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Towards a Sustainability Framework for Hydrogen Refuelling Stations: a Risk-Based Multidisciplinary Approach

Nicola Paltrinieri[a,*], Toshiyuki Yamamoto[b], Andrzej Rusin[c], Roser Sala[d], Yiliu Liu[a], Hitomi Sato[e], Murat Gokcek[f]

[a]Department of Mechanical and Industrial Engineering, Norwegian University of Science and Technology (NTNU), Trondheim, Norway
[b]Institute of Materials and Systems for Sustainability, Nagoya University, Nagoya, Japan
[c]Silesian University of Technology (SUT), Gliwice, Poland
[d]Socio-Technical Research Centre, Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
[e]Institutes of Innovation for Future Society, Nagoya University, Nagoya, Japan
[f]Department of Mechanical Engineering, Nigde Omer Halisdemir University, Nigde, Turkey
nicola.paltrinieri@ntnu.no

Sustainable hydrogen technology is becoming increasingly important as the world moves towards cleaner and more sustainable sources of energy. Hydrogen is a clean and versatile energy carrier that has the potential to play a critical role in the transition to a low-carbon economy. However, to realize this potential, significant technological advancements are needed in the production, storage, and distribution of hydrogen. To achieve these advancements, a multidisciplinary approach is required that involves technical, organizational, social, and economic factors. Sustainable hydrogen technology development is a complex and multifaceted process that requires the integration of various perspectives and expertise. A framework is needed to bring together these perspectives and develop a common approach to assessing risks and opportunities associated with hydrogen technology. This contribution proposes a framework addressing system modelling and analysis issues in clean hydrogen production and storage, with a focus on uncertainties that can impact social, economic, and environmental sustainability of hydrogen production and refueling facilities. By using risk-based performance and degradation models, the framework helps prevent and mitigate accidents and builds organizational safety culture and procedures while better communicating with the public. The framework also identifies optimal operational modes for increasing the feasibility of hydrogen refueling stations, ultimately leading to the development of more efficient, reliable, and lower-cost hydrogen-based technologies. The development of a common risk-based framework promotes sustainable hydrogen technology and identifies new opportunities for growth and collaboration. The framework is developed collaboratively through an international research network. By integrating multiple perspectives and disciplines, the framework can provide a roadmap for the development of sustainable hydrogen technology and create opportunities for future growth and development in the field.

1. Introduction

Produced through other renewable sources such as solar photovoltaics (PV) and wind, hydrogen not only exemplifies clean energy but also serves as an energy storage medium. However, the sustainability of hydrogen hinges upon its safety and consistent accessibility from both a technological and financial standpoint (Dash et al., 2023). Given its high flammability and the difficulty in containing the smallest molecule, hydrogen presents unique challenges (Ustolin et al., 2020). Hybrid renewable energy resources introduce further complexity. Variability, intermittency, and unpredictability of PV and wind power may compromise the performance and reliability of water electrolysis equipment, thereby affecting the purity of the hydrogen produced (Brauns and Turek, 2020). Accidents may occur due to equipment failure, oxygen contamination, human error, or misleading procedures. Addressing these physical and technological challenges necessitates an understanding of human

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behaviour within this novel context, emphasizing the need for safe operational procedures, reliable organizational structures, and robust safety systems.

Public awareness and cost are additional challenges posed by uncertainties. It is crucial that safety-related incidents are effectively communicated, particularly to the local community. However, non-professionals may adopt an overly cautious stance when confronted with uncertainties. Although the cost of hydrogen refuelling stations (HRFSs) can be mitigated to an extent by grid load balancing and low-cost wind and solar power, unexpected incidents like power outages or local accidents can undermine these cost-saving efforts. Financial analysis must therefore account for unexpected scenarios (Hecht and Pratt, 2017).

To tackle the obstacles hindering the advancement of hydrogen, a comprehensive examination of cutting-edge research directions in hydrogen was undertaken by the International Association for Hydrogen Safety Research Priorities Workshop. This workshop identified risk assessment relating to HRFSs as a top-tier priority. More precisely, the development of risk-based strategies is essential to minimize costly and overly cautious designs while ensuring safety, sustainability, and efficiency (Hong, 2022).

In this study, risk is defined as the uncertainties arising from various factors and the potential adverse outcomes of these uncertainties. A novel risk-based philosophy and framework have been proposed. This framework, which integrates understanding, prevention, and mitigation of various risks, utilizes multidisciplinary approaches to analyse and manage the uncertainties surrounding HRFSs. This approach aims to enhance the feasibility of this innovative solution, thereby making hydrogen energy both sustainable and clean. The focus on HRFSs is due to the significant role they play in the emerging hydrogen economy, serving as crucial infrastructure for hydrogen-powered vehicles. Furthermore, the challenges and complexities associated with the safe, efficient, and sustainable operation of these stations provide a fertile ground for multidisciplinary research and innovation, ultimately contributing to the broader goal of renewable energy transition.

2. Risk-based multidisciplinary approach

This scientific endeavor presents a multi-dimensional framework designed to explore the sustainability of HRFSs, taking into account various critical factors. The framework comprises five interconnected dimensions, namely Risk Understanding, Operational and Organizational Safety, Technical Safety, Community Sustainability, and Economic Sustainability. Each dimension is meticulously constructed to address different aspects of risk, safety, public acceptance, and financial viability related to HRFSs. The fundamental aim of this framework is to navigate the complexities of these stations, thereby promoting their safe and sustainable implementation in the future energy landscape.

2.1 Dimension of Risk Understanding

This dimension is dedicated to the comprehension of risks associated with HRFSs. A systematic approach is designed to identify both typical and atypical accident scenarios that could result in uncontrolled hydrogen releases, with a particular focus on those that pose threats to humans and the surrounding environment (Witkowski et al., 2017). Tasks within this dimension include the identification of the hydrogen system structures, the development of potential scenarios for hazardous uncontrolled hydrogen releases, risk analysis in the operation of hydrogen systems, and the determination of the extent of hazardous zones close to key hydrogen system components.

2.2 Dimension of Operational and Organizational Safety

This dimension aims to prevent risks by identifying key parameters and safety requirements of HRFSs. It proposes the development of new procedures to prevent accidents and ensure safety. The promotion of safe operational control, organizational commitment to safety, lessons learned from past accidents, and identification of best safety practices are integral to this dimension (Badia et al., 2021). Tasks include the analysis of past incidents/accidents, identification of key safety performance indicators, and the establishment of a safety culture.

2.3 Dimension of Technical Safety

In this dimension, technical risk mitigation is addressed. These measures mainly include the emergency response systems at HRFSs, such as leak detectors, automatic shutdown systems, and fire-extinguishing systems, are examined (Qi et al., 2021). A probabilistic digital twin model is developed to analyze the effectiveness and performance of these systems under various uncertainties.

2.4 Dimension of Community Sustainability

This dimension focuses on reducing perceived risks by analyzing public acceptance of HRFSs. It takes into account factors such as public knowledge of hydrogen technology, risk perception, perceived benefits, trust, affect, environmental consciousness or travel behavior. A web-based questionnaire survey is conducted, and the effects of risk information variance are examined for effective risk communication strategies.

2.5 Dimension of Economic Sustainability

This dimension aims to reduce financial risks by evaluating the commercial viability of hydrogen production under competitive conditions. HRFSs will be sized using artificial intelligence techniques, and the system will be economically evaluated considering probabilistic hydrogen load demand and uncertain power of renewable energies. Tasks within this dimension include the evaluation of the renewable power system, estimation of hydrogen production costs, development of sensitivity analysis methods, and optimization algorithms for enhancing economic sustainability (Gökçek and Kale, 2018a, 2018b).

2.6 Overall structure

As shown in Figure 1, the dimension of Community Sustainability is pivotal for the framework as it is assumed to be a central aspect for HRFS technology success (Huétink et al., 2010). Operational and organizational safety and Technical Safety have also implications on all the other dimensions, given the dynamics of safety and production models (Boukas and Kontogiannis, 2019) and the system dependability on operational and organizational safety barriers (Hosseinnia Davatgar et al., 2021). On the other hand, Risk Understanding and Economic Sustainability have not been modelled as directly associated, due to the framework focus and the assumption that understanding risk represents the starting point of the approach, while economic sustainability can be considered as one of the beneficial results. However, their indirect influence must not be disregarded (Chen et al., 2021).

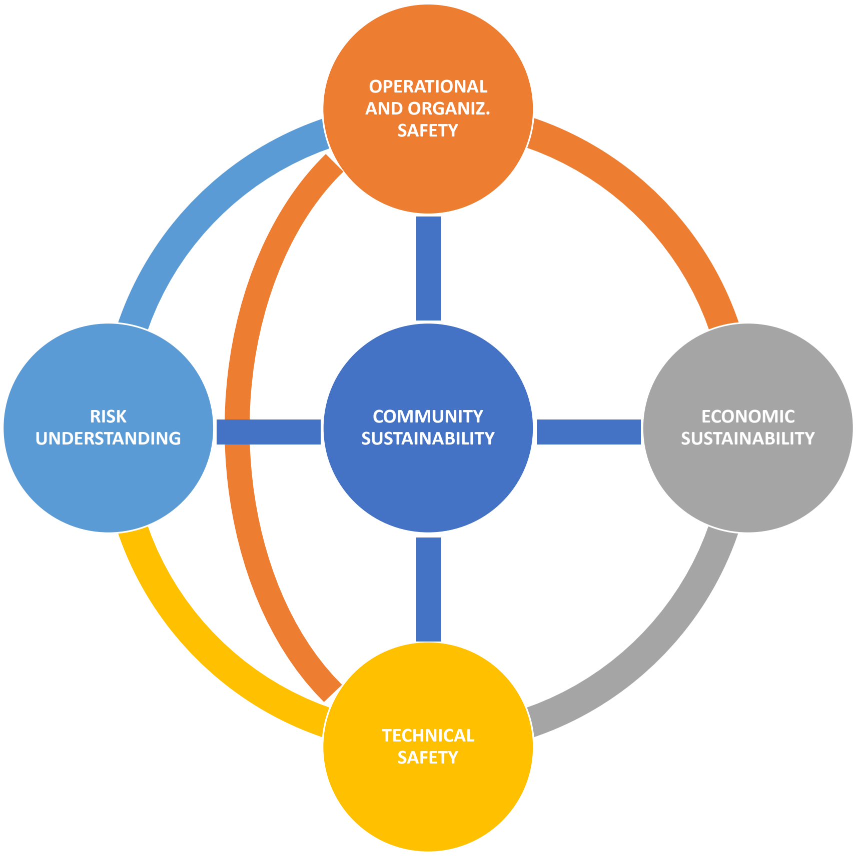

Figure 1 Graphical representation of the five dimensions for HRFS sustainability framework and their interconnections

Each dimension contributes towards sustainability, but the innovative aspect is its risk-based multi-disciplinary approach (RMDA), which serves as a decision-making support tool to address uncertainties impeding further implementations of hydrogen. The framework is proposed and developed with a close integration of technology qualification, operational, societal, and financial analysis, to enable, develop, and evaluate hydrogen techniques and projects.

3. Research techniques

The research techniques outlined within the suggested framework incorporate a risk-based philosophy with a multidisciplinary perspective. Risk refers to uncertainties stemming from various factors and potential detrimental consequences to hydrogen facilities, operators, surrounding communities, investors, and both the local and global environment.
Within the Risk Understanding dimension, analytical and numerical methods are applied to comprehend uncertainties. Techniques such as Event Tree Analysis (ETA), Fault Tree Analysis (FTA), Failure Mode and Effects Analysis (FMEA), and Systems Theoretic Process Analysis (STPA) are used to estimate the likelihood of perilous or unexpected events, leveraging statistical data. Consequences of these events, including heat radiation or pressure waves, are assessed through analytical models and commercial software (Ustolin et al., 2020).
Operational and Organizational Safety utilizes relevant databases (Campari et al., 2023) to identify principal operational and organizational factors. The NOMAC (Nuclear Organization and Management Analysis Concept) methodology is used as a reference to identify and prioritize key organizational behaviours in high-risk contexts (Haber et al., 1991). A comprehensive case study must be carried out, applying quantitative and qualitative techniques, including the Organizational Culture Inventory (OCI) questionnaire to draft a conceptual model of safety culture for hydrogen technologies (Cooke and Szumal, 2000).
In the Technical Safety dimension, methods for comprehending uncertainties are combined with barrier engineering, model-based systems engineering, and digital approaches. Software like AltaRica (Prosvirnova et al., 2013) is used for verifying simulations and facilitating near-real-time assessments. A block-diagram approach is developed to evaluate the effectiveness of protective facilities in mitigating domino effects, such as jet fires.
For Community Sustainability, a web-based questionnaire survey is designed and conducted. Data from the survey is used to construct structural equation models for understanding risk perception mechanisms and discrete choice models for HRFS acceptability. An Integrated Choice and Latent Variable (ICLV) model (Ben-Akiva et al., 2002) is further developed to understand the correlation between risk perception and HRFS acceptability. Lastly, an impact analysis predicts changes in acceptability based on changes in specific risk factors.
The Economic Sustainability dimension sizes the renewable power system for the HRFS with deterministic and probabilistic methods, alongside artificial intelligence techniques. The whole system, inclusive of uncertain interactions, undergoes an economic evaluation, considering factors such as uncertain hydrogen load demand and power generation fluctuations of potential renewable energy sources. Tailored optimization algorithms, like Genetic Algorithm or Particle Swarm Algorithm (Eberhart and Shi, 1998), are employed for dynamic risk assessment, prioritizing both accuracy and efficiency.

4. Discussion

The ongoing project "Sustainability development and cost-reduction of hybrid renewable energies powered hydrogen stations by risk-based multidisciplinary approaches" (SUSHy – EIG Concert-Japan platform) plays a crucial role in the development of the sustainability framework for HRFSs. This initiative ushers in noteworthy scientific and societal implications.
Scientifically, the emerging framework is transformative. It cultivates a common language of risk, providing a solution to multi-objective optimization issues, and creates an adaptable blueprint for a myriad of scenarios requiring new technical concept verification. It embodies an exemplar for cross-sector collaborations, merging humanitarian studies and quantitative data. Moreover, it forges a standardized procedure for planning various hydrogen projects and shares critical insights into risk monitoring data collection in HRFS operations.
Each facet of the project carries distinct scientific implications. The risk identification process under the Risk Understanding dimension can be utilized extensively in studies focusing on uncertain factors in complex systems. The Operational and Organizational Safety dimension supports the formation of high-safety organizations in energy industries, while the Technical Safety dimension offers an innovative digital approach beneficial to other renewable energy projects. The Community Sustainability dimension provides an integrated approach to risk management, and the Economic Sustainability dimension delivers a pioneering approach to multiple optimizations under uncertainties.
Societally, the SUSHy project is poised to bring about significant change. It encourages a symbiosis of cost-effective hydrogen production and risk reduction measures, beneficial to various hydrogen applications. It equips investors with substantial evidence of new HRFS concepts' feasibility and recommends improvements. Policymakers gain valuable insights for compensation policies regarding HRFSs, while the multidisciplinary approach also offers direction for the establishment of procedures and regulations related to these stations.

The application of the framework has the potential to guide authorities in formulating relevant regulations for HRFSs, empowering local communities to conduct pre-assessments on hydrogen projects and avoid potential risks. Moreover, it bridges understanding between European and Japanese industries by providing comprehensive information about mutual demands, requirements, and regulations.
In a global context, the developed framework implications extend to several key objectives (United Nations, 2018). They align with the goal of affordable and clean energy, promoting the feasibility of distributed hydrogen production powered by renewable energy sources. This will render hydrogen energy safer, greener, and more cost-effective. It also supports the goal of decent work and economic growth, emphasizing worker safety, fostering a safety culture, and stimulating job creation in the hydrogen industry.
In terms of sustainable cities and communities, the framework emphasizes accident prevention and effective communication about safety and risks, fostering trust in HRFSs within local communities. This initiative contributes to climate action by advocating for hydrogen, especially green hydrogen, as a key solution to reducing carbon emissions.

5. Conclusions

This contribution presents a robust and comprehensive framework that addresses system modelling and analysis challenges in the realm of clean hydrogen production and storage. The framework pays particular attention to the uncertainties that can influence the social, economic, and environmental sustainability of hydrogen production and refuelling facilities.
By utilizing risk-based performance and degradation models, the framework lays the foundation for preventative measures and mitigation strategies against accidents. It further aids in constructing an organizational safety culture and procedures, while enhancing communication with the public. It identifies optimal operational modes, thereby augmenting the feasibility of HRFSs. This, in turn, paves the way for the evolution of more efficient, reliable, and cost-effective hydrogen-based technologies.
Moreover, the development of a common risk-based framework acts as a catalyst for promoting sustainable hydrogen technology, unveiling new horizons for growth and cooperation. This framework, a product of an international research network, is a testament to the power of global collaboration and integration of various perspectives and disciplines.
By providing a roadmap for sustainable hydrogen technology development, this framework not only addresses the current challenges but also fuels future growth and progress in the field. The implications of this work extend beyond the scientific community, potentially influencing policy-making, industry practices, and societal perceptions of renewable energy. Thus, this contribution signals a promising leap forward in our pursuit of a sustainable energy future.

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