Proceedings of the 33rd European Safety and Reliability Conference (ESREL 2023)
Edited by Mário P. Brito, Terje Aven, Piero Baraldi, Marko Čepin and Enrico Zio

doi: 10.3850/978-981-18-8071-1_P492-cd

Task Analysis and Human Error Identification to Improve the Liquid Hydrogen Bunkering Process in the Maritime Sector

Federica Tamburini

Department of Mechanical and Industrial Engineering, NTNU, Norway. Department of Civil, Chemical, Environmental and Materials Engineering, University of Bologna, Italy. E-mail: federica.tamburini9@unibo.it

Fabio Sgarbossa

Department of Mechanical and Industrial Engineering, NTNU, Norway. E-mail: fabio.sgarbossa@ntnu.no

Valerio Cozzani

Department of Civil, Chemical, Environmental and Materials Engineering, University of Bologna, Italy. E-mail: valerio.cozzani@unibo.it

Nicola Paltrinieri

Department of Mechanical and Industrial Engineering, NTNU, Norway. E-mail: nicola.paltrinieri@ntnu.no

Recently, international concern around global warming issue is growing rapidly. Authorities and organizations are implementing strategic tasks towards climate change effects mitigation in different economic areas. Among the various energy solutions, hydrogen has been recognized as a valid alternative to pursue ambitious climate policies. However, hydrogen energy sector is considered as an emerging one. Therefore, the risks that it may pose against specific targets may not be negligible. In the context of maritime shipping, liquid hydrogen (LH_2) adoption is a challenging topic since the little is known stems from a parallelism with the well-established use of liquified natural gas (LNG). The unexplored risks and lack of operational experience associated with such infrastructures entail the need to investigate the LH_2 value chain, focusing on the bunkering unit, given its crucial role in determining the feasibility of the designed system. In this regard, Human Reliability Analysis (HRA) has been applied to the ship-to-ship bunkering configuration with the aim of identifying the most critical stages of the bunkering process and analyzing how the human contribution affects the operations. The findings show that the transfer unit proved to be the most time significant and human failures led to three main consequences: RPT, icing and operational delay. This work will contribute to lay the foundations for a safe and efficient implementation of H_2 technologies in the maritime sector.

Keywords: Liquid hydrogen, Energy transition, Bunkering, Maritime sector, Emerging risk, Human Reliability Analysis, Task Analysis, Human Error Identification.

1. Introduction

Hydrogen (H_2) is increasingly being considered as one of the most promising alternative solutions that allow to decrease carbon dioxide (CO_2) emissions, to face the problem of global warming. Additionally, hydrogen energy systems are also deemed potentially feasible enablers for the transition from the era of fossil fuel energy to the one of renewable energy (Noussan et al., 2021). In this regard, several hydrogen-based national and international strategies are being proposed by authorities and organizations to pursue ambitious mitigative climate change policies. Among the European nations, Norway is proactively working for a low emission society by 2050 (Ministry of Petroleum and Energy Norwegian et al., 2020). The Norwegian Climate Act (*Lov om klimamål (Klimaloven), LOV-2017-06-16-60*) establishes legally enforceable targets stating that Norway's climate gas emissions shall be diminished by 40% by 2030 and by 90-95% by 2050, as compared to emissions in 1990 (Damman et al., 2020).

Currently, the amount of hydrogen produced by Norwegian industrial processes is equal to around 225,000 tons per year (DNV-GL, 2019). This quantity is commonly referred to as grey hydrogen since it is produced from natural gas, or methane, using a process called steam reforming (SR). SR generates significant emissions; thus, grey hydrogen cannot be classified as clean or low carbon hydrogen. Hence, in order to meet the stringent net zero emissions goals advised by the Climate Acts, blue or green hydrogen, considered as free and low carbon solutions respectively, shall be adopted. Blue hydrogen is the one produced coupling steam reforming processes with Carbon dioxide Capture and Sequestration (CCS), instead green hydrogen is the one obtained through electrolysis (Ustolin et al., 2022). Given the considerable CO_2 storage capacity on the Norwegian continental shelf (NPD, 2012) and the extensive experience of Norway with CCS, this country is in a unique position to become one of the major producers of blue hydrogen in the prolonged period of the energy transition towards the full substitution of energy fossil fuels. The bridging role of blue hydrogen is fundamental while renewable energy infrastructure become affordable and sustainable. Based on these considerations, a potential short-term strategy to curb carbon emissions might be converting into blue hydrogen all the grey hydrogen produced in the country up to now, combining the existing production plants with CCS. In this perspective, in the foreseeable future increasingly volumes of hydrogen will be involved in the common steps of the hydrogen value chain, from the production step to the application step. This means that a scale up of the sequential operations of the line will be required.

Focusing on the maritime sector, the hydrogen value chain is characterized by the bunkering unit that plays a fundamental role in the acceptance and development of specific value chain pathways. During bunkering, hydrogen is stored as compressed gas or in liquefied form at cryogenic temperatures (Aziz, 2021). The adoption of liquid hydrogen (LH_2) in the framework of maritime shipping is a challenging topic since the little is known comes from a parallelism with the proven use of liquified natural gas (LNG). A few ongoing projects are currently trying to assess the feasibility of such operations, but some critical points are still an open issue. There is a general lack of operational experience that do not allow to assess the whole performance of the process. Additionally, hydrogen energy sector is deemed as an emerging one. Thus, the hazards related to LH_2 bunkering may comply with the definition of “atypical” scenarios, i.e., accidents that cannot be captured by standard risk analysis processes, and may pose a non-negligible risk with respect to certain targets (Paltrinieri et al., 2014).

Altogether, the potential increase in hydrogen volumes following grey hydrogen conversion into blue hydrogen will lead to a rise in the number of bunkering sites. In turn, this will involve an increase in the number of people potentially exposed to accident scenarios arising from such unexplored infrastructures. With that comes the need to analyze the overall H_2 bunkering unit given its essential role in establishing the viability and flexibility of specific systems. Therefore, in the current article, the potential scaled up bunkering process has been analyzed through Human Reliability Analysis methodologies to identify the critical steps of the whole process and assess how human faults might threaten the operability of the unit. The aim of the present investigation is to highlight how human contributions can negatively affect the execution of the bunkering operations and consequently, how the operational experience can be improved.

In the following, Section 2 presents the characteristics of liquid hydrogen and Section 3 illustrates the bunkering process together with an overview of the current bunkering infrastructure in place. Then, the methodology considered is provided in Section 4 and applied in Section 5 where the results are also extensively discussed. Finally, the study is concluded in Section 6.

2. Background information

2.1 Liquid hydrogen

Hydrogen (H_2) is the most profuse element on Earth, even though it is naturally available in its oxidized state (water) (Griffiths et al., 2021). It is the lightest substance in the universe, with a density of 0.09 kg/m^3 at 0 °C (Preuster et al., 2017). The lower heating value (LHV) associated to its gravimetric energy density is equal to 118.8 MJ/kg, but the volumetric storage density is extremely low. In fact, at ambient conditions it has a value of approximately 3 Wh/L (Aziz, 2021). These characteristics are the reason why it is crucial to identify an effective storage method for hydrogen.

Among all the possible solutions, LH_2 seems to be the most promising one. In fact, at ambient pressure, hydrogen liquifies at a temperature of −253 °C, leading to a significant increase in its gravimetric and volumetric energy densities (Yin and Ju, 2020). In Table 1, the most relevant properties of liquid hydrogen are collected. The main challenge of LH_2 relates to the boil-off gases (BOG). Each storage tank must be vacuum insulated to ensure a very low thermal conductivity (0.001 W/mK) and excellent insulation that avoid losses to boil-off (Aavik, 2022).

2.1 Bunkering

Bunkering is defined as the supplying of fuel for use by ships, including the logistic of loading and distributing the fuel among accessible shipboard tanks. Depending on how the fuel is transferred, different ways of bunkering exist (RH2INE Consortium, 2021). Four main configurations are important to highlight:

- Truck to ship (TTS)
- Ship to ship (STS)
- Bunker station
- Swappable containers

Table 1. Physical properties of liquid hydrogen.

Property	Value	Reference
Density (kg/m^3)	70.9	(Durbin and Malardier-Jugroot, 2013)
Volumetric energy density (kWh/L)	2.36	(Preuster et al., 2017)
Gravimetric energy density (kWh/kg)	33.3	(Preuster et al., 2017)
Heat of vaporization (kJ/kg)	446	(Godula-Jopek et al., 2012)
Heat of ortho- to para- hydrogen (−253 °C) (kJ/kg)	703	(Godula-Jopek et al., 2012)

The TTS configuration, often referred to as micro bunkering, entails the use of a flexible hose with a crane to transfer the fuel from a supplying truck to the receiving ship. Given the lack of a permanent storage container, this bunkering method offers higher flexibility and lower investment costs compared to a banker station. Nevertheless, the truck size limits the bunker volumes, requiring lengthy bunker times. A high level of flexibility can be achieved also by the STS configuration in which the receiving ship is anchored to the bunker ship that acts as a “movable” fuel station. In this case, attaining high bunker rates and large refueling capacities is possible, but with high investments and operating costs. For the bunker station, for which there are no bunker volume restrictions, the same conclusions can be drawn. Ultimately, swappable containers allow to manage the bunkering operation with flexibility, short bunker times and low investment costs. This approach, however, is impractical when dealing with large volumes. To sum up, TTS, STS, and bunker station configurations can be adopted to bunker LH_2 while swappable containers are not recommended for safety reasons such as the risk related to hoisting liquified gas containers (Ustolin et al., 2022). A schematic illustration of the preferrable methods for LH_2 bunkering is reported in Figure 1.

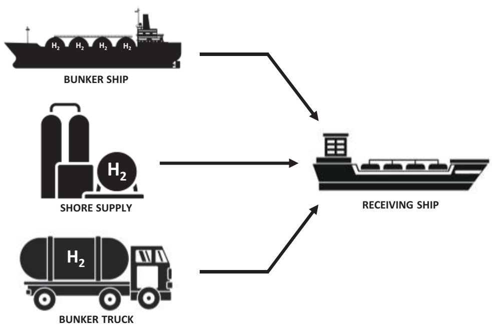

Figure 1. Bunkering methods for LH_2.

LH_2 bunkering requires specific precautions due to the extremely low temperature involved in the operation. Hence, well insulated equipment must be implemented to face the problem of fast vaporization. Additionally, lines must be purged with helium to avoid condensation or solidification once in contact with LH_2 (RH2INE Consortium, 2021).

To transfer LH_2 from the storage tank to the ship, three solutions have been proposed:

- Through a cryogenic pump
- Via pressure differential
- Through a combination of the above

The adoption of cryogenic pumps is the most common solution for STS where large storage volumes are involved. However, pumps can theoretically also be implemented in the TTS and bunker station configurations. Alternatively, the transfer of LH_2 can be done by generating a pressure differential between the two tanks by using vaporizers or combining both the first and second methods listed. These two last strategies intentionally generate BOG (Ustolin et al., 2022).

Nowadays, only two LH_2 bunkering facilities exist worldwide. The first one is in the Port of Hastings (Australia), to load the LH_2 tanker Suiso Frontier built by Kawasaki Heavy Industries (KHI), while the second one is located at the Port of Kobe (Japan), to unload the same ship. The Suiso Frontier has a capacity of 1250 m^3 and can transport 75 tons of LH_2 kept at temperatures of -253 °C. For the next future, KHI is developing a 160,000 m^3 LH_2 hydrogen carrier using 4 tanks of 40,000 m^3 each one (Ustolin et al., 2022).

4. Methodology: Human Reliability Analysis (HRA)

Human reliability analysis (HRA) is a methodical approach for detecting, quantifying, and mitigating the risk associated with human faults in the operation of complex systems (Hou et al., 2021). It has been carried out as a basic step in the probabilistic risk assessment process, which assesses the risk by taking into account all possible incidental scenarios. Fundamentally, human reliability is defined as the probability of successfully completing a task, whereas human errors are the operator behaviors that go beyond the bounds of what is acceptable for the system in which they operate (Porthin et al., 2020).

Since the introduction of the first HRA method, several HRA tools have been proposed for general or specific applications. In the context of the petroleum industry, the Petro-HRA method has been developed (Taylor et al., 2019). This method wants to assess and, if necessary, adapt the Standardized Plant Analysis Risk-Human Reliability Analysis (SPAR-H) methodology by Gertman et al. (2005), against the HRA needs of the petroleum industry. Also, it aims at fully detail the qualitative aspects of the HRA together with the mitigative aspects of the method. The Petro-HRA approach is composed of seven stages: scenario definition, qualitative data collection, task analysis, human error identification, human error modeling, human error quantification and human error reduction. Although the steps follow a linear path, iteration, repetition, and revisitation of some stages is common throughout the whole process (Taylor et al., 2019).

4.1 Task Analysis (TA)

The Task Analysis (TA) is the third step of the HRA. It consists in the description of the single stages that characterize a specific activity from the point of view of the human actions performed as part of a specific step. TA provides a systematic method of organizing information gathered during the previous steps of the HRA with the aim of understanding the sequence of activities that are being analyzed and translating these details into a level of detail suitable for the HRA. The information collected can be displayed through a Hierarchical Task Analysis (HTA) or a Tabular Task Analysis (TTA).

4.2 Human Error Identification (HEI)

The Human Error Identification (HEI) is the fourth step of the HRA. It consists in the identification of potential errors that may arise as a result of man-machine interactions in complex systems and, for each one, recognizing and describing the causes and the likely consequences. Recovery opportunities and performance shaping factors (PSFs) must also be detected because of their probable influence on error probability.

Three of the mostly applied human error identification methods are the Action Error Model Analysis (AEMA), the Human HAZOP and the Systematic Human Error Reduction and Prediction Approach (SHERPA). The first one is known as the "human version" of the Failure Mode and Effects Analysis (FMEA) and can be applied to analyze most categories of actions by relying on knowledge, brainstorming, or guidewords. This last element is used by Human HAZOP as well to pinpoint all the deviations from the intended performance of the various actions and their causes. Instead, SHERPA adopts an error mode taxonomy which the analyst can utilize to define the form of the errors appropriately (Yang et al., 2018).

5. Applied Methodology and Discussion

Given the increasing quantities of hydrogen potentially produced, LH_2 bunkering facilities must be able to manage large volumes while maintaining the entire process safe with a high degree of performance. The bunkering configuration that best handles such quantities is the ship-to-ship (STS) one. Based on these considerations, the STS bunkering method has been selected as a base case for applying the previously described methodology. Attention has been placed on the third and fourth steps of the approach, i.e., the Task Analysis and the Human Error Identification, respectively. In this way, critical tasks have been identified and used as improvement points of the process. Specifically, for what concern the TA stage, HTA has been adopted to define the operational sequence diagram of the STS configuration, instead for the HEI analysis, AEMA has been implemented.

5.1 Task Analysis (TA) application

The second step of the Petro-HRA methodology is the qualitative data collection. Typically, this stage is executed through site visits, interviews and discussions with operators and documentation reviews. In the present article, assumptions based on Petro-HRA theory and expert judgment have been considered to obtain the data for the TA.

The Operational Sequence Diagram (OSD) created while conducting the TA of the entire process highlighted 24 tasks. Three different actors performed those duties: the bunker personnel, the loading arm system

(LAS) operators and the ship personnel. A fourth actor has been considered in the OSD: the walkie talkie. It represents the mean of communication adopted by the bunker operators and is not considered in the task count. Basically, five main groups of tasks have been identified and consist in: precooling operations, loading arm connection and disconnection procedures, inerting and purging processes, transferring operations and, finally, stripping processes. The duration of the different tasks is strongly dependent on two parameters: the bunker volume, varying in the range 200 ÷ 10000 m^3, and the bunker rate, typically in the order of 300 m^3/h (RH2INE Consortium, 2021). Considering these values, a bunkering process may last between 1 and 30 hours.

In the following Gantt chart (Figure 2) the extensions of the tasks aforementioned have been represented qualitatively. In addition, the external operation of cargo has been included. In fact, during STS bunkering, if conditions permit, cargo activities may occur in parallel with loading/unloading actions.

The results underline that the two most time-consuming tasks are the precooling and the transferring operations. Since in the next future an increase in volumes will occur, these two tasks, in particular the transfer one, will certainly be impacted. Specifically, longer time will be contemplated to carry out the operation.

5.2 Human Error Identification (HEI) application

According to the Task Analysis, the impactful operation in terms of time of the STS bunkering procedure is the transfer of LH_2 from the bunker vessel to the ship vessel. This operation consists in the opening of the bunker-side valve to allow for the transfer of LH_2 through the loading arm by bunker personnel after ship staff confirmation of system readiness. Based on that, Action Error Mode Analysis (AEMA) has been applied with the aim of identifying the most critical human errors based on the entity of the consequences. Three latent failure states related to three different issues have been identified and categorized. Specifically, the error of the walkie talkie has been assumed as technical issue, the failure of the bunker-side valve as operative issue and the deterioration of the loading arm as safety issue. The human contribution interests only the technical and operative issues since the loading arm deterioration goes beyond the human input. For the sake of brevity, in the following the AEMA has been descripted and detailed only for the technical issue. Similar reasoning should be done for the operative and the safety ones.

Starting from the condition that the operators act correctly, if a walkie talkie error (e.g., malfunction of the device of communication) occurs, the bunker personnel do not receive the message and the operation is delayed. The same consequence can be obtained due to human mistakes. Indeed, the human error can be seen as an omission, this means that the bunker personnel do not answer to the message sent by the ship personnel, or as a delay, meaning that the bunker operators postponed their response. Likewise, the error can be viewed as "*message sent to another person*", i.e., the ship operators send the message of readiness to the wrong worker. Among all the potential human errors, the only one that leads to a consequence different from the delay of the operation is when the advance condition occurs. In this case, the bunker personnel receive the message of opening the bunker-side valve prematurely. Hence, the purging operation is not still completed and LH_2 may enter in contact with water and freeze it. Lastly, the third different consequence emerged is generated by the safety issue. When LH_2 embrittlement occurs, a leakage or a rupture involves the loading arm and Rapid Phase Transition (RPT) phenomena may occur.

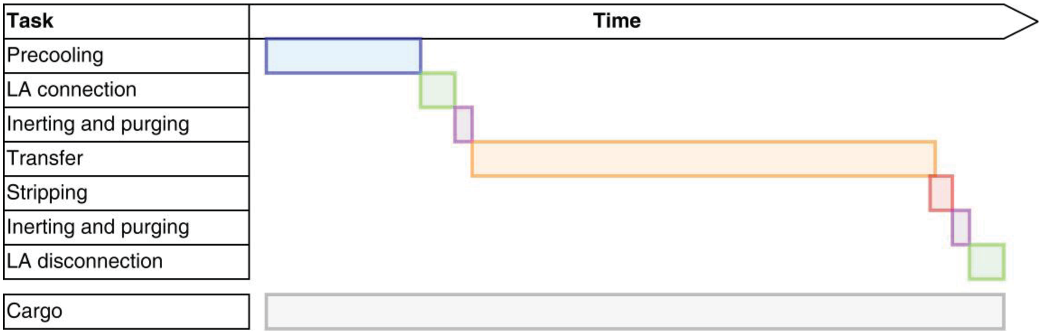

Figure 2. Gantt Chart of STS bunkering operations.

To sum up, from the HEI analysis, three potential consequences have been identified for the LH_2 transfer process:

- Delay of operation
- Icing
- RPT

Future increases in LH_2 volumes will potentially entail an amplification of the identified criticalities (Hydrogen Council, 2022). Larger volumes will result in larger bunkering times and more extensive icing phenomena. These consequences will undoubtedly imply an increase in delays which, in practice, translate into economic losses (Bhonsle, 2022). In addition, increasing quantities will result in greater release rate in case of spill events. In this occurrence, RPT scenarios will be much stronger with a range of action that might be amplified to the point of endangering the health of a huge number of people. In this regard, safety measure should be implemented to face such phenomena. Furthermore, the increase in handled quantities will also impact performance shaping factors (PSFs), such as workload, time pressure and stress. The change in bunkering operation timing will collide with operator shift times and potential errors may occur due to personnel operative stress or work shift change (Swain and Guttmann, 1983).

6. Conclusions

In the current paper, Task Analyses (TA) and Human Error Identification (HEI) methods have been considered to analyze the LH_2 bunkering process with the aim of identifying the most critical stages and investigating how the human contribution influences them. In the end, the entire operation resulted to be composed of 24 tasks and the transfer unit proved to be the most time significant due to its variability in the bunker volumes and bunker rates. For this task, three main consequences have been identified and, from a safety point of view, the most critical turned out to be the RPT phenomenon. On the contrary, from an operational point of view, the phenomenon of icing and the operational delay have been found to be the most significant. In case of occurrence, specific physical and administrative safety barriers should be implemented.

Overall, this work will support to lay the foundations for a safe and efficient implementation of LH_2 technologies in the maritime sector. It paves the way to a future multi-objective analysis aimed at determining the optimized storage capacity and refueling frequency of bunkering facilities, with the objective of keeping the whole operation safe. Furthermore, the work addresses only limited and generic scenarios; thus, it can certainly be improved once the LH_2 bunkering systems will be fully in operation.

References

Aavik, N. J. (2022). Theoretical analysis of pipe flow during liquid hydrogen bunkering. Master's Thesis, Faculty of Technology, Natural Sciences and Maritime Sciences.

Aziz, M. (2021). Liquid Hydrogen: A Review on Liquefaction, Storage, Transportation, and Safety. *Energies, 14, 5917*.

Bhonsle J. (2022). Causes and Consequences Of Vessel Delays in Container Shipping. *Maritime Insight*.

Damman, S., E. Sandberg, E. Rosenberg, P. Pisciella, and U. Johansen (2020). Largescale hydrogen production in Norway – possible transition pathways towards 2050. 1-100.

DNV GL (2019). Production and Use of Hydrogen in Norway. 1-135.

Durbin, D. J. and C. Malardier-Jugroot C. (2013). Review of hydrogen storage techniques for on board vehicle applications. *Int. J. Hydrog. Energy., 38*, 14595-14617.

Gertman, D., H. Blackman, J. Marble, J. Byers, and C. Smith (2005). The SPAR-H Human Reliability Analysis Method. NUREG/CR-6883, U.S. Nuclear Regulator Commission, Washington DC.

Godula-Jopek, A., W. Jehle, J. Wellnitz (2012). *Hydrogen Storage Technologies: New Materials, Transport and Infrastructure*. Wiley-VCH: Weinheim, Germany.

Griffiths, S., B. K. Sovacool, J. Kim, M. Bazilian, and J. M. Uratani (2021). Industrial decarbonization via hydrogen: A critical and systematic review of developments, socio-technical systems and policy options. *Energy Res. Soc. Sci., 80, 102208*.

Hou, L., R. Liu, H. Liu, S. Jiang (2021). Two decades on human reliability analysis: A bibliometric analysis and literature review. *Ann. Nucl. Energy, 151, 107969*, 1-15.

Hydrogen Council (2022). Hydrogen Insights Report: An updated perspective on hydrogen market development and actions required to unlock hydrogen at scale. *McKinsey & Company*.

Ministry of Petroleum and Energy Norwegian and Ministry of Climate and Environment (2020). The Norwegian Government's hydrogen strategy – towards a low emissions society, 1-54.

Noussan M., P. P. Raimondi, R. Scita, and M. Hafner (2021). The Role of Green and Blue Hydrogen in the Energy Transition – A Technological and Geopolitical Perspective. *Sustainability, 13, 298*.

NPD (2012). *CO_2 Storage Atlas Norwegian North Sea*.

Paltrinieri, N., J. Wilday, M. Wardman, and V. Cozzani (2014). Surface installations intended for Carbon Capture and Sequestration: Atypical accident scenarios and their identification. *Process Saf. Environ. Prot., 92*, 93-107.

Porthin, M., M. Liinasuo, and T. Kling (2020). Effects of digitalization of nuclear power plant control rooms on human reliability analysis – A Review. *Reliab. Eng. Syst. Saf., 194, 106415*.

Preuster, P., A. Alekseev, and P. Wasserscheid (2017). Hydrogen Storage Technologies for Future Energy Systems. *Annu. Rev. Chem. Biomol. Eng., 8*, 445-471.

RH2INE Consortium (2021). SuAc 1.1b Hydrogen Bunkering Scenarios. 1-31.

Swain, A. D. and H. E. Guttmann (1983). *Handbook of Human Reliability Analysis With Emphasis on Nuclear Power Plant Applications*. U. S. Nuclear Regulatory Commission.

Taylor, C., S. Øie, and N. Paltrinieri (2017) Human Reliability in the Petroleum Industry: A Case Study of the Petro-HRA Method. *Risk, Reliability and Safety: Innovating Theory and Practice: Proceedings of ESREL 2016*, 1010-1017.

Ustolin, D., A. Campari, and R. Taccani (2022). An Extensive Review of Liquid Hydrogen in Transportation with Focus on the Maritime Sector. *J. Mar. Sci. Eng. 10, 1222*.

Yang, X., I. B. Utne, and C. A. Thieme (2018). A Review of Hazard Identification Techniques for Autonomous Operations in Norwegian Aquaculture. *Probabilistic Safety Assessment and Management PSAM 14*, 16-21.

Yin, L. and Y. Ju (2020). Review on the design and optimization of hydrogen liquefaction processes. *Frontiers in Energy* 14, 530–544.