SOCIAL RISK APPROACH FOR ASSESSING PUBLIC SAFETY OF LARGE-SCALE HYDROGEN SYSTEMS

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ABSTRACT

Social risk is a comprehensive concept that considers not only internal/external physical risks but also risks (which are multiple, varied and diverse) associated with social activity. It should be considered from diverse perspectives and requires a comprehensive evaluation framework that takes into account the synergistic impact of each element on others rather than evaluating each risk individually. Social risk assessment is an approach that is not limited to internal system risk from an engineering perspective but also considers the stakeholders, development stage, and societal readiness and resilience to change. This study aimed to introduce a social risk approach to assess the public safety of large-scale hydrogen systems. Guidelines for comprehensive social risk assessment were developed to conduct appropriate risk assessments for advanced science and technology activities with high uncertainties to predict major impacts on society before an accident occurs and to take measures to mitigate the damage and to ensure good governance are in place to facilitate emergency response and recovery, in addition to preventive measures. In a case study, this approach was applied to a hydrogen refueling station in Japan and risk-based, multidisciplinary approaches were introduced. These approaches can be an effective supporting tool for social implementation with respect to large-scale hydrogen systems, such as liquefied hydrogen storage tanks. The guidelines for social risk assessment of large-scale hydrogen systems are under the International Energy Agency Technology Collaboration Program Hydrogen Safety Task 43. This study presents potential case studies of social risk assessment for large-scale hydrogen systems for future.

Keywords: Social risk, risk assessment, large-scale hydrogen systems, public acceptance

1.0 INTRODUCTION

Large-scale hydrogen energy systems are being deployed in the public sector to achieve a low-carbon sustainable energy society, and several case studies have been conducted globally. In 2023, the Port of Rotterdam will have a hydrogen transport pipeline that will supply companies with imported or produced hydrogen in the port[1]. Norled developed the world's first hydrogen ferry that carries cars and passengers in Norway and demonstrated the transportation of hydrogen between Hjelmeland, Skipavik, and Nesvik in Rogaland in 2021. HySTRA (CO_2-free Hydrogen Energy Supply-chain Technology Research Association) developed a liquefied hydrogen-receiving terminal with a 2,500-kL liquefied hydrogen storage tank in Japan[2].

Since large-scale hydrogen energy systems have a potential impact on the public sector, public acceptance is critical to their deployment. The risks associated with large-scale hydrogen systems are not only limited to safety but can considerably impact the environment, public confidence, and properties.

A risk assessment is an important aspect of hydrogen safety. Conventional safety studies on hydrogen energy systems can be conducted using risk assessment techniques. Jones applied a hazard and operability study to a liquid hydrogen fueling station [3]. The California Energy Commission reported failure mode and effect analysis (FMEA) to identify scenarios due to failure modes in hydrogen energy systems. Matthijsen and Kooi performed a quantitative risk assessment (QRA) with generic data from references[4]. LaChance performed QRA to determine the separation distances for a hydrogen refueling station[5]. Pasman and Rogers used a Bayesian network to compare the risks of compressed and liquefied hydrogen transport and storage[6].

Integrated toolkits for conducting quantitative risk assessments of hydrogen energy systems have been developed to enable the use of these data to support the development and revision of national and international codes and standards. The Hydrogen Risk Assessment Models (HyRAM) is a software toolkit developed by Sandia National Laboratory that provides a basis for conducting quantitative risk assessment for hydrogen infrastructure and transportation systems[7]. HyRAM includes models that have been experimentally validated, and users can conduct risk assessments based on state-of-the-art science and engineering.

Although a wide variety of risks exists in society, each field perceives and responds to individual risks differently. Even within each academic discipline, each specialist conducts research on risks in his/her area, and very few cross-sectional studies have been conducted.

The risks that exist in society are not independent; the relationship is such that if one risk is reduced, another risk is increased. Therefore, some risks must be accepted, and it is necessary to consider risk responses based on a wide variety of potential risks in society.

To examine responses to risk, considering its impact on society, it is necessary to use a definition that is same as that of risk. However, the definition of risk varies from field to field, and the systematic handling of diverse risks in society has not yet been sufficiently optimized.

Our research group created the concept of comprehensive social risk with the aim of supporting the social implementation of advanced science and technology by appropriately addressing various risks in society and proposed a risk assessment that not only evaluates risks within a system from an engineering perspective but also considers the entities involved, the development stage, and the values of society. This study provides an overview of the guidelines for the appropriate implementation of the risk assessment and a case study of its application to a hydrogen station. The guidelines for social risk assessment of large-scale hydrogen systems are under the International Energy Agency Technology Collaboration Program (IEA TCP) Hydrogen Safety Task 43.

2.0 SOCIAL RISK APPROACH

2.1 Definition of social risk

The concept of risk is a man-made concept; therefore, it has been defined in a variety of ways depending on the field and is still actively discussed.

Commonly used risk indicators include individual and societal risks. According to the Center for Chemical Process Safety Glossary, individual risk is an indicator of risk to a person in the vicinity of a hazard, and societal risk is a measure of risk to a group of people. It is generally expressed in terms of the frequency distribution of multiple-casualty events. Societal risk defined by Health and Safety Executive is set out to provide a single measure of the chance of accidents that could harm several people in one go, around onshore non-nuclear major hazard sites. It is defined as the external impact; however, it has not been defined from the perspective of social activities.

This paper defines social risk as a comprehensive risk concept related to safety issues and activities of society, including the impact on life, health, and environment.

In this study, we adopt the definition of risk given by ISO 31000, the international standard for risk management, “the effect of uncertainty on the objective”[8]. Here, an effect is a deviation from what is expected in a positive and/or negative direction, and the key feature is that risk is defined by both positive and negative effects. In the safety field, as defined in ISO/IEC Guide 51, risk is often treated as "the combination of the probability of occurrence of harm and the degree of that harm," dealing only with negative impacts[9]. On the other hand, comprehensive social risk covers impacts related to social activities, in addition to safety-related impacts, making it difficult to take appropriate risk responses simply by examining the impact of each one. It is necessary to consider both positive and negative impacts because activities to reduce one risk may increase the risk of other activities.

The term of "objectives" in the ISO 31000 risk definition considers that risks vary depending on the organization's objectives. Objectives can have different aspects, such as financial, health and safety, and environmental reach objectives, and can be set at different levels, such as strategic, organization-wide, project, product, and process levels. In the case of comprehensive social risk, risks are analyzed and evaluated from diverse perspectives; therefore, it is important to consider that risks vary depending on the objectives.

2.2 Social risk assessment guideline

The guidelines for conducting comprehensive social risk assessments were originally available at Yokohama National University. These guidelines were adapted for the risk assessment of hydrogen refueling stations in Japan. These guidelines are summarized below.

The guidelines feature three categories of entities that require risk assessment: government, business, and citizens. Because the purpose of risk assessment differs for each entity, the risks for assessment also differ.

In advanced science and technology, in which internal and external conditions change before social implementation, appropriate risk assessment is required according to the stage of development. In the planning stage of the social implementation of a technology, the feasibility of introducing the technology to society is assessed, and the impact of the technology if introduced to society is also assessed. In the development stage of elemental technologies, many aspects have not yet been determined, and uncertainty exists in the risk assessment itself.

In the introduction stage where demonstrations are conducted in specific regions or limited areas, studies are conducted with the participation of entities represented by citizens and users. Detailed analyses and evaluations are conducted based on more specific information than that in the planning phase.

In the social diffusion phase (diffusion phase), the impact on society is comprehensively evaluated based on evaluations conducted during the planning and implementation phases. It is also necessary to consider the situation in which the implemented technology declines.

These guidelines are organized into three phases (planning, introduction, and diffusion) according to the stage of social implementation of advanced science and technology, and the items to be considered in the assessment are organized according to each of the abovementioned phases.

2.3 Social risk assessment process

2.3.1 Objective and stakeholders

In setting the objectives, the social goals to be achieved by the technical system are defined. Since risks differ according to the objectives, they change according to the systemic interdependencies of societal aspects linked to goals set for the society. The social goal is the social image that will change depending on the effects and benefits that the entity wishes to obtain by introducing a technological system. To set a social vision, diverse stakeholders must be involved. Social goals should be determined by a process that is acceptable to diverse stakeholders. The stakeholders and affected fields are shown in Fig. 1.

Once the goals are established, the next step is to set the risk criteria. Risk criteria are used as indicators for the risk assessment. The risk criteria vary according to impact area. Before capturing the risk, it is necessary to sort out the affected entities and fields of influence. Comprehensive social risks are broadly classified as "intra-entity impacts" and "extra-entity impacts." The former consists of "human life/health," "property," "livelihood/productive activities," and "human mind," while the latter consists of "natural environment" and "social environment." The "social environment" is subdivided into "politics/institutions," "economy," and "culture/science and technology."

For social/economic risks, if there is an existing science and technology with similar usage patterns, it is often used as the basis for discussion. The introduction of a new science and technology system is considered to have a positive impact in terms of economic ripple effects and job creation and a negative impact in terms of increased social cost burden and decline in existing technology. Similarly, in the case of environmental risks, existing and alternative technologies are often used as a basis, and the risks are often discussed from the perspective of life cycle assessment, including investigation, facility design, manufacturing, construction, operation, and disposal.

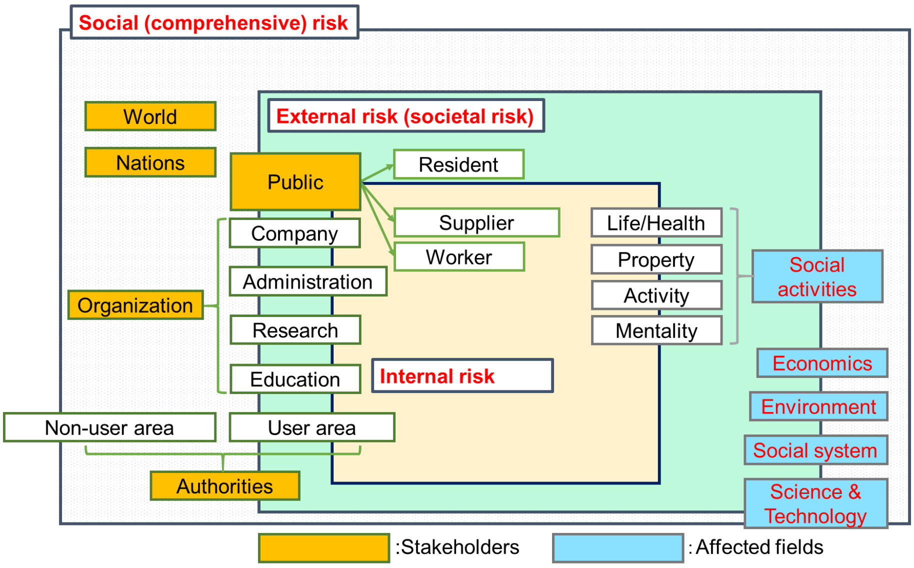


Figure 1. Stakeholders and affected fields based on social comprehensive risk.

2.3.2 Risk identification

In risk identification, risks are extracted based on organized entities and impact areas. Conventional risk identification is mainly by hazard identification; however, in terms of comprehensive social risks, it may be impractical to conduct a detailed analysis because of the time and cost involved. In such cases, risks requiring detailed analysis are identified, prioritized within the scope of limited resources, analyzed, and evaluated, as described ahead. However, when prioritizing, it is necessary to reflect the values of each entity; therefore, it is desirable to involve as many relevant entities as possible in this stage.

2.3.3 Risk analysis

Risk analysis provides the basis for risk assessment and decision making regarding the need for risk response and optimal risk response strategies and methods. When choices involving different types and levels of risk must be made for decision making, risk analysis can provide decision-making material.

A variety of risk analysis methods have been developed, and appropriate techniques can be selected according to the subject matter. For example, techniques suitable for each risk assessment process are listed in IEC 31010 Annex B, and appropriate techniques can be selected by referring to the advantages and disadvantages of each technique[10].

In comprehensive social assessment, because it is necessary to analyze a variety of risks, the difference in the accuracy of analysis is often large. For example, in the case of risks arising from equipment failure, failure rates for each piece of equipment are maintained in a database, and a quantitative analysis of the impact of failure can be conducted using event tree analysis (ETA) and numerical simulation. However, environmental, social, and economic risk analyses are conducted based on limited information and strong assumptions; thus, the granularity of the results is very different from the results of the risk analyses. Therefore, it is important to consider the accuracy of each risk analysis when normalizing the risks of the different impact areas in the comprehensive risk evaluation, as described below.

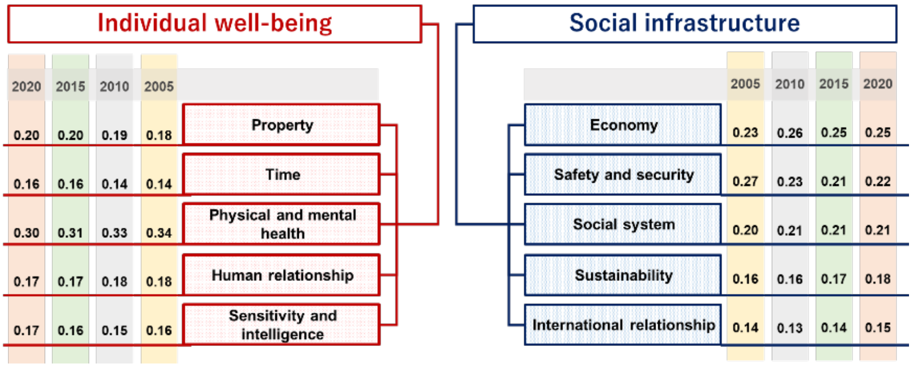
2.3.4 Risk evaluation

Based on the results of the risk analysis, the risk is assessed by estimating the magnitude of the risk and comparing it to the risk criteria. The risk assessment for each impact may be qualitative, semi-quantitative, quantitative, or a combination of these. It often varies according to the impact area. In the case of physical risk, risk is calculated using a combination of the frequency of occurrence and impact used in conventional engineering systems, and a quantitative risk assessment is performed using a risk matrix or other judgmental quantitative assessment or quantitative risk assessment that precisely calculates the frequency of occurrence and impact.

Analysis of environmental, social, and economic risks often involves a bird's-eye view evaluation from the perspective of the impact on society. The evaluation criteria include comparisons with existing science and technology of similar uses. In many cases, risks are evaluated using social surveys and interviews with experts, and the evaluation remains qualitative.

In this assessment, which analyzes and evaluates diverse impacts, a comprehensive evaluation framework that considers each other's impacts is necessary, rather than evaluating each impact area separately. Multiple risk criteria are required by society, and a system that satisfies one indicator but not another is unacceptable.

It is not easy to normalize and evaluate multiple risks in a comparable manner. As an example of a comprehensive evaluation method, this guideline uses the method of setting weights based on values in society. The method of setting weights and handling multiple risk criteria is adopted as a multi-criteria analysis in the latest international standard for risk assessment techniques IEC31010[10]. The weights are set by quantifying social values using the hierarchical analysis method and are used as risk weights. The Center for the Creation of Symbiosis Society with Risks conducts a questionnaire survey on affluence every five years. The questionnaire survey, which broadly classifies the components of affluence into individual life and social infrastructure, is conducted for each of the subdivided items, takes into account factors such as population distribution and generation, and calculates weight coefficients using the hierarchical analysis method. The survey is conducted every five years, and the authors used the hierarchical analysis method to calculate the weight coefficients, as shown in Fig. 2[11].



2020	2015	2010	2005	
0.20	0.20	0.19	0.18	Property
0.16	0.16	0.14	0.14	Time
0.30	0.31	0.33	0.34	Physical and mental health
0.17	0.17	0.18	0.18	Human relationship
0.17	0.16	0.15	0.16	Sensitivity and intelligence

	2005	2010	2015	2020
Economy	0.23	0.26	0.25	0.25
Safety and security	0.27	0.23	0.21	0.22
Social system	0.20	0.21	0.21	0.21
Sustainability	0.16	0.16	0.17	0.18
International relationship	0.14	0.13	0.14	0.15

Figure 2. Survey of social value in Japan. Coefficients were calculated by the analytic hierarchy process. Data for 2005 and 2010 were obtained from MRI report (2010).

3.0 CASE STUDIES OF SOCIAL RISK APPROACH TO HYDROGEN ENERGY SYSTEMS

3.1 Hydrogen refueling station in Japan

We adopted the social risk assessment approach for hydrogen refueling stations in Japan. A comprehensive social risk assessment of hydrogen and gasoline refueling stations was performed from the perspective of social risk. Individual detailed risk assessment results were obtained from the literature[12].

First, in accordance with the guidelines described above, the entities were divided into five broad categories: “individuals/households,” “organizations,” “communities,” “countries,” and “the world,” with “individuals” subdivided into “neighborhood residents,” “users (drivers),” and “employees.” The characteristics of hydrogen stations were reflected by subdividing “organizations” into “operators,” “government,” and “research/educational institutions,” and “regions” into “system deployment regions” and “non-system deployment regions.”

In addition to “human life/health,” “property,” “activities,” and “human mind,” “natural environment,” “politics/institutions,” “economy,” and “culture/science/technology” were set as the areas of influence. Fig. 1 can be used for the relationship between the entities and the impact areas at the hydrogen stations.

In addition to interviews with experts and a questionnaire survey of citizens, the results of the survey (Fig. 2) on lifestyles and affluence conducted by the Center for the Creation of a Society at Risk and Symbiosis were used to reflect the values of society as a whole in risk identification. Physical risks strongly related to “life/health,” “property,” “activity,” and “human mind,” as well as risks related to the environment, economy, and social systems, were identified as high-priority analysis targets.

The results of the risk assessment of an organic hydride hydrogen stand are shown as an example of the results of the physical risk analysis. The stand model is based on a model we conducted in the past[12]. The analysis first used a Hazard Identification Study, a risk identification method based on guide words, to identify significant impact scenarios. This qualitative evaluation method can identify not only risks within the stand but also risks outside the stand by incorporating external hazards into the guide words. In addition, by comparing the results with and without safety measures, it is possible to verify the effectiveness of current safety measures. The 648 scenarios identified were organized in a matrix of the frequency of occurrence and degree of impact, and it was confirmed that the current method is sufficient to reduce risk. The twenty-one scenarios with a frequency of occurrence of 4 (sufficiently likely to occur) and a severity of impact of 4 (serious hazard) under the current safety measures were all natural disaster-derived scenarios. The extracted severe impact scenarios were subjected to a detailed risk analysis during the introduction/implementation phase. It is desirable to conduct a detailed analysis of the risks associated with large-scale disasters, including social losses, since the assessment should not be limited to disaster prevention measures but should also include post-disaster recovery.

In the comprehensive assessment, in addition to the results of the physical risk analysis, the results of the risk analysis on the environment, economy, and social systems, which were identified as items requiring critical analysis, should be integrated. For hydrogen stations that are not yet sufficiently widespread, it is difficult to make an absolute assessment of risk; therefore, the assessment was made by that have already been accepted.

The results of the trial-integrated assessment of hydrogen stations and existing gas stations are shown in Fig. 3. The overall evaluation value was calculated by multiplying the value-based weights for each of the environmental, economic, convenience, and safety factors, as well as the physical risk factors, by the relationship between the value factors.

Notably, the overall evaluation value is only a calculation result based on a trial run and can vary greatly depending on the selection of items to be evaluated, the assumptions used in the evaluation of individual items, the evaluation method, and the setting of evaluation criteria.

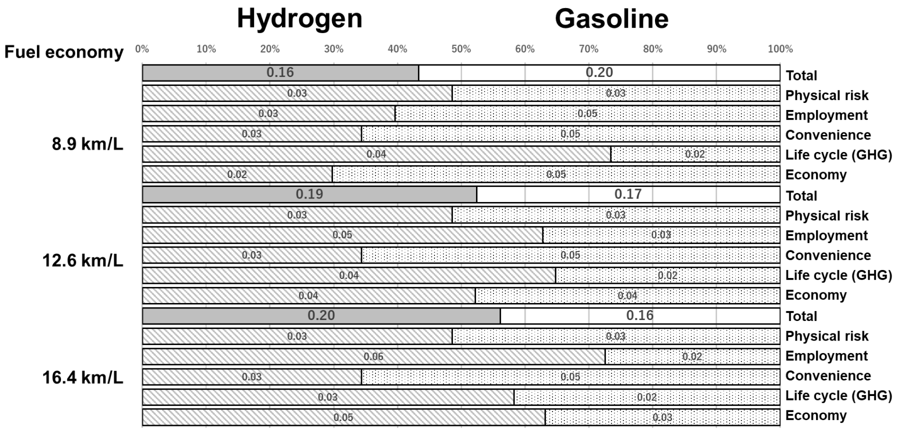


Figure 3. Comparison between hydrogen and gasoline refueling stations in Japan based on social risk assessment approach.

3.2 SUSHy Project

Despite scientific breakthroughs and public policy efforts over the last decade to promote the widespread deployment of emergent hydrogen technologies, significant challenges remain. Beyond the complex technical processes involved in the production and distribution of hydrogen, there are a host of socioeconomic aspects that dictate the safe and sustainable use of these technologies. These challenges are multidimensional in nature, and research data are often scarce. Therefore, international and cross-disciplinary collaboration with a view toward a holistic risk approach is key to addressing them comprehensively and effectively.

The project titled "SUStainability and cost-reduction of Hydrogen stations through risk-based, multidisciplinary approaches" (SUSHy Project) builds upon the social risk approach and emphasizes its relevance in the context of hydrogen safety. SUSHy Project (2022) is an ongoing European-Japanese research project, which was launched last spring and funded through the European Interest Group CONCERT-Japan platform. This project advances the current state-of-the-art hydrogen technologies by contributing toward improving aspects of their efficiency, reliability, and cost-effectiveness. In brief, the SUSHy Project aims to develop an interdisciplinary, integrated, and risk-based approach to ensure safe operation, encourage public technology acceptance, and improve the economic viability of financial ventures related to hydrogen production and fueling stations. The systemic analysis of hybrid renewable-energy-powered (HREP) hydrogen production and fueling facilities is at the core of this project, particularly considering the aspects of accident risk reduction, occupational safety, and process management and optimization.

The idea for the SUSHy Project was conceived to address the following methodological issues. On the one hand, for hydrogen to be a genuinely sustainable alternative fuel, it is essential to make it safe and reliably accessible by addressing the technical and financial uncertainties caused by the integration of hybrid renewable-energy resources in its production process. On the other hand, it is equally important to understand how people experience this emerging energy transition while promoting the widespread adoption of hydrogen technologies. This would mean going beyond the traditional scope of risk reduction for industries, which concerns operational safety measures and reliable prevention and management mechanisms, to further include the social sphere, considering community perceptions of hydrogen fueling technologies and disaster preparedness. Acknowledging this need, the SUSHy Project aims to develop a new, interdisciplinary, risk-based philosophy and framework that integrates our current understanding, analysis, and reduction methods for various types of risks related to clean hydrogen technologies.

The SUSHy Project's research team has two innovative pursuits. The first objective is to propose and develop a novel, risk-based, multidisciplinary approach (RMDA) that can assist decision makers in identifying and minimizing the technical, financial, and safety uncertainties associated with HREP hydrogen technologies. Second, by employing pioneering state-of-the-art tools, the intent is to improve the efficiency of HREP hydrogen production and fueling stations and facilitate their widespread implementation for commercial use. To develop the abovementioned RMDA framework, the project initially involves selecting, verifying, and integrating existing fragmented methodologies for uncertainty and risk identification, analysis, and evaluation and then builds upon this approach with new knowledge related to hazardous scenario building, influencing risk factors, and accident prevention and mitigation measures for hydrogen safety. Overall, the design of the RMDA framework incorporates seamless technical expertise and operational, societal, and financial analyses to evaluate and enable similar hydrogen technologies and projects.

The SUSHy Project has five key tasks to achieve this goal. The first task entails the development of a methodological framework to identify and analyze typical and atypical accident scenarios involving uncontrolled releases of hydrogen, with a particular focus on those that directly endanger neighboring communities and the environment. The next task is reviewing valuable lessons from related past accidents and cataloguing best safety practices, regulations, and rules in different socioeconomic contexts to help define key performance indicators in a standardized way that is useful for benchmarking and progress monitoring. Task three involves modeling scenarios (from task one), using a probabilistic digital twin approach to analyze the effectiveness and performance of protection and emergency response systems for HREP hydrogen stations (e.g., from detectors, alarms, and automatic shutdown systems to emergency exhaust and fire-extinguishing systems and anti-explosion walls) under the uncertainties involved in various scenarios. Task four explores the level of public acceptance for HREP hydrogen stations, considering aspects of hydrogen technology familiarity, risk perception, perceived benefits, environmental consciousness, mobility behavior, and social interactions, to understand citizen attitudes and delineate effective risk communication strategies. The final task involves evaluating the economic viability of HREP hydrogen stations using artificial intelligence techniques to examine different probabilistic scenarios for hydrogen demand as well as control for unreliability issues stemming from renewable energy sources.

The comprehensive study scope of the SUSHy Project brings to the forefront the social risk approach and underscores its importance in contemporary risk-reduction research. While—at the time of writing—the project is still in its early research stages, its overall impact upon completion is expected to greatly benefit from incorporating the social risk approach into its design and pursuing such synergies among its objectives. Therefore, it is worth highlighting the expected contribution of SUSHy Project through the lens of social risk.

From an industrial process safety perspective, the outcomes of the project are expected to guide risk-managing authorities to formulate policy concerning critical requirements, procedures, and regulations for hydrogen fueling station siting, operation, and management (e.g., for locations and minimum safety distances to other facilities). Moreover, the proposed framework could enable local communities to conduct a pre-assessment of hydrogen projects to prevent and mitigate risks related to technology, environment, and safety issues. From a management and finance standpoint, the results of the SUSHy Project could provide prospective investors in hydrogen technologies with evidence of the feasibility of new HREP hydrogen station concepts and suggestions to facilitate their implementation. Additionally, the expected research-based standards could assist decision makers in establishing new and adjusting existing compensation policies for the deployment and operation of HREP hydrogen production and fueling stations. The outcomes could also guide new business development entities in building and managing distributed HREP hydrogen technologies and further clarify the roles of engineers and project managers with respect to environmental protection and climate change mitigation. Furthermore, the findings are expected to inform spatial planning and local governance on how to relieve tensions concerning community satisfaction and welfare, quality of life of neighboring residents, local environment, and hydrogen-related project finances. Lastly, it should be noted that these outcomes are expandable and transferable. In other words, findings related to enhancing the cost-effectiveness of HREP hydrogen production and risk reduction measures are not limited to fueling stations for commercial vehicles but can be relevant for other hydrogen applications, such as powering offshore platforms.

4.0 POTENTIAL CASE STUDIES OF LARGE-SCALE HYDROGEN SYSTEMS

This section introduces two potential cases for the social risk assessment of large-scale hydrogen energy systems: a liquefied hydrogen storage tank and hydrogen transport. These cases affect public areas and require societal considerations.

4.1 Liquefied hydrogen storage

To establish the global hydrogen supply chain which imports hydrogen from overseas sources till 2030, LH2 (liquefied hydrogen) will be promising as hydrogen large carrier. This LH2 system, which consists of H2 liquefiers, stationary LH2 tanks, LH2 carriers and etc., would expand to the existing commercial LNG systems.

From a perspective of inventory, a LH2 storage tank is a typical large-scale hydrogen energy system. In Japan, a pilot LH2 storage tank and unloading facilities were constructed at Kobe Port for demonstrating the concept of the global hydrogen chain. The pilot site is located on a 10,000 m^2 area of land in the northeast section of Kobe Airport Island in the Port of Kobe. The capacity and outer diameter of the storage tank are 2,500 m^3 and 19 m, respectively. This tank employs a vacuum perlite thermal-insulation between the outer and inner vessel.

In the future, commercial storage tanks will have a capacity of 50,000 m^3 and a different thermal insulation structure. From the perspective of social risk, the safety distance and social impact on public areas should be studied.

4.2 Hydrogen transportation

Hydrogen transportation system is another large-scale hydrogen energy system from a perspective of distributed area. Hydrogen pipelines are a way to supply companies and the public with hydrogen. Because the pipelines will run in public areas, social risk should be taken into account for public acceptance. A possible way to deploy hydrogen pipeline is to replace pipelines for refinery or natural gas to hydrogen. Hydrogen has been used for refinery and the replacement of pipeline for refinery can be a useful way to build hydrogen pipeline network.

As mentioned earlier, the Port of Rotterdam plans to import 4 million tons of hydrogen annually in 2030 and build a 200 MW electrolysis plant to produce hydrogen. Hydrogen can be transported through a pipeline approximately 40 km in length. A part of pipeline in the port was used for refinery. The social risk can be a point to be considered in the use of refinery pipeline. The refinery pipelines are used in the industrial area and the design and operation of pipeline are also suitable to hydrogen. However, when the pipeline will be extended to public area, social risk assessment should be required.

Another way to deployment of hydrogen pipeline is the replacement of natural gas pipeline. The natural gas pipelines have been distributed in the public area with the social acceptance. Since the physical and chemical properties of hydrogen are different from those of the natural gas, the risk associated with the change should be identified. Material compatibility to hydrogen is a risk factor.

Based on the technical standard of natural gas pipelines, Tokyo plans a hydrogen-powered town in the Harumi area, where hydrogen will be transported through pipelines under public roads and the electricity produced by hydrogen will be supplied to residents.

Another method of transporting hydrogen is on public roads. Linde Gas has a plan to produce and ship hydrogen on public roads from Leuna to Vigraneset, Norway. The transport route includes narrow roads, tunnels, and ferries. Therefore, societal considerations and involvement are required.

5.0 CONCLUSION

This study introduced a social risk-based approach for the deployment of large-scale hydrogen energy systems developed by the subtask of IEA TCP Hydrogen Safety Task 43. Social implementation of large-scale energy systems requires risk management from the perspective of social activities. Risks in society affect each other, so that the reduction of one risk leads to the occurrence of new risks and an increase in other risks. Therefore, it is important to identify, analyze, and evaluate risks from various perspectives. Herein, we present a case study of a large-scale hydrogen energy system, which is necessary to attain a low-carbon society in the future and to create a comprehensive social risk concept to implement such a system in society. Guidelines for comprehensive social risk assessment were developed to conduct appropriate risk assessments for advanced science and technology activities with high uncertainties to predict major impacts on society before an accident occurs and to take measures to mitigate the damage and to ensure good governance are in place to facilitate emergency response and recovery, in addition to preventive measures. These guidelines were adapted for the risk assessment of hydrogen refueling stations in Japan and can be improved and deployed for large-scale hydrogen systems in the future.

6.0 ACKNOWLEDGMENTS

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7.0 REFERENCES

1. Hydrogen economy in Rotterdam (Handout), https://www.portofrotterdam.com/sites/default/files/2021-06/hydrogen-economy-in-rotterdam-handout.pdf.
2. HySTRA, http://www.hystra.or.jp/en/, 20 February 2023.
3. Jones, N., A Schematic Design for a HAZOP study on a Liquid Hydrogen Filling Station, *International Journal of Hydrogen Energy*, **9**, 1984, pp. 115-121.
4. Matthijsen, A. and Kooi, E., Safety distances for hydrogen filling stations, *Journal of Loss Prevention in the Process Industries*, **19**, 2006, pp. 719-723.
5. LaChance, J., Risk-informed separation distances for hydrogen refueling stations, *International Journal of Hydrogen Energy*, **34**, 2009, pp. 5838-5845.
6. Pasman, H. and Rogers, W., Risk assessment by means of Bayesian networks: A comparative study of compressed and liquefied H2 transportation and tank station risks, *International Journal of Hydrogen Energy*, **37**, 2012, pp. 17415-17425.
7. Ehrhart, B. D., Hecht, E. and Groth, K., Hydrogen Risk Assessment Models (HyRAM) (V.3.1) (Technical Reference Manual), Sandia National Laboratories Report No. SAND2021-5812.
8. ISO 31000:2018, Risk management – Guidelines
9. ISO/IEC Guide 51:2014, Safety aspects – Guidelines for their inclusion in standards, 2014.
10. IEC 31010:2019, Risk management – Risk assessment techniques, 2019.
11. Hienuki, S., Noguchi, K., Shibutani, T., Saigo, T. and Miyake, A., The Balance of Individual and Infrastructure Values in Decisions Regarding Advanced Science and Technology, *Sustainability*, **11**, 2019, pp. 3385. https://doi.org/10.3390/su11123385.
12. Nakayama, J., J Sakamoto, J., Kasai, N., Shibutani, T. and Miyake, A., Preliminary hazard identification for qualitative risk assessment on a hybrid gasoline-hydrogen fueling station with an on-site hydrogen production system using organic chemical hydride, *International Journal Hydrogen Energy*, **41**, No. 18, 2016, pp. 7518-7525.