

Article

Vitalization Strategies for the Building Energy Management System (BEMS) Industry Ecosystem Based on AHP Analysis

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Abstract: The combination of building energy management technology and technology of the Fourth Industrial Revolution has a significant potential for reducing energy consumption and, hence, CO₂ emissions. However, numerous studies have indicated barriers preventing market growth. These challenges are mainly attributed to characteristics of the ecosystem of the building energy management systems (BEMS) industry. This study aimed to identify the major challenges hindering the deployment of BEMS in combination with Fourth Industrial Revolution technologies and to derive policies conducive to the achievement of the effective BEMS industry ecosystem. An analytic hierarchy process (AHP) survey was conducted on key players in the ecosystem to achieve this. The main elements of the ecosystem, economic, institutional, technology, and social system that earned weight, followed a decreasing trend in this order. Among the sub-elements, the payback period, upfront cost, electricity pricing scheme, energy consumption/CO₂ emission reduction, and government support system ranked first to fifth places, respectively. This result can be used to determine the element in need of priority allocation of resources while establishing an effective BEMS. However, the priority depends on the development stage at which the industry is at, and other elements should not be overlooked.

Keywords: BEMS; energy conservation; climate change; Fourth Industrial Revolution; technology; industrial ecosystem; AHP



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1. Introduction

Since Fourth Industrial Revolution began, the global economy has been undergoing major transformations and the energy sector is facing an energy system transition. Energy systems are equipped with sensors, wireless and network communication, cloud computing, and smart mobile devices. Changes in energy production, distribution, and consumption are innovated [1–3].

It has been established that energy management systems (EMSs), building energy management systems (BEMSs), industrial companies and factory energy management systems (I/C/F/EMSs), and home energy management systems (HEMSs) dependent on computer-aided automation and data technology have demonstrated their energy saving effects [4,5]. The energy saving of EMSs can be improved by enhancing functions and integrating Fourth Industrial Revolution technologies, such as artificial intelligence, Internet of Things, cloud computing, big data, and mobile devices [4]. The BEMS sector has witnessed rapid growth and BEMS are emerging as key technologies of the movement towards decentralized energy generation and control [6]. Big data technologies are leading the technical advancement of BEMS [7,8]. By analyzing building energy use patterns, energy consumption and intelligent control of energy can be predicted. Intelligent control facilitates energy conservation by optimizing the energy consumption of buildings while ensuring the occupants comfortable [6,9].

With the remarkable advancement of technology, the combination of BEMS and Fourth Industrial Revolution technology is evidently trending within the EMS business. Based on a survey of 335 Korean companies in the energy management industry [10], including BEMS, Smart Grid (SG), Demand Response (DR), and Energy Service Companies (ESCOs), 61% of the companies have introduced Fourth Industrial Revolution technologies. In particular, 95% of the BEMS companies have integrated Fourth Industrial Revolution technologies. The scale of the BEMS market is expected to grow rapidly based on key technologies of Fourth Industrial Revolution. In a study published by Navigant Research [11], it was estimated that the global BEMS market will be valued at USD 12 billion by 2025 compared to USD 4 billion in 2017. Despite the positive outlook for the BEMS market, the complete transition to state-of-the-art technology is unlikely due to diverse barriers, such as high upfront costs, skepticism about new technology, lack of institutional infrastructure, inaccessible finances, technology standardization, and cyber security issues [10,12].

This study aimed to identify major challenges hindering the deployment of BEMS in combination with Fourth Industrial Revolution technologies and to derive policies for the design of a sound and effective BEMS industry ecosystem. Based on such policies, BEMS can contribute to climate change mitigation through energy conservation, establish equitable and democratic markets, and create a new growth engine for the economy. For this purpose, the BEMS industry ecosystem is defined in this study, while the key players and the main and sub-elements of the ecosystem, are identified. In addition, challenges in establishing a sound ecosystem are identified and policies are proposed. An analytic hierarchy process (AHP) survey was conducted on the key players of the BEMS industry ecosystem.

This study draws out implications for the design of policies for a more productive, equitable, and effective BEMS industry ecosystem by identifying the priority among elements consisting of the ecosystem. To the best of our knowledge, this study is the first attempt to propose optimized characteristics of the BEMS industry ecosystem, define ecosystem elements, and identify barriers based on these elements. The expert survey provides policy guidance in promoting the BEMS industry.

The remainder of this paper is organized as follows. The research background and conceptual framework are presented in Sections 2 and 3. The significance of the AHP methodology applied in this study and the AHP analysis procedure is described in Section 4. The results of the AHP analysis, discussion, and implications are presented in Section 5. A summary and proposed policies are presented in Section 6.

2. Background

Based on the importance of energy demand management technology in climate change mitigation, various studies have been conducted on BEMS. Numerous studies have focused on experiments exploring the feasibility of optimized models for BEMS. These models were applied to different scope-building-specific [13], a common platform integrating multiple vendors' locked-in systems [14], and city-specific, with public open data sources [15], which demonstrated energy efficiency performance in different settings of optimization and proposed conditions for better performance. Orland et al. [16] conducted an experiment in an office setting using a model and real-time energy feedback. This model focused on user education and behavioral changes and yielded a significant energy-saving performance.

Despite the potential of energy-saving technologies, a myriad of barriers has been encountered with respect to their market deployment. In numerous studies, barriers hindering the deployment of smart energy management technology have been identified, with respect to policy and regulatory, economic, social, and technical aspects. Literature mainly focuses on policy and regulatory elements. Based on the literature, institutional barriers are due to the government inaction or inadequacy in changing and creating institutions to deploy new energy-efficient building technologies. Barriers include non-functional [17] or inadequate institutions [18], lack of financial incentives and mismatching market mechanisms [19], legal system and administrative issues [20], lack of political and

external financial support [21], lack of flexible energy tariffs and support incentives [22], inadequate tax policies [23], deficiencies in public policy and regulation [24], lack of policies promoting market opportunities [25], mandatory and incentive policies [25–27], traditional restrictive regulations [28,29], and restricted access to finance [27].

The economics of new technology adoption has a significant effect on decision-making regarding energy-efficient technology investments. This includes the fear of additional cost [30,31], higher additional costs [19], business potential [26], and profitability [29].

Social factors originating from social values and stakeholder behaviors also hinder the deployment of energy-efficient building technologies. Social barriers such as disinterest in energy efficiency improvements [17], stakeholder resistance [29,32], perceived risks [19,33], behavioral change [26], security and privacy issues [1,31,33], and public awareness of energy efficiency [22,34] were identified.

Technical issues can be divided into four categories: technology, scalability and development level of the industry's technology ecosystem, technology readiness level, and technology standardization. Barriers include the lack of technical skills [17]; inadequate information [5,17,19,30]; intelligent technology (IT) infrastructure, governance, and professionals [1]; design and operation standards [33]; lack of good cooperation and acceptance [21]; existing practices in the industry itself [24]; lack of basic data and energy audits as technical support [34]; controllability of the system [31]; technical feasibility and innovativeness [26]; adaptability of technologies and auxiliary resources [29].

Despite there being many existing studies on the barriers to the deployment of EMS technology, no research on the challenges to the promotion of the BEMS industry ecosystem, in terms of a comprehensive perspective, has been conducted. Studies in the field of BEMS have been limited to identifying the characteristics of related technologies, application models, and energy-saving performance. Therefore, this study significantly contributes to the BEMS research by identifying challenges and policy priorities to vitalize the BEMS industry ecosystem.

3. BEMS Industry Ecosystem

In various studies, the industrial ecosystem has been described as a concept of biological evolution [35,36]. The elements of the ecosystem are connected via interactions among themselves and their interdependency. The ecosystem has a hierarchical multilayered structure. The levels of this multilayered structure differ depending on their internal structures and functions. The functions of lower-level elements depend on the functions of higher-level elements. Similarly, the proper functioning of higher-level elements depends on functioning of lower-level elements. Each element has a different influence on the ecosystem. When an element does not function, the effective operation of the entire ecosystem is affected. The larger the effects of problematic elements within an ecosystem are, the greater the ineffectiveness of the entire ecosystem. The ecosystem evolves through changes in interactions or the transformation of each element's characteristics and function. The environment surrounding the ecosystem is a critical factor affecting the ecosystem evolution.

The BEMS industry ecosystem consists of various players and elements [37–40]. Representative players include enterprises and service consumers, who are market participants. Both academia, supplying and developing technology, and the government, establishing regulations, support policies, and legal systems, play important roles in this state-of-the-art technology-based field. Academia also represents an important adviser group with respect to the development direction of the BEMS ecosystem, such as market order and governance.

In this study, four main elements were identified based on a literature review: technology, economic system, social system, and institutional system. Figure 1 illustrates the BEMS ecosystem comprising key players and various components. Each component consists of subcomponents. As described in Section 2, barriers to the deployment of energy management systems, in combination with Fourth Industrial Revolution technologies have been identified in numerous studies. In this study, the focus is placed on sub-elements

of the BEMS industry ecosystem. Sub-elements become barriers when they adversely affect the operation of the entire system. For example, a barrier with a high upfront cost is the malfunctioning sub-element, “upfront cost” of the main element, “economic system”. Although each main component may contain various sub-elements, only the core sub-elements were considered as components of the ecosystem in this study, focusing on problems that were repeatedly reported in literature.

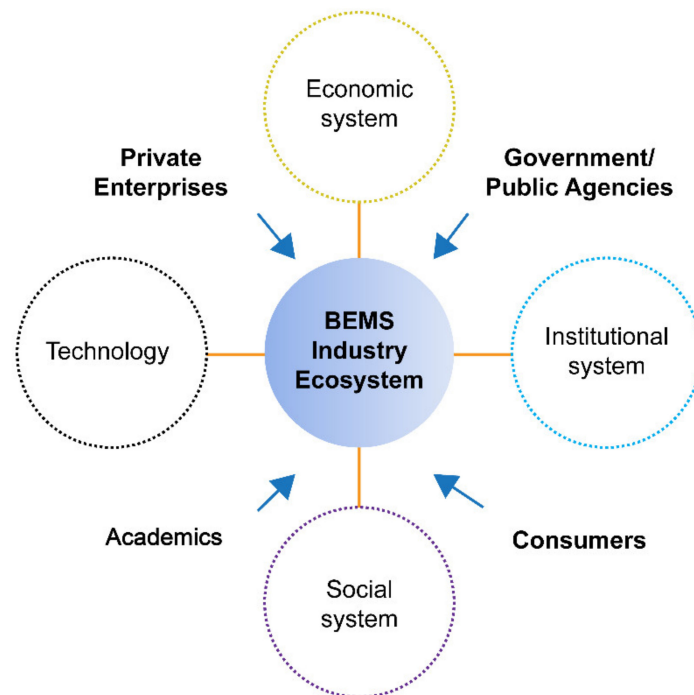


Figure 1. BEMS industry ecosystem.

The authors held two expert seminars to identify the main and subcomponents of the BEMS industry ecosystem. The experts represent the player groups of the ecosystem including government and public agency officials, academics, and businesspeople. In the seminars, discussions were held about elements selected from literature. Table 1 shows the hierarchical structure of the key components that were selected as the main and subcomponents of the BEMS industry ecosystem based on the literature review and expert seminars. Table 1 also includes the definitions of the ecosystem elements.

Table 1. Elements of the BEMS industry ecosystem and definitions.

Main Elements		Sub Elements		Source (Literature)
Element	Definition	Element	Definition	
Technology	Maturity of BEMS-related element and system technologies	Technology Readiness Level	Development level of BEMS-related technology	[17,34]
		Scalability of the Industry's Technology Ecosystem	Technological expansion potential of the BEMS industry ecosystem by incorporating technology of the Fourth Industrial Revolution	[24,26,29]
		Development Level of the Industry's Technology Ecosystem	Maturity of the BEMS industry's technology ecosystem including trained technicians, Research & Development (R&D) infrastructure, and technology commercialization	[1,31,34]
		Technology Standardization and Certification	Standardization and certification of BEMS-related communication protocols	[1,33]
Economic system	Economic factors affecting the deployment of BEMS technology and the characteristics of the BEMS market	Upfront Cost	Initial investment cost for the BEMS	[30,31]
		Payback Period	Payback period of BEMS investment	[26,29]
		Energy Consumption/CO ₂ Emission Reduction	Energy consumption and CO ₂ emission reduction through BEMS	[6,9]
		Ease of Market Entry of Small and Medium Enterprises	Level of market concentration (monopoly)	[19]
Social system	Social factors affecting customers' human rights, privacy, and equitable access to benefits based on the growth of the BEMS industry	Job Creations	Job creations by expanding the BEMS market	[12]
		Responsiveness to Customer Characteristics and Needs	Possibility of providing differentiated services that can meet various customer needs	[34]
		Cyber Security	Level of cyber security	[1,31,33]
		Awareness of Customers	Level of understanding and information on BEMS of potential customers	[22,34]
Institutional system	Institutional factors affecting the development of the BEMS ecosystem, such as legislation, policies, programs, financial support, governance, etc.	Level of the Market Intervention of the Government	Degree of government intervention in the BEMS industry ecosystem	[17,24]
		Government Support System	Government-supported loans, subsidies, R&D/demonstration support, professional training	[18,25]
		Electricity Pricing Scheme	Possibility of expanding BEMS investments according to the electricity rate system	[20,30,31]
		Ease of Access to Finances	Financing conditions such as ease of borrowing, debt service coverage (DSCR), and liquidity of funding	[19,21,27]

4. Methods

4.1. Methodology: AHP

When making a decision, the decision maker always wants to choose the best solution. A true optimal solution exists only when a single criterion is considered. However, in the case of real decisions, it is insufficient to simply base a decision on one criterion. Perhaps

some conflicts and sometimes unmeasurable objects should be considered. Multi-criteria decision analysis (MCDA) is a unique tool to assist in decision-making when more than one conflicting criterion exists [41]. Although a number of MCDAs have been proposed over the years, they differ from each other in many areas, including the theoretical background and the type of question and results. Hierarchical analysis is a typical decision-making method for solving complex real-life decision-making problems. The AHP analysis method was developed by Saaty (1980) as a technique for selecting an optimal alternative, by hierarchically classifying a number of attributes and weighing each attribute. The stratified analysis method is characterized by stratifying a complex problem, decomposing it into major and detailed factors, and deriving weights through pair-wise comparisons of these factors. The stratified analysis method is recognized for its usefulness in that it can obtain quantitative results by measuring relative weights or preferences in a systematic ratio using a model.

Recently, the fuzzy multiple attribute decision making (FMADM) methodology, which combines the fuzzy concept with MCDA, has been utilized in response to inaccuracies [41,42]. There are many reasons why inaccuracies occur. This is because of information that cannot be quantified, is incomplete, cannot be obtained, and is partial ignorance. The fuzzy set theory developed by Zadeh [43] is used to solve this problem and evaluates the relative importance of attributes by reflecting on inaccuracies and determining the grade of alternatives to the attributes. Among the diverse FMADM methods, the technique for order preference by similarity to ideal solution (TOPSIS) has a logic that can express human rational choice that considers the best and worst targets simultaneously [44]. The VIKOR methodology compares the proximity of the ideal alternative to give an eclectic prioritization and contributes to solving the multi-criteria decision-making problems in a fuzzy environment where the subjective judgment of the evaluator is involved [45]. This fuzzy technique is significant as it can reflect the diversity of decision criteria and the subjective judgment of evaluators [46].

AHP, the methodology adopted in this study, is the most widely applied method among MCDA techniques. It aims to derive policy implications for building an effective BEMS industry ecosystem, and focuses on the tendency of which factors experts consider more important rather than the accuracy of factor prioritization. In other words, AHP attempted to find which factors are more influential for the promotion of the BEMS industry rather than an optimal alternative applicable to a given situation. In addition, the uncertainty and incomplete information were insignificant in our study. Respondents of the AHP survey have been deeply involved in the BEMS market and related policies, so they have a firm opinion on the weight of each factor according to their experiences. Accordingly, in this study, AHP analysis is more suitable than FMDCA, as the latter attempts to find the most accurate answer in situations of uncertainty and information incompleteness. Furthermore, the AHP methodology is advantageous in that the analysis process is simple, and it is easy to obtain signal information of decision makers in the process of evaluating the importance of elements or alternatives. In addition, it is easy to consider both quantitative and qualitative factors due to the nature of the analysis process. The detailed analysis process of AHP analysis is as follows.

AHP was developed based on the fact that humans use a step-by-step or hierarchical analysis process when making decisions as follows. The first step begins with setting up a hierarchical structure, followed by establishing relative importance (weight). It follows the principle of logical consistency. Hierarchy is a way to systematize and structure the complex problems we encounter in business management, policy development, or everyday life, and it is a tool that presents the flow of functional information transmission. In general, the hierarchical structure of the selected problem is divided into three stages: goals, criteria, and alternatives. Certain hierarchical levels may be given numerical values or described in words. In most cases, targets are placed at the highest level, evaluation or selection criteria are placed at the second level, and alternatives are placed at the lowest level. In addition, a crucial feature in the hierarchical structure of a given system is that it enables the analysis

of AHP and verification of the consistency of pairwise comparisons in the second stage of AHP by ensuring that each factor is interrelated and relatively different.

The methodology is based on each matrix $n \times n$, where rows and columns correspond to the factors analyzed in the problem. Therefore, the a_{dc} value represents the relative importance of the factor of line d against the factor of column c and is also valid for evaluating alternatives [47]. A pairwise comparison matrix A is obtained based on the decision maker's judgment on a_{cd} at each level (see Equation (1)).

$$n \times n \quad (1)$$

A pair-wise comparison matrix is constructed with respect to goals in each category. The weights for each category are computed using $Aw = \lambda_{\max}XW$, where A is the comparison matrix of size $n \times n$, for n criteria. This is also called priority matrix, and w is the eigenvector of size $n \times 1$, also called priority vector, which is the weight. Further, λ_{\max} is the maximum eigenvalue.

Finally, it is reviewed to establish the consistency of the answers to the questionnaire data. The logical consistency is secured when responses of experts satisfy ordinal as well as cardinal consistency. Ordinal consistency requires consistency in the order of importance among the factors. If A is more important than B and B is more important than C , A should be more important than C . Cardinal consistency is a concept related to the degree of importance. If an expert responds that A is twice as important as B and A is four times more important than C , B should be twice as important as C . Satty [48] sets the maximum acceptable inconsistency rate at 0.1. If the consistency ration (CR) value is greater than 0.1, the respondents are considered inconsistent and excluded from analysis. The consistency index (CI) is obtained using $(\lambda_{\max} - n)/(n - 1)$.

4.2. Expert Survey

In this study, an AHP survey was conducted with relevant experts to identify methods that can be used to build an effective BEMS industry ecosystem. The purpose of the survey was to identify and prioritize key elements for the vitalization of the BEMS industry.

The structure of the questionnaire used for the AHP survey consisted of two hierarchy layers. The experts were requested to make pairwise comparisons among components of the BEMS industry ecosystem. In the first step, priorities and weights were derived through pairwise comparisons of the main elements. The purpose of the pairwise comparisons at this stage was to obtain the weights for each field to determine the overall priority of the sub-elements in the next stage. In the second step, the priorities and weights were determined through pairwise comparisons between the sub-elements of each field. The overall priority and weight can be derived by multiplying the obtained priority and weight by the weight of each field obtained in the first step. Figure 2 illustrates the hierarchical structure of the AHP survey.

To obtain data for the evaluation of the ecosystem, a survey was conducted with experts in the field. Experts were selected from three sectors: academia, government/public agency officials, and private enterprises. These represent the key players in the ecosystem. Seven to eight experts were selected from each sector. Consumers were excluded from the expert groups because consumers' comprehension of the BEMS ecosystem was determined to be insufficient during expert seminars that were conducted to prepare survey logistics and questionnaires. The BEMS industry is considered to be technology-oriented; it is in an infant stage in Korea.

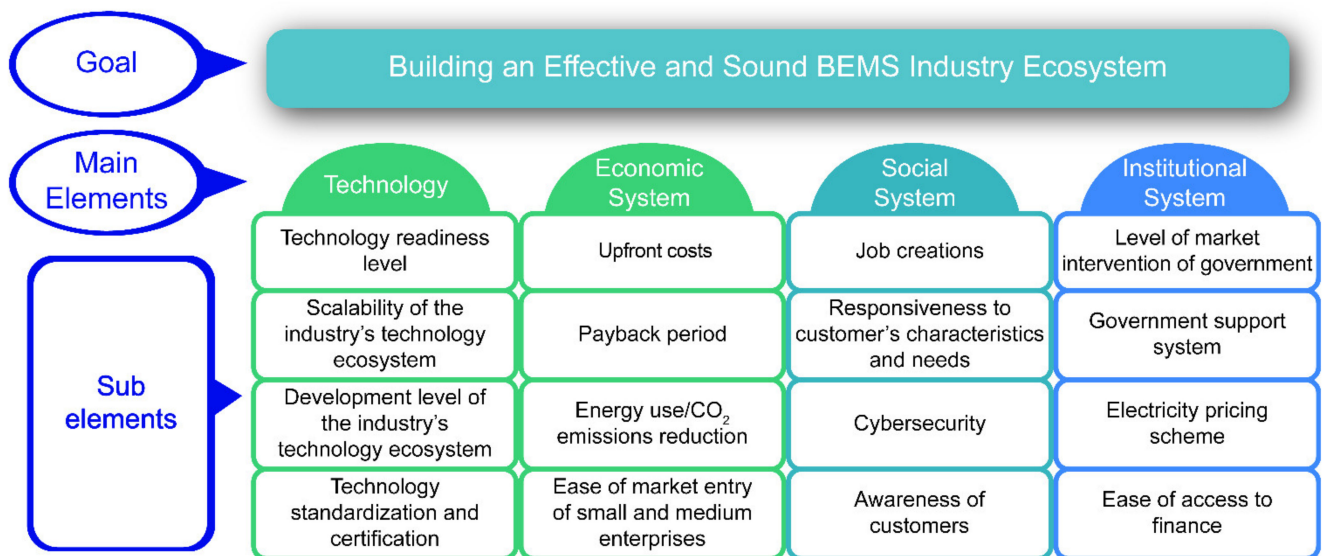


Figure 2. Hierarchical structure of the AHP survey on the BEMS industry ecosystem.

A total of 22 experts from three sectors were surveyed. Table 2 describes the characteristics of the sector and expert requirements. The questionnaire was sent to eight experts from academia, seven experts from the business sector, and seven experts from the government and public sector. Among these experts, 21 responded to the questionnaire. When the consistency test indicated erroneous responses, we asked for the answer to be clarified. Hence, three survey responses that were considered to be difficult to solve the consistency problem were excluded from the analysis, that is, two from the government and public sector and one from the business sector. The AHP analysis was conducted on the remaining 19 surveys.

Table 2. Expert groups selected for the survey.

Sector	Characteristic and Requirements
Academia	Zero Energy Building (ZEB), BEMS-related research institutes and universities; experts with experience in BEMS-related national policies or public/private projects
Government/Public	Government officials in charge of central government departments and local governments related to energy efficiency and BEMS
Private enterprises	Head of the department in charge of BEMS-related companies and affiliated research institutes and experts

5. Results and Discussion

5.1. Results of the Evaluation of the Main Elements

Based on the analysis of the importance of the main elements in the upper level of the BEMS industry ecosystem's hierarchy, the average importance of each element was 16.7% (technology), 48.8% (economic system), 8.6% (social system), and 25.9% (institutional system). As shown in Table 3, the same priorities of the elements were obtained for all sectors. This means that all expert groups evaluated the importance of the main elements in the same way regardless of the sector.

Figure 3 shows that each stakeholder group scored a slightly higher than average for a specific element. This difference corresponds to the role of each stakeholder group in the BEMS industry ecosystem. Experts from the business sector place greater weight on economic factors than other groups. The average score of the economic factor was 48.8%, but experts from the business sector assigned a weight of 55.2%. Policymakers are paying more attention to the role of the institution. The group of scholars, consisting of professors and researchers, assigned a greater weight to technology than the average. In this group,

the difference in the weights between the technology and institution elements was 3.3%, which is much lower than the difference of 9.2% obtained for all stakeholders. This shows that academics believe that the elements constituting the ecosystem must be balanced to promote the BEMS market. This is also evident in the fact that this group assigned the social element the highest score among all groups.

Table 3. Importance of each main and sub element by sector. (Unit: %)

Main Elements	All Stakeholders *			Policymakers (PMs) *			Business *			Academia *		
2-13 Technology	16.7 (3)			13.7 (3)			13.6 (3)			21.6 (3)		
1-13 Economic system	48.8 (1)			47.3 (1)			55.2 (1)			44.4 (1)		
Social system	8.6 (4)			8.2 (4)			8.1 (4)			9.1 (4)		
Institutional system	25.9 (2)			30.9 (2)			23.2 (2)			24.9 (2)		
Subelements	Unweighted	Weighted	Rank	Unweighted	Weighted	Rank	Unweighted	Weighted	Rank	Unweighted	Weighted	Rank
Technology												
Technology Readiness Level	21.5	3.6	12	30.4	5.1	8	18.7	3.1	12	16.8	2.8	13
Scalability of the Industry's Technology Ecosystem	26.1	4.4	9	14.5	2.4	13	45.7	7.6	5	21.1	3.5	10
Development Level of the Industry's Technology Ecosystem	28.3	4.7	7	18.9	3.2	11	19.9	3.3	10	40.5	6.8	6
Technology Standardization and Certification	24.1	4.0	11	36.2	6.1	6	16.1	2.7	13	21.6	3.6	9
Economic System												
Upfront Cost	26.5	12.9	2	38.7	18.9	2	27.0	13.2	2	20.4	10.0	4
Payback Period	43.1	21.0	1	39.6	19.3	1	42.8	20.9	1	40.1	19.6	1
Energy Consumption/CO ₂ Emission Reduction	17.6	8.6	4	13.6	6.6	5	21.7	10.6	3	17.1	8.4	5
Ease of Market Entry of Small and Medium Enterprises	12.8	6.3	6	8.1	4.0	9	8.5	4.2	9	22.3	10.9	2
Social System												
Job Creations	18.5	1.6	16	19.4	1.7	15	18.1	1.6	16	16.8	1.4	16
Responsiveness to Customer Characteristics and Needs	31.5	2.7	13	41.8	3.6	10	37.6	3.2	11	21.1	1.8	15
Cyber Security	26.2	2.3	14	15.7	1.4	16	19.9	1.7	15	40.5	3.5	10
Awareness of Customers	23.7	2.0	15	23.1	2.0	14	24.4	2.1	14	21.6	1.9	14
Institutional System												
Level of the Market Intervention of the Government	16.8	4.3	10	23.6	6.1	6	17.7	4.6	8	12.4	3.2	12
Government Support System	28.9	7.5	5	35.0	9.1	3	26.7	6.9	6	26.1	6.8	6
Electricity Pricing Scheme	36.3	9.4	3	30.9	8.0	4	32.6	8.4	4	41.6	10.8	3
Ease of Access to Finances	18.0	4.7	7	10.5	2.7	12	23.0	6.0	7	20.0	5.2	8

* Numbers in parentheses represent the rankings of the main elements.

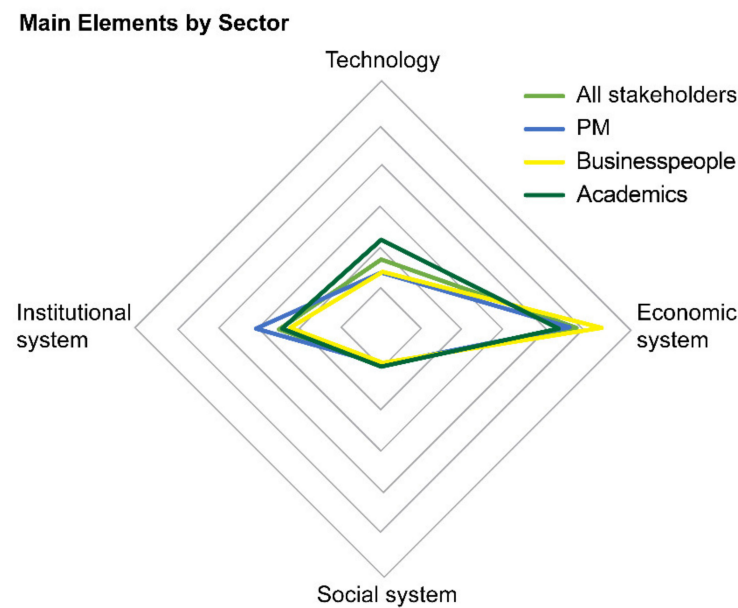


Figure 3. Consistency of the results of the evaluation of the main elements among sectors.

This result indicates that the respondents are paying more attention to economic elements that are directly linked to economic feasibility because Korea's BEMS industry remains in its infancy. The importance of social elements can be easily overlooked in the early stages of market formation because they include ethical aspects such as the equitable structure, social contribution, consumer awareness, and stability of the system.

5.2. Results Obtained for the Sub-Elements

Based on the analysis of the weights assigned to the sub-elements by all respondents, the payback period is ranked the highest in all sectors, as shown in Table 3. The upfront cost, electricity pricing scheme, energy consumption/CO₂ emission reduction, and government support system were ranked second to fifth places, respectively.

Among the economic factors, the payback period and upfront cost, which are directly related to the profitability, ranked first and second places, respectively. This can be explained by respondents' belief that profitability should be guaranteed first to expand and advance the BEMS industry.

The electricity pricing scheme (third place) belongs to the institutional system due to the structure of the electricity market, which is monopolized by a government-owned enterprise. In Korea, the tariff strongly depends on political considerations [45]. However, the tariff is one of the key factors determining the profitability of BEMS investments and, thus, also retains economic attributes.

Energy consumption/CO₂ emission reduction (fourth place) is an element that conveys the essential goal of the BEMS project. This means that stakeholders in the BEMS industry consider the pursuit of ethical responsibility for climate change and solid performance in achieving economic benefits based on an efficient use of energy to be a key factor in revitalizing the industry.

The government support system was ranked fifth. Energy conservation and efficiency represent a technical field that is crucial for climate change mitigation. The energy saving potential of BEMS is strengthening by integrating smart grid technology in buildings, which facilitates the bidirectional flow of power and information. For commercializing and activating new technologies, the government's proactive measures, including the establishment and renovation of the regulatory system, and the introduction of support policies and financial programs play crucial roles in the early stages of market formation. The fact that this element is ranked fifth indicates that government support measures and pre-emptive actions are critical.

The ease of the market entry of small and medium enterprises (SMEs), development level of the industry's technology ecosystem, ease of access to finance, scalability of the industry's technology ecosystem, and level of market intervention by the government were ranked sixth to tenth place, respectively. The proportions of economic, technological, and institutional elements were balanced. The ease of market entry of SMEs ranking sixth is noteworthy. This indicates that an environment in which a large number of players compete by providing various services on the market, boosts the industry. In the technology element, development level and scalability of the technology ecosystem scored high. This means that the technology ecosystem should be built based on a balanced combination of soft/mid/hardware technology and the related personnel, and its scalability should be secured.

Technical and social elements were ranked outside the top ten places. The social system element did not possess a sub-element within the top ten while responsiveness to customer characteristics and needs earned the highest weight. The fact that the importance of the service that meets the characteristics and demands of consumers received a high weight, indicates that the satisfaction of the consumers is a major factor driving industrial growth.

The responses of all stakeholders are consistent with the responses of each stakeholder group. However, inconsistencies were observed within each stakeholder group with respect to the sub-element scores. The largest disagreement among the expert groups was observed for the technology element. The weights were assigned in the order of the development level of the industry's technology ecosystem, the scalability of the industry's technology ecosystem, technology standardization and certification, and technology readiness level. However, all expert groups assigned different weights to the sub-elements. Academics, policy experts, and businesspeople assigned the highest weight to the development level of the industry's technology ecosystem, technology standardization and certifications, and scalability of the industry's technology, respectively (see Figure 4). This means that there is no consensus among the expert groups with regard to which sub-elements of the technology element are most important. This might indicate that the technology field is neglected in discussions about the growth of the BEMS industry.

In the case of the economic system, all groups prioritized the payback period. However, sector-specific differences were observed for other sub-elements. The government/public sector ranked upfront cost, energy consumption/CO₂ emission reduction, and the market entry potential of SMEs second, third, and fourth place, respectively. Academics ranked the market entry potential of SMEs, upfront cost, and energy consumption/CO₂ emission reduction second, third, and fourth places, respectively. The business sector ranked upfront cost second, followed by energy consumption/CO₂ emission reduction and finally the market entry potential of SMEs. The payback period and upfront cost insignificantly differ from the average value in all sectors, but the ranking of the energy consumption/CO₂ emission reduction and market entry potential of SMEs differs depending on the sector. The value assigned to the energy consumption/CO₂ emission reduction by businesspeople is two points higher than the average value. On the other hand, policymakers and businesspeople assigned values below the average to market entry potential of SMEs, whereas academics assigned a value that is 4.6 points higher than the average. Based on these results, it can be inferred that the perception of sub-elements differs depending on the sector. In terms of economic elements, policy experts and academics assigned higher scores to upfront cost and market entry potential of SMEs, respectively. This indicates that policymakers prioritize policy for lowering upfront cost in removing the barriers to market entry. The fact that this group recognizes the importance of this element more importantly than other stakeholder groups, along with the payback, demonstrates government's will to remove cost barriers and guarantee profitability in the beginning of the market formation.

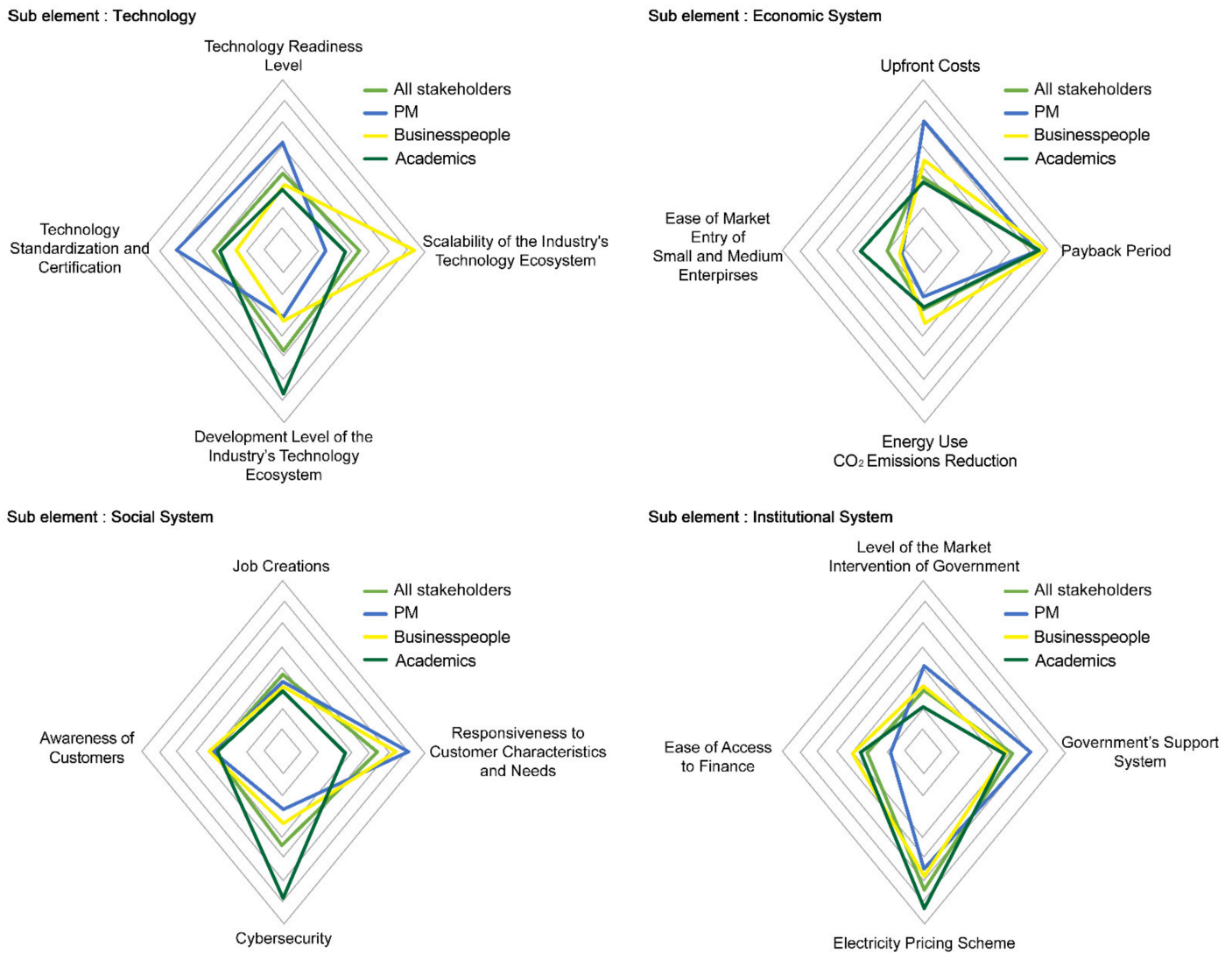


Figure 4. Consistency of the sub-element evaluation results among sectors.

Attention must be paid to the fact that academics attach greater importance to the ease of SMEs’ market entry than other groups. As scholars, indirect players in the market, they are committing to the role of proposing perspectives for a balanced and sound development of the industry. In this context, they believe that easy access to the market by enterprises of various sizes, not the oligopoly by large corporations, will strengthen the health of the market and is a critical factor in the development of an effective ecosystem.

In the case of social elements, the job creation effect and awareness of potential customers received similar weights from all sectors. On the other hand, academics assigned the responsiveness to customer needs a lower weight than the other sectors. This reflects that the public sector and private corporations place importance on improving the diversity and quality of services. Academics attach a higher importance to cybersecurity. When cybersecurity of BEMS is weak, a forged IP (Internet Protocol) packet can be entered when requesting a service from a provider to induce a connection to another site or it blocks the communication with the system. This prevents EMS access and loses control of devices and sensors. In addition, there is a possibility that monetary damage may occur if a malicious service is installed through the alteration of the execution code or device, programming the system to obtain control or to alter power consumption data. Academics include BEMS technology scientists, which explains the heightened concern about social doubts

regarding this technology generated by technical vulnerability in cybersecurity, which is based on expertise.

Among the institutional elements, the electricity pricing scheme received the highest weight, followed by the government support system, ease of financing, and degree of government intervention in the market. Compared with other main elements, the consistency of the responses to each subelement is higher for this main element. Among the respondent groups, policymakers exhibit a different characteristic than others. Instead of the electricity pricing scheme, they selected the government support system as the most important element. They also scored the level of government intervention in the market higher than the other groups (~1.8 points higher than the average). On the other hand, academics assigned a lower weight to this sub-element (~1 point lower than the average). Academics also weighted the government support system element below average, while scoring the electricity pricing scheme and ease of access to finances higher. This reveals that the perspectives on leadership, with respect to the creation and growth of the BEMS market, of the policymakers and academics differ. In other words, policymakers recognize that government policies and institutions play decisive roles in the growth of the industry, whereas academics believe that the market should lead industrial growth through price signals, private finance, and competition.

6. Implications

The combination of building energy management technology and Fourth Industrial Revolution technologies has enormous potential in reducing energy use and CO₂ emissions. Due to the diversity and economic feasibility of these technologies, the market has been growing rapidly. However, challenges that prevent market growth have been reported in numerous studies. These challenges are mainly due to the characteristics of the elements constituting the BEMS industry ecosystem. In this ecosystem in which various stakeholder groups participate and hierarchically structured elements interact, elements with features that contradict market promotion challenge the achievement of the expected outcome of BEMS, which contributes to climate change mitigation and the value added through new business. In addition, the characteristics of a few elements in an ecosystem often determine the characteristics of the overall ecosystem.

In this study, the BEMS industry ecosystem was characterized based on a literature review and expert seminars. The main and sub-elements of the BEMS industry ecosystem were identified, key stakeholder groups were described, and the role of each group was discussed. Based on an AHP questionnaire, an expert survey was conducted to determine the ranks of the ecosystem elements. This ranking can be used to determine which element should resources of a society be allocated first to establish an effective BEMS industry.

Based on the results of this study, economic elements scored the highest scores with respect to both the main and sub-elements. The main elements were ranked in the following order by experts: economic system, institutional system, technology, and social system. The same order was obtained for all stakeholders and each group. Among the subelements, the payback period and upfront cost of the economic system were ranked first and second place, respectively. The electricity pricing scheme, energy consumption/CO₂ emission reduction, and government support system, which are subelements of the institutional and economic systems, were ranked third, fourth, and fifth place, respectively. Technology elements generally belong to the middle- and low-rank groups. Social elements belonged to the low-rank group. The evaluations of specific sub-elements within each stakeholder group often differed from those of all stakeholders and is noteworthy. These differences are mainly due to the roles of the stakeholder groups in the BEMS industry ecosystem. For instance, policymakers place more importance on institutional elements, whereas businesspeople score economic feasibility factors higher than others.

The results of this study have implications for the design of policies for the promotion of the BEMS market. First, securing economic feasibility is the foremost task with respect to the expansion of the BEMS market. For this purpose, diverse measures, such as government

subsidies and Research & Development for rapid technological advances [49,50], can be considered. However, the results of this study show that the reform of the electricity tariff system is the most critical solution for securing economic feasibility. In particular, in a monopolized electricity market, such as Korea, the reform of electricity tariffs will have a significant impact on the economic feasibility of BEMS technology [49].

Second, it is necessary to establish a consensus on the government's role in enhancing the BEMS industry ecosystem. This study shows that each stakeholder group has a different view of leadership roles in the ecosystem. While the government emphasizes its proactive role, academics and businesspeople emphasize measures facilitating market functions such as price signals and ease of financing. As the BEMS market remains at an infant stage, the government's active support is crucial, but should be strengthening the market function.

Third, to facilitate the participation of diverse players and respond to customer needs, the market entry barriers of SMEs should be removed. In the current BEMS industry, which is technology-intensive and focuses on equipment, big technology companies with financial strength already retain a significant market share. For the ease of entry of market underdogs, an ecosystem in which open platforms and software businesses are well developed is necessary.

Fourth, the importance of social elements should not be overlooked while establishing an equitable BEMS industry ecosystem. Social elements are associated with the ethical characteristics of the ecosystem, such as the equitable distribution of benefits based on the growth of the BEMS industry, privacy protection, and consumer power. Thus, the nature of the overall ecosystem strongly depends on the nature of each social element. The results of this study show that the overlooked importance of social factors can lead to an unhealthy ecosystem in which suppliers' power overrides that of the consumers.

Fifth, the technology ecosystem is the foundation for the development of the entire ecosystem and industry growth, especially in the BEMS industry. Technology elements, including a sufficient number of technical experts, technology R&D, and technology standardization and certification, are required for the expansion of the industry.

Based on the results of this study, a balanced development of ecosystem elements must be pursued to promote the industry. Ecosystem elements should be given priority according to the stage of industrial development. The focus should be placed on specific elements depending on the stage, but other elements should not be overlooked.

The aim of this study was to identify strategies for establishing a more productive, equitable, and effective BEMS industry ecosystem. The novelty of this study is the application of a comprehensive approach in terms of the ecosystem's overarching technology, economy, society, and institution compared with previous studies that were confined to technology identification, application of technology models, and the estimation of the energy-saving performance. This study is the first attempt in proposing optimized characteristics of the BEMS industry ecosystem, defining ecosystem elements, and identifying barriers based on these elements. The expert survey provides policy guidance for the promotion of the BEMS industry. However, this study has several limitations. As the survey used for the analysis in this study was an expert survey, consumers were excluded, which is a limitation in that their opinions were not reflected although they are members of the ecosystem. Therefore, a research conducted from the perspective of general consumers can enrich the implications for the development of the industrial ecosystem. This can be explored in future study.

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