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Risk identification for the introduction of advanced science and technology: A case study of a hydrogen energy system for smooth social implementation

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HIGHLIGHTS

- New technology priority risks were identified by comparison with current technology.
- A hydrogen energy system was evaluated against a gasoline energy system.
- Individual and infrastructural values were obtained from a survey of experts.
- Hydrogen disadvantages and differences within/among expert fields were observed.
- Analysis from multiple viewpoints is required to implement new technology smoothly.

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ABSTRACT

A method of risk identification is developed by comparing existing and advanced technologies from the viewpoint of comprehensive social risk. First, to analyze these values from a multifaceted perspective, we constructed a questionnaire based on 24 individual values and 26 infrastructural values determined in a previous study. Seven engineering experts and six social science experts were then asked to complete the questionnaire to compare and analyze a hydrogen energy system (HES) and a gasoline energy system (GES). Finally, the responses were weighted using the analytic hierarchy process. Three important points were identified and focused upon: the distinct disadvantages of the HES compared to the GES, judgments that were divided between experts in the engineering and social sciences fields, and judgments that were divided among experts in the same field. These are important risks that should be evaluated when making decisions related to the implementation of advanced science and technology.

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Introduction

The hydrogen energy system (HES) is one of the technologies expected to be introduced for environmental benefit and energy efficiency. This advanced science and technology is currently in the experimental demonstration stage, so limited relevant information is available for decision-making. Recently, there has been significant research interest in many areas relevant to hydrogen energy including the development of HESs [1,2], safety [3–9], the environment and economy [10–13], and acceptability [14,15]. However, risk management and risk identification efforts targeting HESs have relied upon limited approaches, and many have focused only on the technologies and systems themselves [16,17]. Against this background, Market [18] showed that the HES supply chain is complex and indicated that comprehensive analysis is necessary for decision support. Additionally, analysis using multifaceted indicators, such as sustainable development goals, is required, and a framework for technology assessment that takes into consideration the complex relationship between science/technology and society is required [19]. Therefore, it is necessary to systematically and comprehensively identify the risks inherent to the social implementation of an HES from the viewpoint of management, and to determine the priority of risk countermeasures.

When information describing the relationship between a technology and society is limited in the planning and introduction stage of a new technology, subjective information from experts and specific fields must be used with due attention to objective information [20]. There is a hierarchy in this method of reflecting such subjective information [21,22]. Classification by hierarchy has been often used for risk identification and assessment focusing on cost, time, and environmental indicators in the fields of machinery, civil engineering, and construction [23,24]. For example, research into the project management of infrastructure development [25–27] and analyses of technologies such as oil pipelines, wind power generation, heat supply and demand systems, waste treatment technology, and expressways have been conducted [28–31]. There is also significant discussion on the related supply chains and their problems [32]. However, many studies targeting civil engineering and the construction and manufacturing industries have used limited indicators for cost and time. In this regard, Kuo [33], Kodeir [34], and Kelly [35] considered regional and urban influences, and performed analyses using relatively multifaceted indicators rather than research on individual technologies. In contrast, though also targeting the construction industry, Sakthiganesh [36] insisted on the importance of considering the life cycle of a project or technology. Additionally, risk indicators for society as a whole have been widely used in the existing research.

Previous research has targeted existing, well-known technologies and projects. It is possible to judge such technologies and projects in combination with objective information because potential risks are clarified by previous technical knowledge. However, sufficient knowledge and experience are generally lacking for the assessment and decision-making regarding advanced science and technology. Affesa [37] pointed out that the judgments made by people with low knowledge and information might hinder technical discussions and decision-making. Therefore, when comparing advanced sciences and technologies, it is necessary that people with some previous knowledge and experience of the target technology (or some related peripheral technology) perform the comparison. Hierarchic methods have also been applied to advanced science and technology, as well as to future technology forecasts [38,39]. In these previous studies, informative proposals have been put forth by mathematically addressing the uncertainties and ambiguities related to the subjective judgments of experts in the relevant field to contribute to the decision-making process.

Several studies of HESs have been conducted that provide sufficient information and/or experience to the general public or involve experts in related fields. In studies of the general public, researchers have attempted to reduce subjective and sensory reactions by conducting questionnaire surveys after the respondents learned about the characteristics of hydrogen energy or were otherwise provided with sufficient information [40–44]. In contrast, studies involving experts include analyses using environmental, economic, social, and technical indicators focusing on hydrogen production [45] as well as financing costs [46]. The research in this area has mainly focused on the social (economic and policy) impact of hydrogen production. Therefore, there remains a need to promote more comprehensive and systematic research on the risks and impacts of advanced science and technology, taking into account both individual quality of life and the well-being of society.

The objective of this study was therefore to establish a comprehensive method to identify the risks associated with the implementation of an advanced science and technology. To do so in this paper, we clearly define the risks and scope of value impacts and use a hierarchical structure, including multiple impact indicators to measure these values in terms of individual and infrastructural well-being through a survey of experts. We then compare the survey results for an HES and a gasoline energy system (GES) and present an adaptation example that identifies high-priority risks to be addressed when introducing an HES.

Methods

Overview of this research

The method used in this study consists of the five steps shown in Fig. 1: 1. Set values to compare, 2. Create a hierarchy structure, 3. Create a questionnaire, 4. Conduct a survey, and 5. Perform analyses using the analytical hierarchy process (AHP). Note also that a trial survey was first conducted to ensure useful main survey results.

This research adopted the perspective of comprehensive social risk illustrated in Fig. 2 to systematically identify the risks that the implementation of an advanced science and technology with limited knowledge and experience brings to society as a whole, and then stratify these risks using multifaceted indicators applicable to technological development. The main feature of this research is that it does not focus on the effects associated with the technology, but on how society approaches an advanced science and technology as a whole.

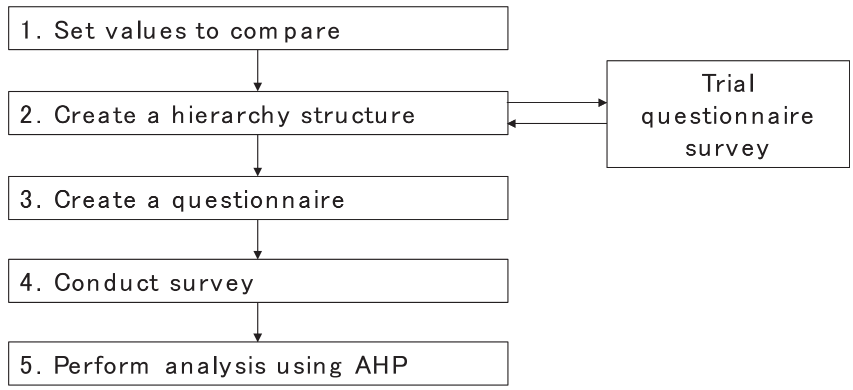

Fig. 1 – Flow chart of relative risk identification for advanced science and technology.

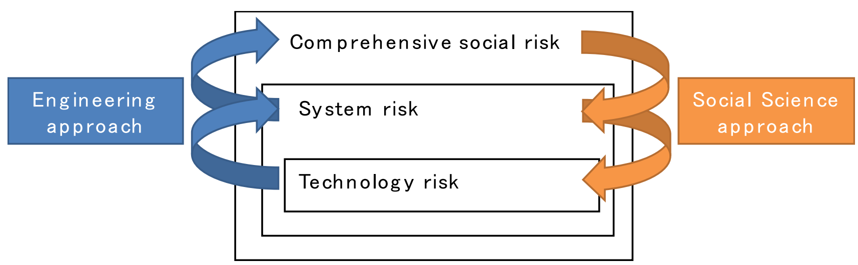

Fig. 2 – Concept of risk identification applied in this study.

Therefore, risk was defined in this study as "the effect of uncertainty on objectives" in accordance with the risk management guidelines of ISO 31000. This effect includes both positive and negative aspects [47].

Setting values to compare

The structure of the individual and infrastructural well-being hierarchy used to identify the risks incurred by advanced science and technology is shown in Fig. 3. This hierarchy was created and applied with reference to Kinehara et al. [48], Noguchi [49], and Hienuki et al. [50], and was divided into these two categories according to the extent to which each value can be affected by government decision-making. Individual well-being is largely dependent on infrastructural well-being and is a basic element of individual happiness. Infrastructural well-being is based on the basic framework of a social system that supports the lives of individual residents,

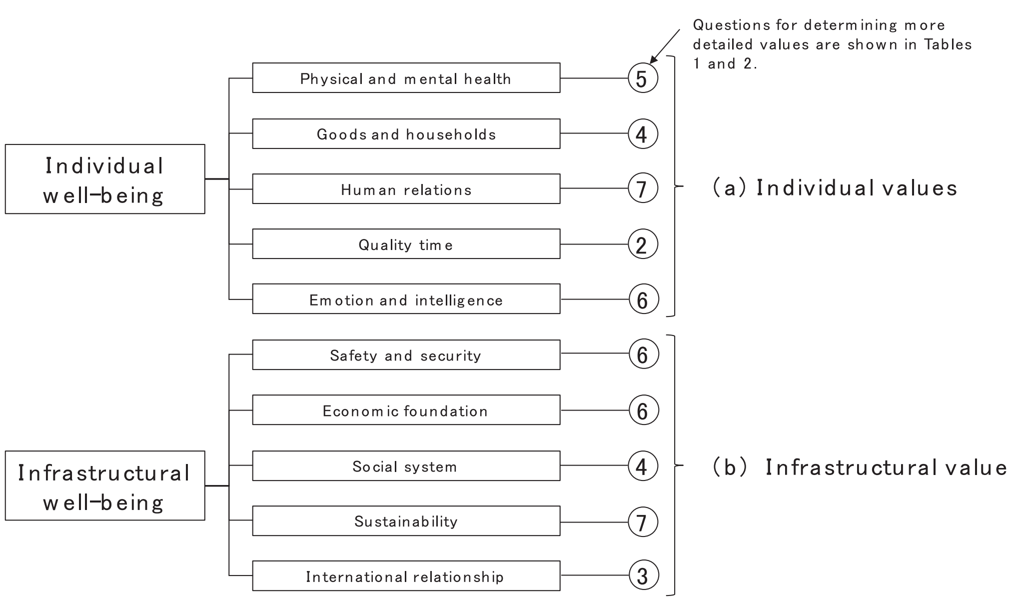

Fig. 3 – Value structure associated with individual and infrastructural well-being.

such as that provided by a country or a municipality. Individual well-being was evaluated on the basis of five values: physical and mental health, goods and households, human relations, quality time, and emotions and intelligence. Infrastructural well-being was also evaluated on the basis of five values: safety and security, economic foundation, social system, sustainability, and international relationships. The following points from previous studies [48–50] were considered when constructing this model.

- Based on the risk categories discussed at the World Economic Forum [51], five components of individual well-being and five components of infrastructural well-being were defined. Hienuki et al. [50] presented a detailed description of these five individual and five infrastructural values.
- There is a certain level of social infrastructure required to ensure happiness among individuals. This infrastructure should ensure the safety, stability, efficiency, and sustainability of people's lives and economic activities. There are also well-being factors based on the foundations of individual livelihoods that directly affect other factors relating to individual values.
- The distinction between "individual well-being" and "infrastructural well-being" is based on whether individuals can participate in decision-making (when government involvement is strong). If individuals can participate in decision-making, the value is considered to be associated with individual well-being.
- Individual well-being is dependent on social well-being and other basic elements that constitute the feeling of well-being for individuals. Specifically, individual well-being is achieved by living a life with close connections to individuals and family, acquaintances and friends, neighborhoods and organizations to which one belongs, as well as society in general.

To examine the values for science and technology in more detail, a joint research project was conducted between the Mitsubishi Research Institute and Yokohama National University-Risk Symbiosis Society Creation Center. Based on the results of this research, the five values of individual well-being and Infrastructural well-being were further divided into 24 values (Table 1) and 26 values (Table 2), respectively.

Questionnaire survey

A trial survey was first conducted to verify the validity of the method, followed by the main survey. In both surveys, an expert was asked to judge the provided value system with regard to the relationships between each value item and the implementation of an HES in society. At the same time, that expert was also asked to evaluate a GES to provide a representative example of an existing energy system for comparison.

Trial survey

In the trial survey, the questionnaire consisted of the following two steps:

Table 1 – Details of values for individual well-being.

No.	Values	Assessment examples
Physical and mental health (5)		
a1	I am healthy/I do not have a serious disease	Impact on personal health
a2	I have maintained my physical ability	Maintenance and growth of physical ability
a3	I do not feel stress	Stress during normal times and accidents
a4	I have no mental problems	Impact on mental illness, dementia, etc.
a5	I'm motivated	Individual motivation and satisfaction
Goods and households (4)		
a6	I can choose products and services that suit my taste	Ease of selection of products and services
a7	I live in a comfortable living environment	Comfort and convenience of living environment
a8	I have an income to buy what I want	Impact on personal income
a9	I have enough savings and assets	Impact on personal savings and assets
Human relations (7)		
a10	I have a good relationship with my family and partner	Relationships with family and partners
a11	I have good friendship	Relationships with friends
a12	I can count on others at work	Contribution at work, retention of expertise
a13	I have others that I can rely on at work	Relationships with colleagues and team
a14	I am contributing to society	Sense of individual contribution to society
a15	I am protected by and benefit from society	Improvement of social security and safety net
a16	I feel a sense of unity and belonging	Participation in social activities
Quality time (2)		
a17	I have free time	Sufficient free time
a18	I have time to pursue my hobbies and work	Time to pursue hobbies and work
Emotion and intelligence (6)		
a19	I am moved by the actions and thoughts of others	Heightened interest in humans
a20	I am impressed by science and technology	Created interest in new technologies and products
a21	I am impressed by culture and art	Heightened interest in culture and art
a22	I am moved by natural phenomena	Heightened interest in nature
a23	I improve my knowledge and comprehension and use them to gain information	Heightened interest in quality learning and information
a24	I send out results such as work using my ability	Test skills, motivate work

Table 2 – Details of values for infrastructural well-being.

No.	Values	Assessment examples
Safety and security (6)		
b1	It protects life and living environment in normal social life	Impact on life at time of service provision
b2	It protects social functions in normal social life	Functional continuity when providing service
b3	It protects life and living environment in the event of accident or disaster	Impact on life in times of accident or disaster
b4	It protects social functions in the event of accident or disaster	Functional continuity in times of accident or disaster
b5	It protects life and living environment from terrorism and crime	Impact on life in the event of terrorism or crime
b6	It protects social functions from terrorism and crime	Functional continuity in the event of terrorism or crime
Economic foundation (6)		
b7	It maintains and develops a key industry	Economic ripple effect
		Market size
		Capital investment
b8	It creates and develops new industries	New demand creation effect
		Potentiality
b9	It is inexpensive	Service price
		Raw material price
b10	It provides various products and services	Form of service provision
b11	It will reduce the unemployment rate	Job creation effect
b12	It has a good working environment	Working environment of workers
Social system (4)		
b13	It reflects the will of the people	Implementation of policy in line with the will of the people
b14	It is unfair	Benefit and burden fairness
b15	It is an orderly system	Appropriateness of standards and regulatory system
b16	It is a system that recognizes freedom and diversity	Usage of services, freedom of usage
Sustainability (7)		
b17	It contributes to the maintenance of the climate	Emissions of greenhouse gases
b18	It contributes to the sustainability of the ecosystem	Discharge of harmful substances
b19	It contributes to the maintenance of the living environment	Generation of noise and odor
b20	It contributes to the sustainable securing of necessary and sufficient energy	Energy security
b21	It contributes to the sustainable securing of essential and scarce resources	Degree of dependence on scarce resources
b22	It contributes to appropriate resource and energy prices	Impact on resource and energy prices
b23	It contributes to the sustainability of food and water	Food and water security
International relationships (3)		
b24	It contributes to peace without war	Presence or absence of circumstances that are involved in a dispute and conflict factors
b25	It contributes to international issues	Contribution to international issues
b26	It increases the reputation of this country in the eyes of other countries	Evaluation from other countries

Establish the relationship between technology and individual and infrastructural values: Indicate the presence or absence of a relationship between the advanced technology and existing technology for each value.

- Risk assessment of technology based on the value system: Based on the value of having "related" with either advanced or existing technology, which of the above advanced and existing technologies dominates from the viewpoint of "individual and infrastructural well-being"?
- These responses were compared and evaluated via a five-step evaluation, and respondents were asked to freely describe what kind of risk items were considered with the above evaluation in mind.

In the trial survey, we used the structure shown in Fig. 3 to comprehensively examine the risk posed by an HES from various points of view and to judge whether the answers later obtained from the questionnaire were appropriate. For this evaluation, we selected five experts, defined in Table 3, with specific knowledge of the HES who could evaluate the impact of the system on individual and infrastructural values from multiple perspectives.

Two main improvements were made to the questionnaire based on the results of the trial survey. First, the content of the questionnaire was adjusted to address the distinction between the introductory period and the diffusion period of advanced science and technology. We improved the questionnaire such that it included the following explanatory note: "Please judge from many viewpoints, such as during the introductory or introduction-diffusion period of a technology, at the time of an accident, and during recovery" and "Although there are many perspectives, please evaluate in terms that are considered important for comparison." Although the stage of technological development could be specified as a precondition in the questionnaire, i.e., the early stage of introduction or after a complete transition, it was decided to leave the setting of the precondition to the respondent in order to avoid leading respondents to a particular answer. Second, the questionnaire was re-designed to help efficiently identify risks via supplementary explanations, such as "Specific examples to consider when evaluating risks" and "Risk items listed from an engineering viewpoint." For social science experts, some of the risks listed by the engineering experts were extracted and added as "Risks listed from an engineering perspective." In order to obtain responses to "What kind of phenomenon happens from the viewpoint of an engineering system" and "What kind of influence does it have from the viewpoint of social science," the subjects were separated into the engineering and social sciences fields and asked to complete the relevant survey questions. This was done because, in order to determine the influence of technology from a social point of view, it is necessary to have some knowledge of what kind of phenomenon will occur from an engineering point of view. In the questionnaire, the risk items listed in advance from an engineering point of view were accordingly added as reference information for the social science point of view. The questionnaire used for the main survey reflects these improvements as shown in the outline presented in Appendix A.

Table 3 – Experts targeted in trial survey.

Target		Specialization
Experts (5 persons)	A	Product safety/machine safety
	B	Risk management
	C	Global warming and energy saving technology
	D	Renewable energy
	E	Infrastructure systems

Main survey

Based on the results of the trial survey, the revised main survey was completed by seven experts in the engineering field who "extracted what happens" and six experts in the social sciences who "extracted its impact." In addition, the viewpoints of each stakeholder entity, such as administration, academics, think tanks, suppliers, users, and manufacturers, were widely covered. The experts and their affiliations are defined in Table 4.

The goal of this research was to establish a method that contributes to the identification of various risks associated with the implementation of advanced science and technology. Therefore, to avoid ambiguous judgments (distinguishing between equal or indeterminate) comparing two technologies, the questionnaire was developed to both investigate each value item as well as the relationship between the two technologies. The questionnaires therefore asked the respondents to indicate the presence or absence of a relationship between each value item, make a relative evaluation of the HES and GES based on a 5-point scale (i.e., 1: hydrogen has an advantage, 2: hydrogen has a slight advantage, 3: hydrogen and gasoline are about the same, 4: gasoline has a slight advantage, and 5: gasoline has an advantage), and provide reasons for their responses (when 1 or 5 was selected).

Estimation of relative value

The relative value of each questionnaire item was estimated as shown in Fig. 2 based on the AHP using the responses obtained from the 13 experts in Table 4. The weights between individual and infrastructural well-being and between the component values of well-being, obtained in the second step of the questionnaire, were also analyzed using AHP. The

Table 4 – Experts targeted in main survey.

Target		Affiliation or Specialization
Engineering Experts (7 people)	A	Supplier (Energy supplier)
	B	Supplier (Energy supplier)
	C	Supplier (Energy supplier)
	D	User (Car company)
	E	Maker (Manufacturer)
	F	Government (Fire department)
	G	Academician (Safety engineering)
Social Science Experts (6 people)	H	Government (Security)
	I	Government (Dissemination)
	J	Academician (Environ science)
	K	Academician (Sociology)
	L	Academician (Management)
	M	Research Institute (Consultant)

relative weights between the value categories were calculated by taking the average of all the responses.

The standard scoring system in AHP is called the Saaty scale, which runs 9–(7)–5–(3)–1–(1/3)–1/5–(1/7)–1/9 [52]. However, some problems were pointed out for the weighting by the equally spaced scale, depending on the measurement target and index [53]. To improve these issues, Fuzzy theory, for example, reduced the ambiguity of the respondents' answers [54,55], and the effectiveness of using a non-linear (not equal-spaced) function instead of a linear function (equal space) was indicated [56,57]. In this research, we converted the survey results of pair comparisons on a 5-step scale into scores of 9–3–1–1/3–1/9. The risks of advanced science and technology may be known only in specific disciplines and by specific experts. For example, the broader economic and environmental risks of HESs can be recognized, regardless of expertise, but it is necessary to respect the judgment of experts with knowledge and experience in the development of fuel cells, the assessment of accident damage at hydrogen stations, and the identification of narrow risks, such as peoples' acceptance of risk. Therefore, in this study we adopted a biased scale, instead of an equally spaced scale, to increase the weight of risks we considered important, while respecting each expert's expertise.

Result and discussions

Relative evaluation of hydrogen and gasoline energy systems

The relative results of the 24 individual values (a1–a24) and the 26 infrastructural values (b1–b26) are shown in Fig. 4 for the HES and GES. There are four values for which the HES was judged to be more than twice as disadvantageous as the GES, shown in Table 5. For experts in the engineering field, they were "I have free time (a17)" and "It is inexpensive (b9)," and for experts in the social sciences field, they were "I have no mental problems (a4)" and "It contributes to appropriate resource and energy prices (b22)." Next, we describe the values for which the HES was judged to be more disadvantageous than, but less than twice as disadvantageous as, the GES. According to experts in the engineering field, the HES is relatively disadvantageous based on two values of individual well-being: "I do not feel stress (a3)," "I can choose products and services that suit my taste (a6)"; and eight values of infrastructural well-being: "It protects life and living environment in normal social life (b1)," "It protects social functions in normal social life (b2)," "It protects life and living environment in the event of accidents and disaster (b3)," "It protects social functions in the event of an accident or disaster (b4)," "It maintains and develops a key industry (b7)," "It has a good working environment (b12)," "It reflects the will of the people (b13)," and "It is an orderly system (b15)." However, experts in the social sciences judged that the HES is relatively disadvantageous based on three values of individual well-being: "I do not feel stress (a3)," "I can choose products and services that suit my taste (a6)," and "I live in a comfortable living environment (a7)"; as well as seven values of infrastructural well-being: "It protects life and living environment in normal social life (b1)," "It protects social functions in normal social life (b2)," "It protects life and living environment in the event of accidents and disaster (b3)," "It is inexpensive (b9)," "It has a good working environment (b12)," "It is unfair (b14)," and "It is an orderly system (b15)." The values for which the HES was judged to be relatively advantageous include ten individual

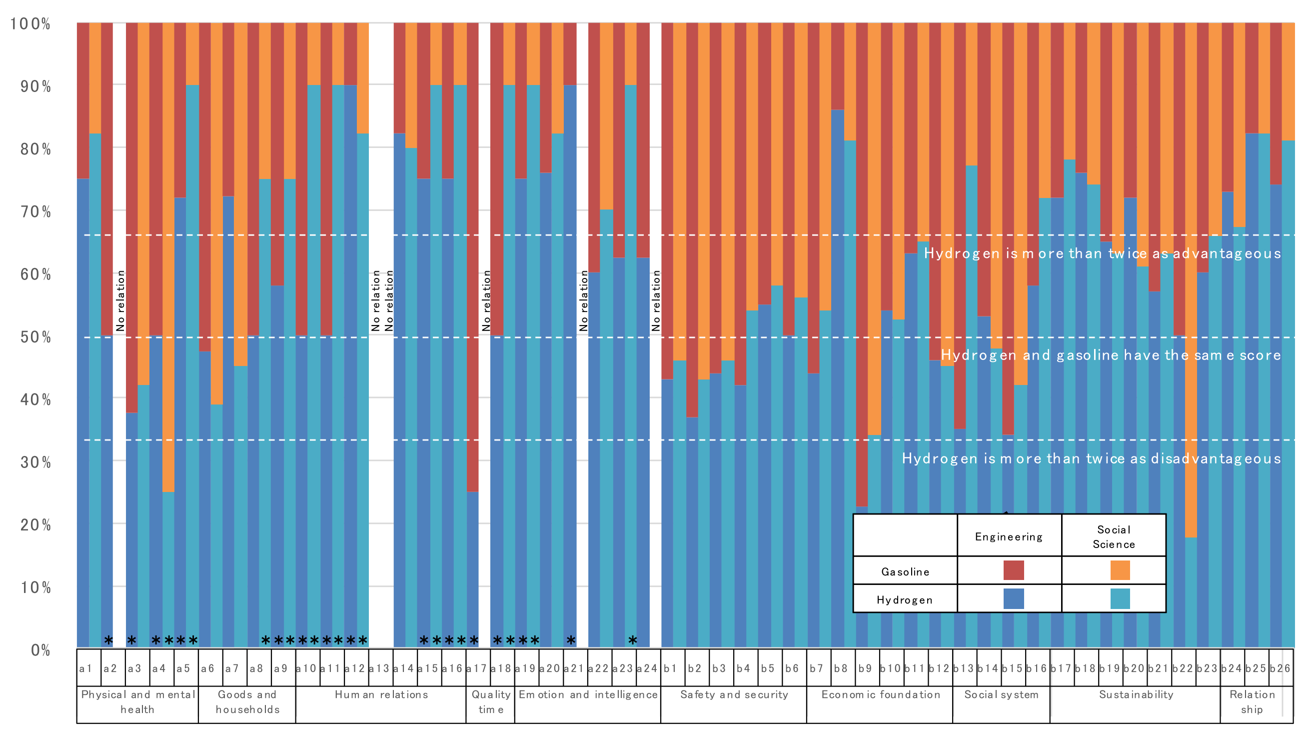

Fig. 4 – Details of relative evaluation values: individual values (a)1–24 and infrastructural values (b)1–26.

Table 5 – Reasons for judgment that the HES is more than twice as disadvantageous as the GES.

	Field (H_2 Score)	Specific risk	
		Hydrogen	Gasoline
I have free time (a17)	Engineering (0.25)	• Less time to care for optimal use of energy	• Creating of free time via efficiency improvement of daily life by using gasoline
It is inexpensive (b9)	Engineering (0.23)	• Suitable infrastructure for HES production and storage Technology development that can reduce costs of transportation, use, and maintenance • It is a problem if it is made from oil • Development of hydrogen production and power generation technology • Impact of manufacturing and transportation costs • High equipment costs • High hydrogen prices • Higher price of hydrogen than gasoline as a provision for reducing environmental impact	• Increase in crude oil prices • Actual results • High cost of drilling in future • Security situation in oil-producing countries • Influence of oil-producing countries • Introduction of carbon tax • Inexpensive in the short term due to the impact of low crude oil prices
I have no mental problems (a4)	Social science (0.25)	• Worried about explosion	- No description-
It contributes to appropriate resource and energy prices (b22)	Social science (0.18)	• Currently expensive (two experts answered) • Price is unclear	• Currently cheap • Low risks compared to current hydrogen regulations

values and seven infrastructural values for engineering experts, and four individual values and eight infrastructural values for social science experts.

These results shows that both categories of experts judged that the HES is more disadvantageous than the GES in terms of price and convenience. Additionally, difficulties associated with workplace and transport handling have not been resolved. Finally, there are psychological effects associated with the threat of an accident or explosion, such as anxiety and stress that a sufficiently safe rational regulatory system has not been established, as well as anxiety associated with an uneven distribution of hydrogen fueling stations, that have not been addressed.

Based on these results, the cost evaluation items of the questionnaire were considered to be quantitative evaluation items, including the supply chain/evaluation of cost reduction possibility, evaluation of increase/decrease in degree of convenience when using the HES, number of hydrogen fueling stations, magnitude of the influence of people's anxiety and stress, etc. Additionally, the results indicate that research into the HES should include clarification and resolution of the problem of HES regulation, as well as the examination and resolution of the problem of instituting a hydrogen taxation system. The risks that need to be considered qualitatively include the impact of the difficulty of transporting hydrogen, the impact of the shale oil spread on the economics of the HES, and unexpected disaster and accident scenarios.

Values with divided opinions between engineering and social science experts

A total of five values were identified for which the opinions of the engineering and social sciences experts were divided according to field. Among them, the values "I live in a comfortable living environment (a7)" and "It is unfair (b14)" were highly rated by the engineering experts, while the values "It protects life and living environment in the event of accident and disaster (b3)," "It maintains and develops a key industry (b7)," and "It reflects the will of the people (b13)" were highly rated by the social science experts. Among these differences, as shown in Table 6, there was a particularly large difference in the judgment for "I live in a comfortable living environment (a7)" and "It reflects the will of the people (b13)." With regard to the former, the experts in the engineering field judged that the HES would have a significant impact on the natural environment, energy efficiency, and living environment. However, the social science experts recognized its superiority in terms of energy efficiency, but based on the relatively small number of hydrogen stations compared to gas stations, they felt that the HES was disadvantageous. This latter feature prompted the engineering experts to mention that the general public does not understand the features of HES correctly, that they are not recognized, that negative information precedes them, and that they offer a smaller number of stations and secured safety. Hence, the number of fueling stations is listed as a risk in this paper. The social sciences experts indicated that the HES is advantageous in terms of reducing environmental impact in addition to being a decentralized energy system, whereas most of the benefits of the GES are monopolized by oil-producing countries and oil companies.

Values with greatly divided opinions among the same field experts

Researchers within the same field provided very different judgments for 17 values. The experts in the engineering filed produced different judgments for three individual (a1, a3, a24) and seven infrastructural values (b7, b10, b11, b12, b14, b16, b21), and the experts in the social science field produced different judgments for one individual (a2) and six infrastructural values (b2, b9, b10, b14, b20, b21). Among these values, the two most extreme responses were obtained for "It

Table 6 – Values for which opinion is divided between specialized fields.

	Field (H_2 Score)	Specific risk	
		Hydrogen	Gasoline
I live in a comfortable living environment (a7)	Engineering (0.72)	• Establish CO2-free technology • Establishment of energy saving, environmental friendliness and convenience • Improved quality of living environment by using fuel cells	- No description-
	Social science (0.45)	• Contribution to zero energy use of housing • Number of hydrogen stations	• Number of gas stations • Whether an environmental impact reduction system will be introduced
It reflects the will of the people (b13)	Engineering (0.35)	• Characteristics of hydrogen are not properly understood by the public • Common information describing negative impacts is rare (same as for nuclear power plant) • Low awareness	• Gasoline stand reduction and ensuring safety
	Social science (0.77)	• Because local production for local consumption is decentralized, it is familiar to people • Expectations for reducing environmental impact • Finally, the market to determine success	• Profit monopoly by crude oil countries and major oil companies • Finally, the market to determine success

maintains and develops a key industry (b7)" among the engineering experts and "It can enjoy various products and services (b10)" among the social science experts. Because the HES score was 0.44 for the former and 0.52 for the latter, the result of the total score from each field is close to an intermediate value (Fig. 3). Table 7 lists the reasons provided for these judgments.

For "It maintains and develops a key industry," one engineering expert judged that the HES has an advantage, two experts judged that the HES has a slight advantage, two experts judged that the GES has a slight advantage, and two experts judged that the GES has an advantage. They indicated that the cost of introduction, operation, and maintenance, environmental and energy problems, oil demand, maturity of the technology, environmental regulation, and technology development were all risks to the implementation of the HES. For "It can enjoy various products and services," two social science experts judged that the HES has an advantage, two experts judged the HES and GES to be about the same, one expert judged that the GES has a slight advantage and another expert judged that the GES has an advantage. These identified risks show that the expected future social image of the HES differs considerably among experts, as there are significant differences in the answers depending on the perspectives of specialized fields and stakeholder positions.

Sensitivity analysis of scale effects

The study used a biased scale to respect the views of experts who gave a clear answer between HES and GES. To verify this effect, we compared the differences between the biased scale and two equally spaced scales (Case 1: 9–5–1–1/5–1/9, Case 2: 5–3–1–1/3–1/5). Table 8 shows the results for items that were answered by at least five experts in one engineering field and that had a difference of 0.05 or more from the biased scale score. All the results of the HES score are described in Appendix B.

Comparing the Bias case and Case 1, the more respondents to the slight advantage of hydrogen, the higher the hydrogen score of Case 1 (a1, a16, b8, b24, b26). Similarly, the more respondents to the slight advantage of gasoline, the lower the hydrogen score (a3, b9, b13). This is because the weight of the slight advantage answer is relatively large compared to the Bias case. Therefore, the biased scale in this study assumes that the weight of the advantage answer is large by making the weight of a slight advantage relatively small.

Next, the results of b8 illustrate that the Bias case showed a score 0.05 higher than that of Case 2; that is, the biased scale treated the hydrogen advantage answer more heavily compared to Case 2. When comparing Case 1 and Case 2 on an equally-spaced scale, Case 1 has a large difference in weight between each answer; hence, if an answer other than About the same is selected, then the superiority of the selected technology tends to increase (b8, b9). Therefore, the greater the weighting between answers, the more the advantages and disadvantages between the two technologies are clearly indicated in the score.

From the above comparison results, it is possible to clearly show the different weightings between technologies by increasing the weights between answers, and to further demonstrate an advantage by using the biased scale. However, care had to be taken when setting the criteria that recognized the differences between the two technologies. For example, we considered items that showed a difference of more than double when comparing HES and GES. This is the case if the score for either technology is greater than 0.66 or less than 0.33. Depending on the scale, there is a possibility that this reference value may be exceeded (not exceeded) (b13).

Research effectiveness for hydrogen energy decision-making

This study identified the risks associated with the implementation of an HES through a qualitative comparison with a GES. The results of the questionnaire-based comparison indicate that the following three points should be discussed when evaluating the social implementation of a HES.

Table 7 – Values for which opinion is divided within each specialized field.

	Field (H_2 Score)	Specific risk	
		Hydrogen	Gasoline
It maintains and develops a key industry (b7)	Engineering (0.44)	• Whether hydrogen infrastructure is established • Development potential • Difficulty of technological development due to cost • Economic problem • Emergence of hydrogen energy alternatives • Slow development of hydrogen energy technology • Hydrogen energy price • A solution to the world energy problem • High-cost equipment • Contribute to development by creating new industries	• Decrease in domestic oil demand • Current and stability performance • Future increase in material and resource costs • Stable supply of crude oil • Environmental regulations (CO2 emissions, etc.) • Development of crude oil mining technology (such as CCS) • Gasoline price • Environment issues • Raw material cost escalation • Underpinning industrial development through conventional stable energy supply
It provides various products and services (b10)	Social science (0.52)	• Using various raw materials • Future diversification of hydrogen-related products • There are few related products • Uncertainty in manufacturing, transportation, and storage costs	• Impact on diversity • Diversity according to characteristics of autos, such as gasoline quality (regular, high-octane) • There are already assets in the petrochemical industry

Table 8 – Differences by scale.

Engineering	H2 score			Number of respondents				
	9-3-1 (Bias case)	9-5-1 (Case1)	5-3-1 (Case 2)	Hydrogen has an advantage	Hydrogen has a slight advantage	About the same	Gasoline has a slight advantage	Gasoline has an advantage
a1	0.75	0.83	0.75		4			
a3	0.38	0.33	0.38			2	2	
a16	0.75	0.83	0.75		4			
b8	0.86	0.88	0.81	5	2			
b9	0.23	0.16	0.24				5	1
b13	0.35	0.30	0.35			2	3	
b24	0.73	0.78	0.72	1	3	1		
b26	0.74	0.80	0.73	1	5	1		

First, we should focus on the score of every emerging science and technology value that is lower than those for the existing science and technology. For the case study in this paper, this relative score indicates the priority of risks to be discussed for the social implementation of the HES. The proposed method can provide information that contributes to decision-making in terms of systematically and comprehensively identifying risks among fields based on limited information. In particular, looking at the stated reasons for judgment in detail will clarify the issues that need to be addressed.

Second, there is a risk associated with values split between the engineering experts and social science experts. Notably, though social scientists tend to make judgments based on the risk information identified by the engineering experts as necessary to understand the technical features of the HES, the two expert groups often produced different results. This quantitatively indicates that opinions differ when making decisions on advanced science and technology from an engineering point of view and a social science point of view, even when the same information is provided.

Third, there is the risk associated with values split between experts in the same field. Engineering experts include suppliers, users, manufacturers, administrators (fire departments), and academics, while social sciences experts include administrators, academics, and think tanks. In other words, these value splits quantitatively demonstrate that judgments differ greatly not only between specialized fields but also according to the perspective of the stakeholders within each field.

By classifying integrated information and opinions using detailed values, it becomes possible to identify hidden risks. Even if one is an educated person with knowledge regarding the HES, there are differences in the judgments used in decision-making because of the complexity of the relationship between science/technology, and society. However, many different stakeholders are involved in energy policy discussions; the results of this study show that it can be very difficult and even unrealistic to fully accommodate multiple opinions in order to satisfy all stakeholders when making policies and decisions. Unfortunately, all societies must ultimately make decisions. Therefore, we need to understand the decision-making process based on this diversity of opinions.

Challenges associated with the proposed method

The following issues were identified from the results of the survey. First, the interpretation of the questionnaire may differ depending on the respondents. In this regard, a relative evaluation was made depending on the preconceptions of the respondent. For example, when the respondent's judgment was based on "I live in a comfortable living environment (a7)", it was not possible to completely identify how the respondent assumed the comfortable range of living environment. However, it was possible to improve the interpretation of the results using supplemental free-response text provided for each specific risk. In addition, we found in the trial survey that the content of a response changed depending on the spread of the technology when the indirect effect and future scenario response was provided. At this point, more specific and detailed risk items can be determined by conducting additional surveys for specific implementation situations.

Second, the relative evaluation standard was not consistent. The respondents found it difficult to distinguish between "advantage" and "slight advantage", while "somewhat superior" was difficult to understand. Hence, the responses should be made simpler, e.g., "superior," "equal," and "disadvantageous." However, when specific criteria are set, it is still difficult to achieve consistency between the reported values.

Third, our method can be expanded to include more experts and apply improved analytical methods. In this study, we analyzed the answers of seven experts in the engineering field and six experts in the social science field. For a more convincing analysis, the number of experts needs to be increased. Increasing the number of experts involved can reduce the likelihood of overlooking important risks. Furthermore, it is necessary to consider the possibility for improvement by applying the Fuzzy AHP and analytical network process (ANP).

Conclusion

In this study, we created a framework to systematically and comprehensively capture the socially integrated risks associated with the implementation of advanced science and technology and demonstrated its effectiveness by applying it to the adoption of the HES.

The results of a survey questionnaire identified three particularly important risks in implementing an HES: hydrogen is clearly considered inferior to gasoline, there is diverging opinion of values between experts in the engineering and social sciences fields, and there exists disagreement in values among experts in the same field. These three types of risk were regarded as critical to the introduction of the HES.

From the point of view of both the engineering and social sciences experts, there was a considerable difference between the HES and GES in terms of the values related to price and convenience. Additionally, it was indicated that the HES is difficult to handle in terms of workplace, transportation, stress caused by accidents and explosions, and psychological effects such as anxiety and stress, even if accidents do not actually occur. Finally, the failure to institute a rational regulatory system and the inability to address an uneven distribution of hydrogen fueling stations were identified as relatively high risks was well.

The HES case study conducted in this research indicated that it is possible to contribute to the identification of important and high-priority risks by adopting the proposed comprehensive social risk approach when making decisions on the introduction of an advanced science and technology. It is important to systematically identify such risks from a macro perspective, regardless of whether they are quantitative, qualitative, or analytically possible. Thus, the problems associated with the implementation of advanced science and technology and caused by unexpected accidents and disasters should be the focus of significant continuing research efforts.

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Appendix A

Table A1 – Outline of questionnaire

Values	Assessment example	Risk examples cited from an engineering point of view (Described only on social sciences expert questionnaires)	Relationship between value and technology		Risk relative assessment					Specific risk	
					※ Check the option close to your idea. Leave it blank if evaluation is difficult						
			Hydrogen	Gasoline	1. Hydrogen has an advantage	2. Hydrogen has a slight advantage	3. About the same	4. Gasoline has a slight advantage	5. Gasoline has an advantage	Hydrogen	Gasoline

Appendix B

Table A2 – Hydrogen score for each scale

	Engineering			Social science		
	9-3-1 (Bias case)	9-5-1 (Case1)	5-3-1 (Case2)	9-3-1 (Bias case)	9-5-1 (Case1)	5-3-1 (Case2)
a1	0.75	0.83	0.75	0.83	0.87	0.79
a2	0.50	0.50	0.50	–	–	–
a3	0.38	0.33	0.38	0.42	0.39	0.42
a4	0.50	0.50	0.50	0.25	0.17	0.25
a5	0.72	0.74	0.69	0.90	0.90	0.83
a6	0.48	0.49	0.49	0.39	0.41	0.42
a7	0.73	0.77	0.71	0.45	0.48	0.47
a8	0.50	0.50	0.50	0.75	0.83	0.75
a9	0.58	0.61	0.58	0.75	0.83	0.75
a10	0.50	0.50	0.50	0.90	0.90	0.83
a11	0.50	0.50	0.50	0.90	0.90	0.83
a12	0.90	0.90	0.83	0.83	0.87	0.79
a13	–	–	–	–	–	–
a14	0.83	0.87	0.79	0.80	0.80	0.75
a15	0.75	0.83	0.75	0.90	0.90	0.83
a16	0.75	0.83	0.75	0.90	0.90	0.83
a17	0.25	0.17	0.25	–	–	–
a18	0.50	0.50	0.50	0.90	0.90	0.83
a19	0.75	0.83	0.75	0.90	0.90	0.83
a20	0.76	0.80	0.74	0.83	0.87	0.79
a21	0.90	0.90	0.83	–	–	–
a22	0.60	0.63	0.60	0.70	0.70	0.67
a23	0.63	0.67	0.63	0.90	0.90	0.83
a24	0.63	0.67	0.63	–	–	–
b1	0.43	0.40	0.43	0.46	0.44	0.46
b2	0.37	0.35	0.38	0.43	0.43	0.44
b3	0.44	0.44	0.45	0.46	0.44	0.46
b4	0.42	0.43	0.44	0.54	0.56	0.54
b5	0.55	0.57	0.55	0.58	0.61	0.58
b6	0.50	0.50	0.50	0.56	0.58	0.56
b7	0.44	0.44	0.45	0.54	0.56	0.54
b8	0.86	0.88	0.81	0.81	0.82	0.76
b9	0.23	0.16	0.24	0.34	0.36	0.38
b10	0.54	0.56	0.54	0.53	0.51	0.51
b11	0.63	0.65	0.62	0.65	0.70	0.65
b12	0.46	0.44	0.46	0.45	0.43	0.45
b13	0.35	0.30	0.35	0.77	0.77	0.72
b14	0.53	0.51	0.52	0.48	0.46	0.47
b15	0.34	0.32	0.35	0.42	0.39	0.42
b16	0.58	0.58	0.57	0.72	0.74	0.69
b17	0.72	0.76	0.70	0.78	0.81	0.75
b18	0.76	0.80	0.74	0.74	0.76	0.71
b19	0.65	0.68	0.64	0.63	0.63	0.61
b20	0.72	0.76	0.70	0.61	0.62	0.60
b21	0.57	0.57	0.56	0.63	0.63	0.61
b22	0.50	0.50	0.50	0.18	0.13	0.21
b23	0.60	0.63	0.60	0.66	0.68	0.65
b24	0.73	0.78	0.72	0.68	0.69	0.65
b25	0.83	0.87	0.79	0.83	0.87	0.79
b26	0.74	0.80	0.73	0.81	0.86	0.78

Appendix C. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijhydene.2020.03.234.

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