations which greatly affects the quality of service and operational efficiency (Liu et al., 2018). Therefore, many studies have been conducted to investigate the optimal locations of charging stations (Luo et al., 2021). For example, Akbari et al. (2018) used a genetic algorithm (GA) method to calculate the optimal number locations of charging stations necessary. Kabli et al. (2020) proposed a two-stage stochastic programming model to investigate where to expand the power grid and charging stations to provide enough energy for electric vehicle (EV) charging stations. Aqidawati et al. (2021) extended the models of Mehar and Senouci (Mehar and Senouci, 2013), Chen and Hua (2014) to construct a network of EM charging stations in Surakarta, Indonesia.

The battery swapping technique is one of the most time-efficient and easy to use charging methods for EMs (Ahmad et al., 2018). In this method, the depleted motorcycle battery is simply swapped with a new one at a public battery charging station. The main advantage of this type of battery charging stations is that they allow more flexibility in the distribution of electrical energy. Charging can occur during off-peak hours, while during peak hours, excess electricity can be exported to other places it is needed, making for the most appropriate distribution and utilization of electricity given the charging capacity within an area (Rao et al., 2015). However, the most obvious drawback of using the battery swapping technology is the need to overcome the technical problems associated with batteries. For example, battery durability may affect the driving range, leading, for example, to a reduction in range if the replacement battery is an older one. The different battery designs of different brands of EM can also cause problems in the marketing of electric vehicles (Allegre et al., 2009). Amiri et al. (2018) constructed a method that could take into account the number of batteries that are not fully charged in a battery swapping station, the power loss during charging, and the release of battery capacity to find the ideal locations for battery swapping stations. They solved this problem using the NSGA II algorithm. Sun et al. (2019) used a periodic fluid model to find the optimal battery purchase quantity and operation strategy for battery swapping stations while considering the charging cost and battery demand over time. Huang et al. (2021) used descriptive statistics and ANOVA analysis to examine consumer acceptance of battery swapping stations for EMs in Taiwan. Their results showed that aesthetic and hedonic properties had a positive influence on consumer acceptance.

The term plug-in hybrid electric vehicle (PHEV) actually refers to vehicles that use a combination of both electric and fuel energy sources, and they have evolved with the development of EM technology. In addition to the aforementioned CCM and BST energy charging models, some electric motorbike manufacturers have combined the two technologies to provide two energy charging systems at the same time. This approach gives consumers more flexibility in terms of energy charging. By combining the two systems, the convenience of CCM and the stability of BST energy charging can be combined to complement each other's shortcomings and advantages (Allegre et al., 2009). For example, Goussian et al. (2019) presented an EM power supply system based on passive parallel topology with a hybrid combination of lithium manganese nickel 18650-type cells and lithium-ion capacitors.

Previous studies on electric cars or scooters have mostly focused on the technological improvements related to batteries (Goussian et al., 2019) or determining the locations of charging stations (Aqidawati et al., 2021; Feng et al., 2021). In the case of EMs, most past research has been on consumer acceptance. There has been no discussion of whether it is better to adopt a charging, swapping, or hybrid energy charging mode. The promotion and popularity of EMs require significant government support to facilitate technological advances and lower purchase costs, which are key factors in the success of EM promotion. This study aims to examine the selection of energy charging models for electric motorbikes based on various criteria and integrating stakeholders' opinions, to provide a more comprehensive analysis and recommendations.

3. Methodology

In the implementation of any decision or policy, there are often many different opinions from the various decision-making bodies and stakeholders that must be considered. The conventional BWM approach uses averaging to integrate the opinions of different experts, which can result in information loss and may not provide a full representation of the experts' opinions (Lo et al., 2019). Bayesian BWM improves these drawbacks, fully capturing the opinions of the expert group by using the concept of probability to obtain the optimal combination of weights (Mohammadi and Rezaei, 2020). In addition, the conventional compromise ranking solution VIKOR, which uses positive and negative ideal solutions as the basis for making selections, is prone to decision situations that are limited to local optimal alternatives (Huang et al., 2021). This study uses a revised version of the original VIKOR model to more reflect real-world problems.

3.1. Research process

The research process of this study can be divided into three phases (see **Figure 1**), as follows.

Phase 1: Exploring and constructing an evaluation framework

A literature search of relevant works was conducted to find the relative keywords. A list of the indicators related to the energy charging models of the energy charging facilities was compiled, and a preliminary research framework formed. Based on this framework, an expert meeting was held with representatives from industry, government, and academia involved in the EM industry. The expert representatives confirmed the reasonableness and appropriateness of the index framework, and after two roundtable meetings, the evaluation framework was finally constructed.

Phase 2: Expert interview/performance survey/model building

The BWM expert questionnaire and the revised VIKOR performance questionnaire were designed based on the evaluation framework, and a third expert meeting was held to explain the meaning of the indicator framework, how to fill out the questionnaire, and discuss the questions. Each expert was given more than two hours to fill out the questionnaire, and the collected questionnaires were sorted and coded.

Phase 3: Evaluation/selection/improvement

Three main outputs can be obtained from the application of the BBWM-mV model, as shown in **Figure 1**. First, the optimal group weights, which indicate the final weighting of the group, taking into account all expert opinions in making the decisions. Second, the prioritization of alternatives, based on a comparison with the aspiration level. Finally, specific directions for improvement of the selected alternatives can be proposed. Based on the importance of the indicators (Weights) and the performance of the indicators (Gaps), this study explores the specific indicators that should be prioritized for improvement.

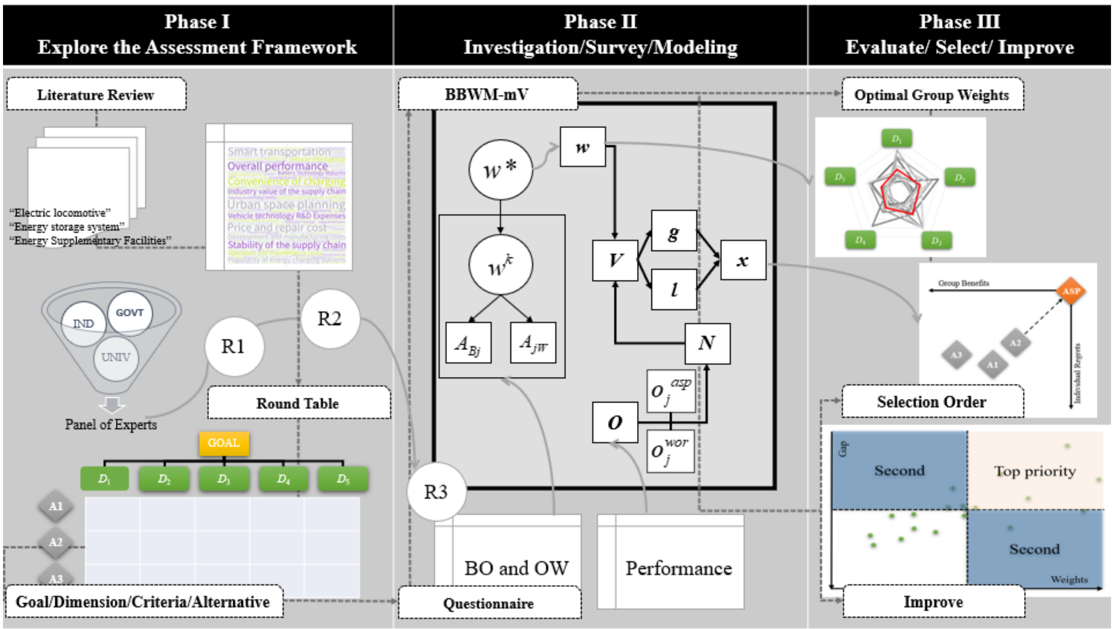

Figure 1. Flow chart of the study process.

3.2. Calculation steps of BBWM

The classical BWM method is effective in reducing the number of pairwise comparisons required and obtaining higher consistency. However, it is not applicable in situations where multiple decision-makers are involved in the decision-making process. Although previous researchers have used arithmetic or geometric averaging to integrate the evaluation results of multiple decision-makers, these methods result in loss of information (Mohammadi and Rezaei, 2020; Rezaei, 2015, 2016). To effectively consider the evaluation results of multiple decision-makers, Mohammadi and Rezaei (Mohammadi and Rezaei, 2020) proposed the Bayesian BWM method which could be applied to integrate the evaluation results of multiple decision-makers in a group decision-making approach in a probability context. The steps for implementing Bayesian BWM are described below (Mohammadi and Rezaei, 2020).

Step 1: Identify the best and worst criteria.

The criteria to be evaluated in the study are identified and the best criterion C_B and the worst criterion C_w are determined.

Step 2: Compare the best criterion with other criteria.

The evaluation scale ranges from 1 to 9 (the higher the number on the scale the higher the relative importance). 1 means that both criteria are equally important and 9 means extremely important. At this stage, we can obtain the Best-to-Others vector (C_{Bj}).

$$C_{Bj} = (c_{B1}, c_{B2}, \dots, c_{Bn}) \tag{1}$$

where C_{Bj} denotes the importance of the best criterion B to criterion j. The comparison value between the best criterion and itself must be 1, i.e., $c_{BB} = 1$.

Step 3: Compare other criteria with the worst criterion.

In this stage, we can obtain the Others-to-Worst vector (C_{jW}).

$$C_{jW} = (c_{1W}, c_{2W}, \dots, c_{nW})^T \tag{2}$$

where C_{jw} denotes the importance of criterion j in comparison to the worst criterion

W. The comparison value between the worst criterion and itself must be 1, i.e., $c_{WW} = 1$.

Step 4: Calculate the optimal group weights of the criteria.

In Bayesian BWM, the process is the same as described in Rezaei (2015), but it treats the weights of the criteria as a probability distribution. The experts' opinions are integrated with the perspective of probability. Using the following probability model, we can find the integrated weight $w* = (w_1^*, w_2^*, \ldots, w_n^*)$ and the individual weight for each decision-maker w^k, $k = 1, \ldots, K$.

$$(C_B^k|w^k) \sim multinomial\left(\frac{1}{w}\right), \forall k = 1, \ldots, K \tag{3}$$

$$(C_W^k|w^k) \sim multinomial\big(w^k\big), \forall k = 1, \ldots, K \tag{4}$$

$$(w^k|w*) \sim Dir(\gamma x w*), \forall k = 1, \ldots, K \tag{5}$$

where multinomial refers to the multinomial distribution, Dir refers to the Dirichlet distribution and $gamma(0.1,\ 0.1)$ refers to the Gamma distribution with shape parameters of 0.1.

3.3. Calculation steps of the modified VIKOR

VIKOR is a well-known MCDM method (Mardani et al., 2016). Although the conventional VIKOR has advantages for the evaluation of alternatives, it may fall into the trap of local optimal alternatives (Huang et al., 2020). The modified VIKOR can effectively alleviate this problem. It can not only rank the existing alternatives, but also provide directions for improvement according to the gap between each alternative and the aspiration level. Therefore, this study adopts the modified VIKOR method which is implemented as follows.

Step 1: Establish an evaluation decision matrix.

By conducting surveys through expert interviews, we obtain a performance evaluation of the three alternatives according to each expert and find the average to obtain the overall performance evaluation matrix *O*. The *o*, *i*, *j*, represents the performance of alternative ai respect to criterion cj as in Equation (6).

$$O = \left[o_{ij}\right]_{b\times n} = \begin{array}{c} Criterion \\ a_1 \\ \vdots \\ a_i \\ \vdots \\ a_b \end{array} \begin{array}{c} \begin{array}{ccccc} c_1 & \cdots & c_j & \cdots & c_n \end{array} \\ \begin{bmatrix} o_{11} & \cdots & o_{1j} & \cdots & o_{1q} \\ \vdots & & \vdots & & \vdots \\ o_{i1} & \cdots & o_{ij} & \cdots & o_{iq} \\ \vdots & & \vdots & & \vdots \\ o_{b1} & \cdots & o_{bj} & \cdots & o_{bn} \end{bmatrix}_{b\times n} \end{array} \tag{6}$$

Step 2: Define the target benchmarks.

The definition of target benchmarks includes the positive ideal point, negative ideal point, aspiration level, and tolerable level. The definition of ideal points is based on actual data collected from the survey (maximum and minimum values for each dimension), as shown in Equation (7). However, the aspiration level and tolerable level are defined according to the decision-makers' aspirations.

$$\begin{gathered} o_{ij}^{+} = \underset{i}{max}\big\{o_{ij}\big|i = 1,2,\cdots,b\big\}, j = 1,2,\cdots,q, \\ o_{ij}^{-} = \underset{i}{min}\big\{o_{ij}\big|i = 1,2,\cdots,b\big\}, j = 1,2,\cdots,q. \end{gathered} \tag{7}$$

Step 3: Obtain the normalized evaluation matrix (***N***).

Equations (8) and (9) are used for normalization to obtain the normalized matrix *N*.

$$N = [n_{ij}]_{b\times q} = \begin{array}{c} \\ a_1 \\ \vdots \\ a_i \\ \vdots \\ a_b \end{array} \begin{array}{c} \begin{array}{ccccc} d_1 & \cdots & d_j & \cdots & d_q \end{array} \\ \begin{bmatrix} n_{11} & \cdots & n_{1j} & \cdots & n_{1q} \\ \vdots & & \vdots & & \vdots \\ n_{i1} & \cdots & n_{ij} & \cdots & n_{iq} \\ \vdots & & \vdots & & \vdots \\ n_{b1} & \cdots & n_{bj} & \cdots & n_{bq} \end{bmatrix}_{b\times q} \end{array} \tag{8}$$

$$n_{ij} = (\left|o_{ij}^{asp} - o_{ij}\right|)/(\left|o_{ij}^{asp} - o_{ij}^{wor}\right|) \tag{9}$$

Step 4: Obtain the weighted normalization evaluation matrix (V).

Using the optimal group weights obtained through BBWM, the weighted normalization evaluation matrix obtained in the previous step is weighted to obtain the weighted normalization evaluation matrix.

$$V = [v_{ij}]_{b\times q} = \begin{array}{c} \\ a_1 \\ \vdots \\ a_i \\ \vdots \\ a_b \end{array} \begin{array}{c} \begin{array}{ccccc} d_1 & \cdots & d_j & \cdots & d_q \end{array} \\ \begin{bmatrix} v_{11} & \cdots & v_{1j} & \cdots & v_{1q} \\ \vdots & & \vdots & & \vdots \\ v_{i1} & \cdots & v_{ij} & \cdots & v_{iq} \\ \vdots & & \vdots & & \vdots \\ v_{b1} & \cdots & v_{bj} & \cdots & v_{bq} \end{bmatrix}_{b\times q} \end{array} = N \times w_j = n_{ij} \times w_j \tag{10}$$

Step 5: Calculate group benefits and individual regrets.

The group benefits and individual regrets are obtained from the following two equations.

$$g = [g_i]_{b\times 1} = \sum_{j=1}^{n} w_j \times n_{ij} = \sum_{j=1}^{n} w_j \left(\frac{\left|o_{ij}^{*} - o_{ij}\right|}{\left|o_{ij}^{*} - o_{\tilde{ij}}\right|}\right) \tag{11}$$

$$l = [l_i]_{b\times 1} = \max_j [v_{ij}] = \max_j \left(w_j \left(\frac{\left|o_{ij}^{asp} - o_{ij}\right|}{\left|o_{ij}^{asp} - o_{ij}^{wor}\right|}\right) | j = 1,\ 2,\ \ldots,\ q\right) \tag{12}$$

Step 6: Calculate the evaluation value of comprehensive benefits.

The two distances are strategically blended, and the strategy coefficient θ is preset to 0.5.

$$x = [x_i]_{b\times 1} = \theta \times \frac{|g_i - g^{asp}|}{|g^{asp} - g^{wor}|} + (1 - \theta) \times \frac{|l_i - l^{asp}|}{|l^{asp} - l^{wor}|} \tag{13}$$

4. Empirical example

In this section, we first describe the empirical problem. Second, an evaluation framework for EMs is constructed. Third, the proposed model is applied to conduct a case study. Finally, a comparative analysis and sensitivity analysis are conducted.

4.1. Problem description

Taiwan is an island nation with a population of about 23 million people. The land transportation network of the island includes railroads, high-speed rail, and mass rapid transit systems. However, except for the city of Taipei, most of the transportation still relies on private carriers. According to the Ministry of Transportation and Communications (2022) on 2022 in Taiwan, the percentage of car ownership per 100 people is over 36%, but the number of scooters is over 97%. This illustrates the popularity of private transportation, especially scooters. In recent years, countries around the world have been advocating the electrification of transportation for the sake of sustainable environmental development and to alleviate climate change. According to Taiwan's Pathway to Net-Zero Emissions in 2050 statement of purpose by the National Development Council, the goal is to have 100% of all new scooters sold to be electric by 2040. For Taiwan, the electrification of scooters is a matter of great urgency.

The high initial costs and accessibility of charging infrastructure are key barriers to the sale of electric motorbikes (Barisa et al., 2016). After reviewing Taiwan's current policies, local governments have set up a subsidy mechanism to reduce the purchase barriers. Another important issue is deciding upon which energy supply system should be used for charging electric motorbikes, which will be a challenge for the government authorities. In Taiwan, the EM industry has different inputs and plans for energy charging models, each required different charging infrastructure, different software and hardware construction costs and different space requirements. Therefore, local governments must evaluate the development strategies and the charging infrastructure, to determine the best direction to take to model and construct a infrastructure for charging EMs, in order to truly and effectively improve the convenience of the charging infrastructure.

4.2. Building the evaluating framework

In this study, experts in the relevant fields were invited to form an expert team, which included researchers from R&D institutions, representatives from enterprises, representatives from relevant government ministries, representatives from research centers, etc. All of the participants had at least 5 years of work experience in the field and were over 30 years old. Details about their background are shown in **Table 1**. It can be seen that the members of the expert team were representative of different sectors and had different among of experience and educational backgrounds. According to the studies by Rezaei et al. (2018) and Quayson et al. (2023), having 4–10 experts who are highly familiar with the subject matter is sufficient. For this study, we invited 11 experts who are government officials, researchers, and industry representatives in Taiwan responsible for the long-term promotion of electric motorcycle policies. Their involvement ensures representativeness and accurately reflects the current direction of electric scooter promotion. Additionally, regarding consumer perspectives, this study includes two government officials, three researchers, and one industry representative among the experts. They have been involved in long-term government-commissioned projects promoting electric motorcycle and have conducted extensive consumer opinion surveys over the years. Therefore, their opinions are well-qualified to represent consumer viewpoints.

Table 1. Background of the experts.

NO.	Sector	Job title	Gender	Education	Age	Experience
1	University	Professor	male	Ph.D.	60	10
2	Industry	General manager	male	Masters	41–50	5
3	University	Professor	male	Ph.D.	60	10
4	University	Professor	female	Ph.D.	41–50	5
5	University	Professor	male	Ph.D.	51–60	10

Table 1. (*Continued*).

NO.	Sector	Job title	Gender	Education	Age	Experience
6	Government	Senior Technical Specialist	male	Masters	51–60	10
7	University	Professor	male	Ph.D.	31–40	10
8	Industry	General manager	male	Masters	41–50	5
9	Government	Senior Technical Specialist	male	Ph.D.	60	10
10	Government	Senior Technical Specialist	male	Ph.D.	41–50	5–10
11	Government	Technical Specialist	male	Ph.D.	31–40	5

First, a prototype of the evaluation framework was compiled based on a review of the relevant literature. After two rounds of the Delphi method, experts removed some inappropriate criteria leaving 18 evaluation indicators divided into five dimensions: Policy, Society, Economics, Environment, and Technology, as shown in **Table 2**, where C21, C33, C34, C35, and C32 are cost-based criteria, while the others are benefit-based criteria.

Table 2. Description of dimensions and criteria.

Code	Dimension / Criterion	Description
D_1	Policy perspective	
C_{11}	Urban space planning	Space utilization of energy charging facilities (number of energy charging stations, land for energy charging stations), and feasibility of shared scooters.
C_{12}	Smart transportation	Feasibility of collecting big data about riding, and feasibility of introducing V2V and vehicle networking.
C_{13}	Popularity of energy charging stations	The number of energy charging stations installed by the government and future expansion (including land lease fees, software, hardware equipment, and construction costs).
D_2	Social perspective	
C_{21}	Price and repair cost	EM purchase price, repair and maintenance costs, energy charging costs, and battery depreciation costs.
C_{22}	Overall performance	Maximum speed, cruising range, and auxiliary functions (automatic parking, electric reversing, etc.) of electric motorbikes.
C_{23}	Convenience of charging	The density of energy charging stations.
D_3	Economics perspective	
C_{31}	Stability of the supply chain	Product mass production cycle, logistics integrity, parts quality, supplier delivery capability.
C_{32}	Industry value of the supply chain	The economic value created by the supply chain.
C_{33}	Research and development (R&D) expenses of the vehicle technology	Cost of EM technology research, design, etc.
C_{34}	Development and manufacturing costs of the battery	Battery cell development costs, and battery module development costs.
C_{35}	Operating and maintenance costs of the energy charging facilities	Daily operational and maintenance costs of energy charging stations.
D_4	Technology perspective	
C_{41}	The degree of intelligent functions of the vehicle	EM intelligence function.
C_{42}	Maturity of battery development technology	Battery cell (pack) performance, safety, reliability, and development time required to increase battery capacity technology.

Table 2. (*Continued*).

Code	Dimension / Criterion	Description
C_{43}	Development of the smart grid system technology	Feasibility of combining energy charging stations to form a smart grid system and EM vehicle to grid (V2G) technology.
C_{44}	Development time of energy charging technology	Shortening the battery charging time (e.g., rapid charging technology), and recharging while the vehicle is in motion (wireless charging, conversion of mechanical energy to electrical energy, etc.).
D_5	Environmental perspective	
C_{51}	Energy sustainability	Impact on peak electricity consumption (with a mechanism to induce and control the consumers' peak charging of energy), the introduction of renewable energy (feasibility of combining energy charging facilities with renewable energy sources).
C_{52}	Impact of materials on the environment	Impact of EM manufacturing on environmental pollution manufacturing.
C_{53}	Potential environmental benefits	Reduction of manufacturing materials, recycling of motorcycle materials, the proportion of recycled materials used, reduction of carbon footprint.

4.3. Application of Bayesian BWM analysis

After constructing the evaluation framework based on the professional opinions of representatives from industry, government, and academia, the Bayesian BWM method was used to integrate the opinions of experts from different backgrounds to determine the weight of each dimension and criterion, to avoid information loss. It can effectively integrate experts' opinion deviations and inconsistencies to obtain the best results through probability distribution.

The importance of the dimensions and criteria are determined through pairwise comparisons. First, the definitions of the evaluation dimensions were explained to the team of expert participants. Second, the method and process for completing the questionnaire were explained. The experts first selected the best evaluation dimensions and then compared them with other dimensions to generate best to other (BO) vectors. They then selected the worst dimension and compared this to the other dimensions to generate the other to worst (OW) vector; the BO and OW results are shown in **Table 3**. The left side of the table is the BO vector for each expert, and the right side is the OW vector. Taking Expert 1 as an example, he considers D1 to be the most important dimension, then D1:D2 = 3:1. Expert 1 considers the least important dimension to be D3, so D1:D3 = 6:1. The weights between dimensions can be obtained from the survey data in **Table 3** using the Bayesian BWM calculation described in Section 3.2. Similarly, the best and worst criteria were selected from among the criteria under each dimension, and then pairwise comparisons and calculations were performed to generate the weights for the criteria.

Table 3. Experts' BO vectors and OW vectors (dimension).

	Best to Other					**Other to Worst**				
Code	D_1	D_2	D_3	D_4	D_5	D_1	D_2	D_3	D_4	D_5
EX1	1	3	6	4	2	6	3	1	2	5
EX2	9	1	3	7	5	1	9	4	2	2
EX3	5	7	3	1	9	2	2	4	9	1
EX4	4	4	3	2	1	2	1	2	3	4
EX5	5	3	1	9	7	2	4	9	1	2

Table 3. (*Continued*).

	Best to Other					**Other to Worst**				
Code	D_1	D_2	D_3	D_4	D_5	D_1	D_2	D_3	D_4	D_5
EX6	5	8	1	3	6	2	1	8	3	2
EX7	1	1	3	9	9	9	9	4	1	1
EX8	1	3	7	5	9	9	4	2	3	1
EX9	3	5	2	4	1	3	1	4	2	5
EX10	2	1	4	3	5	4	5	2	3	1
EX11	7	3	1	5	9	2	4	9	2	1

The analysis results of the optimal group weights obtained after the integration of the weights of the dimensions and the criteria are shown in **Table 4**. The results of the analysis of the dimensions show that $D_3 \succ D_2 \succ D_1 \succ D_4 \succ D_5$, and the weights are 0.25, 0.22, 0.21, 0.17, and 0.15 respectively. The most important criteria under each dimension are C13, C21, C35, C42, and C51, respectively. The global weights of the whole evaluation system can be estimated based on the local weights of the dimensions and the local weights of each evaluation.

Table 4. Evaluation system of local and global weights.

Code	**Dimension/Criteria**	**Local Weight**	**Global Weight**
D_1	Policy	0.21	
C_{11}	Urban space planning	0.37	0.08
C_{12}	Smart transportation	0.25	0.05
C_{13}	Popularity of energy charging stations	0.39	0.08
D_2	Society	0.22	
C_{21}	Price and repair cost	0.39	0.09
C_{22}	Overall performance	0.32	0.07
C_{23}	Convenience of charging	0.30	0.07
D_3	Economics	0.25	
C_{31}	Stability of the supply chain	0.21	0.05
C_{32}	Industry value of the supply chain	0.16	0.04
C_{33}	Vehicle technology R&D Expenses	0.17	0.04
C_{34}	Development and manufacturing costs	0.22	0.06
C_{35}	Operation and maintenance costs	0.23	0.06
D_4	Technology	0.17	
C_{41}	Vehicle intelligence	0.20	0.04
C_{42}	Battery Technology Maturity	0.32	0.06
C_{43}	Smart grid system technology development	0.20	0.03
C_{44}	Energy charging technology development time	0.28	0.05
D_5	Environment	0.15	
C_{51}	Energy sustainability	0.42	0.06
C_{52}	Environmental impact of materials	0.29	0.04
C_{53}	Potential environmental benefits	0.29	0.04

4.4. Evaluation of existing EM energy charging types

After completing the evaluation framework and calculating the weights of the dimensions and criteria, in-depth interviews were conducted with the experts, who, based on their professional judgment, evaluated the overall performance of the conductive charging method (CCM), battery swapping technique (BST), and hybrid CCM and BST methods (HCB) across the 18 criteria.

Evaluations were made on a scale of 1 to 10, with higher scores indicating that the alternative was superior in that criterion. Aspirational and tolerable levels were defined based on the maximum and minimum values of the scale. However, since the five evaluation criteria of C21, C33, C34, C35, and C32 are cost-based, the meaning of the scores will be the opposite of the target setting. The comprehensive evaluation results of the three alternatives are shown in **Table 5**.

Table 5. Comprehensive evaluation of 3 energy charging models.

Criteria	C_{11}	C_{12}	C_{13}	C_{21}	C_{22}	C_{23}	C_{31}	C_{32}	C_{33}	C_{34}	C_{35}	C_{41}	C_{42}	C_{43}	C_{44}	C_{51}	C_{52}	C_{53}
Type	**B**	**B**	**B**	**C**	**B**	**B**	**B**	**B**	**C**	**C**	**C**	**B**	**B**	**B**	**B**	**B**	**C**	**B**
A_1 (CCM)	4.73	4.18	5.73	2.64	6.00	4.64	6.27	5.82	3.55	3.27	3.00	4.64	6.64	5.09	3.46	4.73	4.27	4.27
A_2 (BST)	5.27	5.82	7.46	4.36	6.55	7.46	5.00	5.00	4.36	4.55	4.73	6.46	6.00	5.73	4.18	5.27	4.73	5.46
A_3 (HCB)	5.00	5.36	6.00	4.36	6.55	6.55	5.55	5.73	4.82	4.91	5.00	5.91	5.09	5.36	5.00	5.09	5.09	5.55

The results obtained from **Table 4** were integrated to obtain the weighted normalized comprehensive evaluation matrix shown in **Table 6**. The worst performance of the weighted alternative A1 is for Urban space planning (C11 = 0.047), and the best performance is for Vehicle technology R&D expenses (C33 = 0.012). The other two alternatives are evaluated in the same way. According to the results of the modified VIKOR's analysis, the overall effectiveness is $A_2 \succ A_1 \succ A_3$, which would mean that Battery swapping technique (0.23) is the best choice for an energy charging model in Taiwan, followed by the Conductive charging method (0.24), and lastly, the Hybrid CCM and BST method (0.25).

Table 6. Analytical results of modified VIKOR.

	C_{11}	C_{12}	C_{13}	C_{21}	C_{22}	C_{23}	C_{31}	C_{32}	C_{33}	C_{34}	C_{35}	C_{41}	C_{42}	C_{43}	C_{44}	C_{51}	C_{52}	C_{53}	S_i	Q_i	R_i	**Rank**
A_1	0.05	0.03	0.04	0.02	0.03	0.04	0.02	0.02	0.01	0.01	0.01	0.02	0.02	0.02	0.01	0.04	0.02	0.03	0.44	0.05	0.24	2
A_2	0.04	0.02	0.02	0.03	0.03	0.02	0.03	0.02	0.02	0.02	0.02	0.01	0.02	0.02	0.02	0.03	0.02	0.02	0.42	0.04	0.23	1
A_3	0.04	0.03	0.04	0.03	0.03	0.03	0.03	0.02	0.02	0.02	0.03	0.02	0.03	0.02	0.02	0.03	0.02	0.02	0.46	0.04	0.25	3

4.5. Comparative and sensitivity analysis

To demonstrate the reliability of the results of this study, the results of the proposed model (mVIKOR) were compared with other decision models (BBWM-mWASPAS, COPRAS, TOPSIS, and PROMETHEE), as shown in **Table 7**.

Based on the utility value, a comprehensive evaluation of the alternatives can be obtained for all decision models. Since BBWM-mVIKOR evaluates the difference between the alternative and the aspiration level, the smaller the evaluation value, the better, and the larger the evaluation value for the other models, the better. The results of comparative analysis of the models are consistent across the proposed decision models ($A_2 \succ A_1 \succ A_3$). It can be seen that although each decision model has different theoretical concepts, the decision results in this empirical case are consistent and the Battery swapping technique as the best alternative, which shows our results to be reliable.

Table 7. Results of BBWM-mVIKOR model and four other models for comparison.

	A₁		**A₂**		**A₃**	
	Utility Value	**Rank**	**Utility Value**	**Rank**	**Utility Value**	**Rank**
mVIKOR	0.24	2	0.23	1	0.25	3
WASPAS	0.45	2	0.46	1	0.43	3
COPRAS	0.43	2	0.44	1	0.41	3
TOPSIS	0.00	2	0.01	1	-0.01	3
PROMETHEE	0.14	2	0.21	1	0.01	3

To examine how vital the weighting is to the decision making and evaluation process, we conducted a sensitivity analysis. The results obtained with the Bayesian BWM model showed that D3 (0.246) was the most important dimension in the whole evaluation system. Therefore, in this study, the weights of D3 were adjusted for 9 runs (0.1 to 0.9), and the remaining weights were assigned to other dimensions according to the original proportions (D1 = 0.279, D2 = 0.290, D4 = 0.230, D5 = 0.200), and the sum of the five dimensions of the nine sensitivity analyses must still be 1, as shown in **Table 8**.

Table 8. The weights of the dimensions under the sensitivity analysis.

	D_1	D_2	D_3	D_4	D_5	**SUM**
W^{agg}	0.21	0.22	0.25	0.17	0.15	1.00
Run 1	0.25	0.26	0.10	0.21	0.18	1.00
Run 2	0.22	0.23	0.20	0.18	0.16	1.00
Run 3	0.20	0.20	0.30	0.16	0.14	1.00
Run 4	0.17	0.17	0.40	0.14	0.12	1.00
Run 5	0.14	0.15	0.50	0.12	0.10	1.00
Run 6	0.11	0.12	0.60	0.09	0.08	1.00
Run 7	0.08	0.09	0.70	0.07	0.06	1.00
Run 8	0.06	0.06	0.80	0.05	0.04	1.00
Run 9	0.03	0.03	0.90	0.02	0.02	1.00

Based on the results of the weight assignment, nine calculation and analysis runs were performed, as shown in **Figure 2**. When the weight of D3 was adjusted from 0.1 to 0.3, there was no change in any of the ranking results. However, if the weight of D3 was adjusted to 0.4, the ranking of the first and second places reversed, while the third-place ranking remained unchanged. This shows that weighting affects the decision outcome. However, the Bayesian BWM model was applied to explore the importance of the evaluation system, which can integrate expert opinions more effectively and make a substantial contribution to the decision-making results.

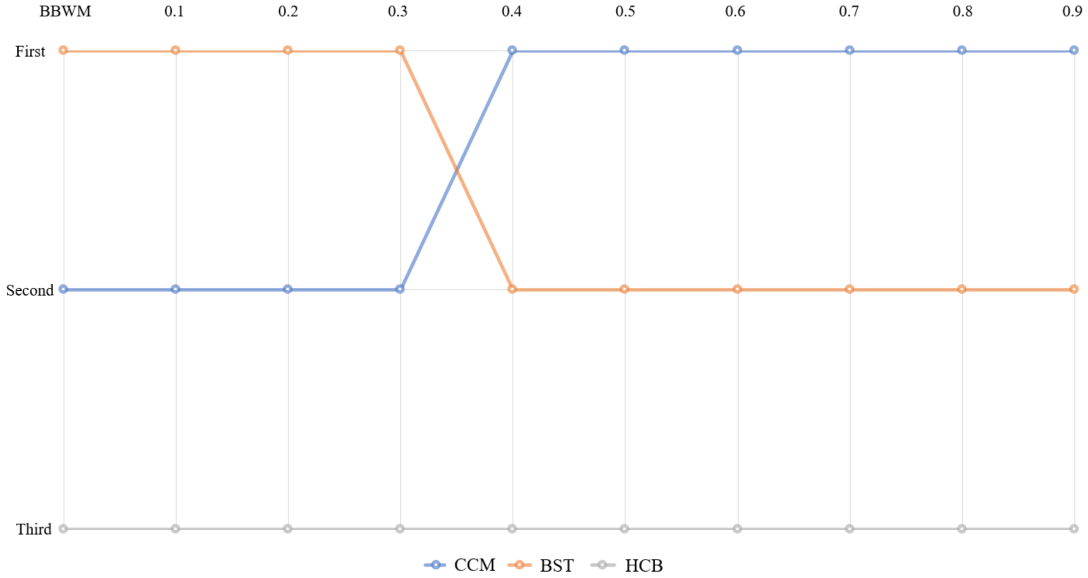

Figure 2. Ranking results of alternatives after nine sensitivity analysis runs.

5. Discussion

Some management recommendations and implications based on the results are discussed. Our results suggest that the development of the EM industry in Taiwan should be directed towards the "Battery swapping technique". It is important to identify specific directions for development of the industry how to improve the alternatives in the government's decisions to promote the use EMs. This study develops an evaluation system and analyzes existing gaps between the alternative strategies for improving battery swapping technology. The results are presented in **Figure 3**. From left to right on the X-axis the weights obtained with the evaluation system range from smaller to larger, while the Y-axis shows the gaps ranging from smaller at the bottom to larger at the top. The indicators that fall in the upper right quadrant represent those with higher importance and larger gaps. The results show the most urgent needs for specific directions of improvement for development of the program.

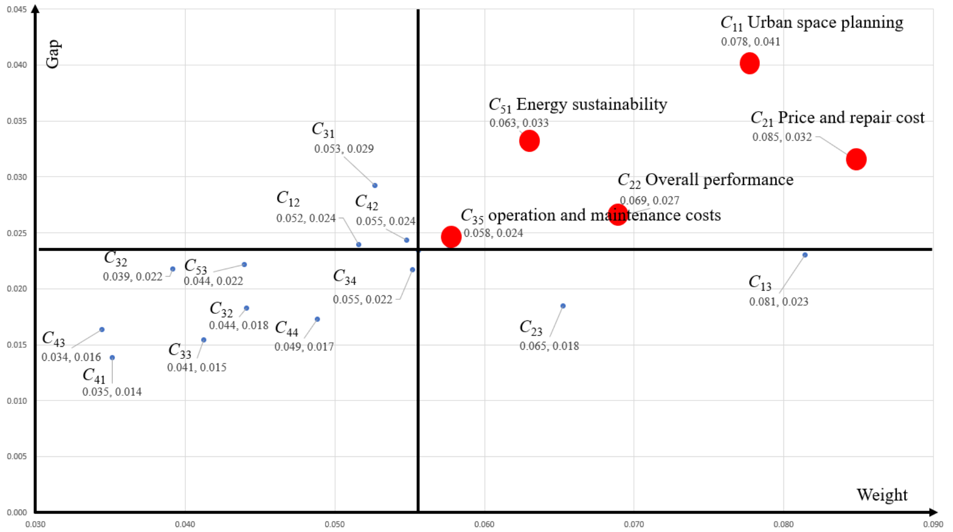

Figure 3. Strategies for improving battery replacement technology.

The analysis shows that the four indicators of Urban space planning, Price and repair cost, Energy sustainability, and Overall performance, are the top priorities for the development of exchange energy storage systems in Taiwan.

First, the construction of energy charging facilities falls into the category of national public construction, and the initial investment cost of single-site construction is high, and land is difficult to obtain in urban areas. As a result, it is impossible to build the large number of energy charging stations required to meet the needs of the public in a short period of time. Therefore, the government should first focus on estimating the number of EMs to be developed in the region then inventory unused space available for infrastructure in the city, such as regional public buildings, privatized government-owned enterprise resources, government-owned or private parking lots, and so on. The construction of energy charging facilities should be made a top priority to improve the energy charging network, revitalize existing areas of state-owned businesses, strengthen investment in the new energy business and promote cross-sector alliances. In addition, the government should take advantage of its government-owned parking management system, increasing the number of parking spaces for EMs and implementing preferential parking rates. The development of sharing economy business models for EMs can also be strengthened to deal with the lack of urban storage space, improve traffic congestion, and improve urban spatial planning.

In terms of price and repair costs, the EM industry and market are still in their infancy. The cost of building an EM is still higher than that of a traditional fuel motorcycle because the production of EMs has not yet reached an economy of scale. Furthermore, the existing environmental regulations and policies could be strengthened, which would affect the willingness of the population to replace their traditional fuel scooters with electric ones. It is thus recommended that regional governments increase purchase incentives to strengthen the replacement rate by providing subsidies for vehicle purchases, strengthening environmental regulations, and amending relevant laws and regulations. On the other hand, the development of the EM industry supply chain could also be improved to facilitate the transformation of the existing traditional motorcycle industry. For example, the government should encourage integration of relevant industry companies, promote the modularization and commonization of infrastructure, and assist traditional motorcycle shops to upgrade the facades as well as mechanical skills. This will improve the convenience of EM repair and maintenance and meet the public’s demand for vehicle repair stations. The government can also encourage the industry to develop business models, such as selling battery-free vehicles with batteries for rent or the sharing of electric vehicles. This will increase the economic scale of the industry and quickly reduce the cost of production and subsequent ownership.

For the improvement of energy sustainability, relevant systems can be designed to encourage off-peak charging and the return of excess stored electricity to the power grid during peak hours. Innovative applications of digital transformation, such as power intelligence and the Internet of Things should be actively developed. Furthermore, specific solutions for integrated power generation should be strengthened, the development of V2G (Vehicle-to-Grid) of energy storage and power consumption should be promoted, and demonstration sites for smart charging of electric vehicles should be actively established. In addition, the practicality and convenience of the energy management system can be optimized, so that charging can be remotely monitored and controlled, and the charging time can be reasonably allocated to improve energy efficiency and maintain grid stability.

Finally, in terms of overall performance, the cruising range of the scooter is one of the biggest considerations for people buying EMs today. Therefore, the government should continue to guide domestic vehicle manufacturers to invest in the research and development of smart battery technology and battery assembly lines and explore new battery cell technology to improve battery energy density, which will effectively extend the cruising range of vehicle batteries. In addition, through the battery management system, the battery module voltage, current, and temperature can be observed and recorded at any time to prevent overcharging and overheating of the battery to achieve a balance between battery performance and life. In addition, the industry is encouraged to form alliances with different industries using complementary technologies, integrate stakeholders, and create resources to establish an industrial value chain and enhance the competitiveness of vehicle and key component manufacturers.

6. Conclusions and remarks

This study is the first to construct an evaluation framework for EM energy charging model selection, which is based on sustainability, technology, and policy, and focuses on five main evaluation dimensions (Policy, Society, Economics, Technology, Environment), including 18 specific evaluation criteria. After integrating the opinions of various parties, this study found that the Economics dimension is the most important in the whole evaluation system, and it is the first priority to focus on for the sustainable development of an EM energy charging strategy. No business model can be sustainable without economic incentives and relying only on government subsidies. According to the analysis, the selection of energy charging facilities for EMs in Taiwan should be directed towards the battery swapping technique.

The focus should be on the improvement of Urban space planning, price and repair costs, energy sustainability, overall performance, as well as operation and maintenance costs. Based on the comparative analysis, it is found that the proposed decision model is consistent with the results of other models, and the sensitivity analysis shows that the criterion weights have a decisive effect on the results. Thus, the proposed model will have the advantage of making a practical contribution to the development of decision science. The results will provide useful and critical decision information for the development of electrification in the transportation industry. The results have sufficiently integrated the different decision-making views of industry representatives. Therefore, the results and recommendations of this study can be used by future governmental authorities for the formulation of related strategies, which will provide constructive assistance to the sustainability and energy policies of the country.

Although the study has provided some practical contributions, improvements can be made in future work. The current model does not consider the interdependency between dimension or criteria. The analytic network process, DANP or other dependent methods could also be used for weight calculation. Other fuzzy concepts might be applied to integrate the various opinions coming from experts. Other empirical examples from different countries are welcomed for comparison with the current results for Taiwan.

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