New knowledge on the safe use of hydrogen on board ships

Our society is faced with climate and environmental challenges in all sectors, and the maritime sector is no exception. In Norway, the ambition is to stimulate green growth in the maritime industry. The Norwegian Maritime Authority (NMA) has taken part in the project "Hydrogen and Fuel Cells for Maritime Applications" (*H2Maritime*) to contribute to research and build new competence on the use of hydrogen and fuel cells in the maritime sector.

Safety issues related to the use of hydrogen are very different from those of conventional fuels and require different safety measures and barriers are required. Operational experience, training materials, operational safety, safety distances and hazardous zones are some of the knowledge gaps.

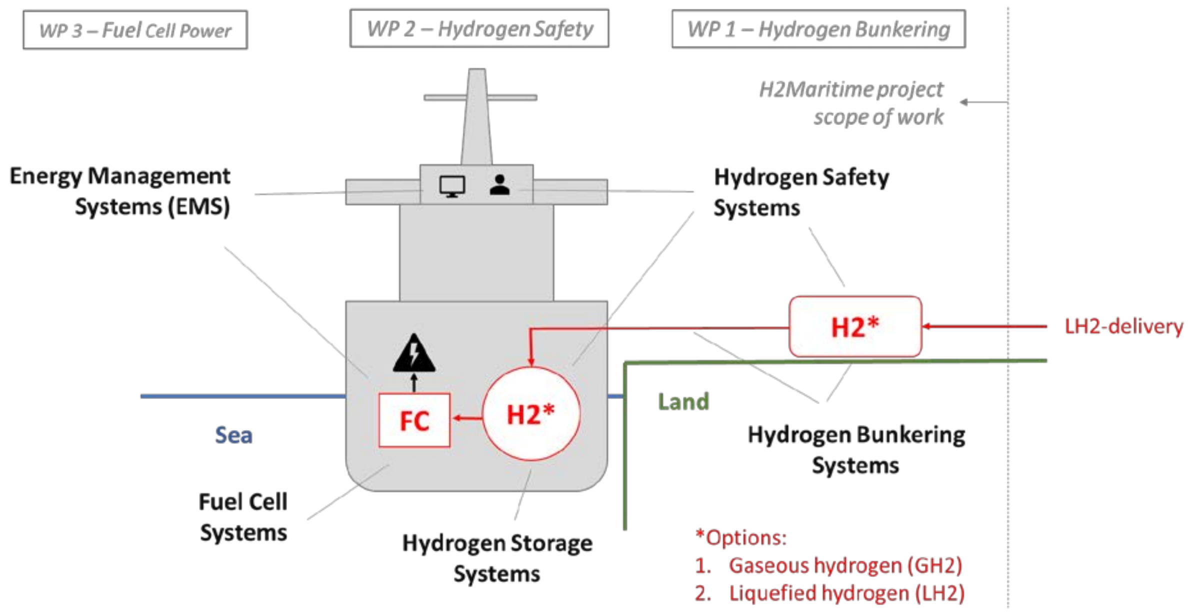
The main objective of the 4-year H2Maritime project (20219–2023) was to establish design criteria and operational philosophies for hydrogen bunkering and storage systems and fuel cell power systems for propulsion.

Institute for Energy Technology (IFE) coordinated and managed the project, which was funded by the Research Council of Norway (80%) and industry partners. Other participants included the Norwegian University of Science and Technology (NTNU), the University of South-East Norway (USN), the Norwegian Maritime Authority (NMA) and the five industry partners Equinor, ABB Marine, HAV Design and Solutions, Umoe Advanced Composites (UAC) and Vysus Group.

The H2Maritime project was organised into three work packages (WPs). New methods, models and simulation tools were developed and used to provide more scientific and technical insight into challenges related to:

- fast refuelling of gaseous hydrogen (GH2) into storage units suitable for small vessels;
- efficient bunkering of liquid hydrogen (LH2) and operation of LH2 storage tanks suitable for larger vessels;
- dimensioning and efficient operation of large maritime hydrogen-based fuel cell systems combined with batteries for propulsion;
- safety issues related to gaseous and liquid hydrogen systems for maritime applications.

Box:
Fast refuelling: > 2000 kg/hour
Gaseous hydrogen into storage units for ships: 250–350 bar
Liquid hydrogen: < –253 °C
Large hydrogen fuel cell systems: 1–10 MW



Hydrogen bunkering and storage (WP 1)

The main research question in WP 1 was: "How should hydrogen refuelling and tank systems for maritime applications be designed, and how can efficient operation of such systems be ensured?" The starting point (system boundary) for the H2Maritime project was the transfer of liquid hydrogen to the bunkering facility. From there, the hydrogen can be transferred to the ship, either in liquid (LH2) or gaseous form (GH2). No maritime bunkering technology, systems or standards and no safety guidelines for the personnel involved existed at the time when the project started.

Three main challenges were identified related to the bunkering and storage of hydrogen. When bunkering large H2 pressure tanks suitable for maritime applications, the challenge is heating of the pressurised hydrogen storage tanks on the ship. In the event of fast H2 fuelling, the temperature in the H2 tank will increase. In composite tanks (fibreglass or carbon fibre) with thermoplastic (HDPE) inner liner, there is a temperature limitation due to the material properties of the thermoplastics. The maximum temperature in composite carbon fibre H2 tanks for passenger cars is 85 °C, while fibre glass-based H2 tanks suitable for maritime applications have a maximum temperature of 65 °C.

When bunkering gaseous hydrogen, the challenges are heat transfer and phase transition in the bunkering facility, which may lead to cavitation during bunkering. Cavitation may occur when the flow rate increases locally, for example, in a pipe reduction or pump, causing the static pressure to drop to such an extent that bubbles start to form. When the flow rate is reduced again, the pressure may increase, causing the gas bubbles to implode. This could result in vibrations and mechanical damage.

Another theory investigated in the project was related to "sloshing" when hydrogen is stored in large LH2 tanks. One possible negative effect caused by sloshing is increased vaporisation and, as a consequence, loss of hydrogen in the tank. A two-dimensional CFD analysis of the sloshing in a LH2 tank was performed in the project, and it was concluded that further research on this topic is not necessary. The sloshing of LH2 is considered to be much less chaotic than other liquids such as LNG (data for sloshing of water was used as reference and comparison to LH2).

More information about the work that has been carried out in WP 1 (selected publications):

- Mathematical models made in MATLAB and ANSYS Fluent:
    - Modelling of temperature calculation in pressurised hydrogen tanks during bunkering, including heat transfer in tank wall (Prasanna Welahettige, Per Morten Hansen, Knut Vågsæther, USN). Contact info: perha@usn.no / knutv@usn.no
    - CFD method developed for hydrogen flow and tank condition during the bunkering of gaseous hydrogen (Netaji Ravikiran Kesana, IFE). Contact info: netk@equinor.com
- Published journal article on flow and hydrogen state in tanks during H2 fuelling. (Netaji Ravikiran Kesana, Prasanna Welahettige, Per Morten Hanse, Øystein Ulleberg, Knut Vågsæther). Link: Modelling of fast fueling of pressurized hydrogen tanks for maritime applications, *International Journal of Hydrogen Energy*

- Vågsæther K., Hansen P.M. (2023) Modelling of LH2-bunkering, Report USN 7300-1700084
- Hansen P.M., Vågsæther K. (2023) Hydrogen process and system models using EES, Report USN 7300-4700113
- Helgesen G. (2023) Heat exchangers for hydrogen tank filling, Report IFE/E-2023/002 Contact info: geir.helgesen@ife.no
- Article on «Explosive phase transition in LH2», presented at ICHS 2021 (Knut Vågsæther, Per Morten Hansen, Dag Bjerketvedt). Link: *Explosive phase transition in LH2*

Hydrogen safety (WP 2)

The main research question in WP 1 was: "How should the systems for the maritime hydrogen bunkering be designed and safely operated?" This work package focused on liquid hydrogen (LH2).

The main results of WP2 are summarised in the IFE report "H2 Safety in Human Operations". A case study on a liquid hydrogen (LH2) bunkering facility was carried out.

Different ships, H2 systems and bunkering methods require different risk approaches. A case study was chosen focusing on the LH2 bunkering of a passenger vessel where the hydrogen storage tank was located above deck was selected.

The method used is part of a CRIOP analysis ("Crisis Intervention and Operability Analysis") and provides an approach to assess weak points (problems/challenges) regarding human factors. The final report provides recommendations on measures and/or barriers for safety in human operation during LH2 bunkering.

In the case study, the scenario analysis focused on human functions, responsibilities, roles, tasks and teamwork during hydrogen refuelling and bunkering operations. By analysing two scenarios, potential hazards were identified, as well as information that should be included in the human system interface (HSI) of the control system. Both scenarios involved a leakage in a hose connection.

In the first scenario, a small leakage developed and spread. In the second scenario, a sudden leakage occurred.

A number (55) of learning points were identified, which can be grouped into the following categories:

- teamwork, task allocation, and communication
- human-system interface (HSI) and situational awareness
- facility design
- system design
- working hours (time of day)
- working environment
- competence and training
- procedures
- emergency response
- bunkering operation

The IFE report suggests measures or barriers related to the findings. One important example from the case study is related to the operator who worked near the LH2 bunkering tower and who was not able to identify the leakage due to obstacles in the line of sight. Here, several measures were recommended. One specific suggestion was to arrange for the operators to carry out monitoring tasks at a safe distance from the bunkering system by using surveillance cameras. A small control room on the quay with access to the control system and monitors for surveillance of the facility is another proposed measure to prevent the operators from losing their attention during the 1-hour bunkering process at night-time, possibly in cold weather or rain.

The case study demonstrated that it is essential to include a human-centred approach to ensure a successful implementation of a maritime H2 bunkering system. This includes focus on the human factors and how to support those who operate the system to succeed. Moreover, the report concludes that it is important to involve the end user representatives in the development and evaluation process. Furthermore, the greatest potential for improvements is at early stages of the system design phase, before changes become too costly.

More information about the work that has been done in WP 2 (selected publications):

- Conference article on how the CRIOP method is used in relation to risk analysis of a case study. The article also discusses whether CRIOP is a useful tool for identifying challenges and potential improvements based on a preliminary/early analysis.
  Lunde-Hanssen, L.S., Ulleberg, Ø. (2022). Safety in human operation during bunkering of liquid hydrogen – Preliminary findings of CRIOP scenario analysis. In Proceedings of the 10th International Seminar on Fire and Explosion Hazards (ISFEH 10, 2022). University of South-Eastern Norway
  Link: https://openarchive.usn.no/usn-xmlui/handle/11250/3030345
- Final report including results from a case study and provides recommendations on measures and/or barriers for safety in human operation during LH2 bunkering (Linda Lunde-Hanssen and Øystein Ulleberg, IFE)
  Lunde-Hanssen, L.S., Ulleberg, Ø. (2023). H2 Safety in Human Operations – and Safety guideline. IFE/E-2023/004. ISBN: 978-82-7017-945-9. Institute for Energy Technology, Halden, Norway.
  Link: https://ife.brage.unit.no/ife-xmlui/handle/11250/3065257

Fuel cells (WP 3)

The main research question in WP 1 was: "How can energy management systems (EMS) for hybrid fuel cell systems be optimised with respect to overall efficient operation and lifetime of the batteries and fuel cells?" One of the objectives was to reduce the implementation costs and, consequently, lower the threshold for adopting the technology. The combination of fuel cells and batteries in hybrid systems is considered to be ideal for maritime applications. The primary objective of this activity (WP 3) was to gain detailed knowledge on the design and operation of 1–10 MW maritime hybrid fuel cell power systems. There are no standards or guidelines for the design and operation of hybrid fuel cell systems for maritime applications. There is also a lack of knowledge on how to optimise the energy management systems and fuel cell system controls in terms of fuel cell lifetime.

The work package was divided into two sub-studies, where NTNU worked on "modelling of power and energy management for fuel cells for maritime applications" and IFE on "experimental validation of fuel cell operation for maritime applications". A PhD-study on the design of hybrid fuel cell/battery systems for maritime vessels was completed at NTNU under the supervision of IFE. It is worth noting that as soon as he had received his doctor's degree, the student was employed as a systems engineer at Teco2030 to develop maritime fuel cells.

IFE has further developed a laboratory setup for performing tests of hydrogen-powered PEM fuel cells of up to 20 kW in hybrid setups with maritime battery systems for testing and developing fuel cell management strategies. PEM is an abbreviation for "Proton Exchange Membrane", and PEM fuel cells are low-temperature fuel cells.

The project has looked at energy efficiency and a cost-effective design. Digital tools have been developed to optimise the dimensioning of fuel cell and battery systems based on the actual operational profile of vessels.

In addition, advanced models of vessel energy systems have been developed to examine the effect of control philosophy for the interaction between fuel cells and batteries in terms of energy efficiency. This is seen in the context of the lifetime of fuel cells and batteries.

More information about the work that has been done in WP 3 (selected publications):

- Balestra L., Yang R., Schjølberg I., Utne I., Ulleberg Ø. (**2021**) Towards Safety Barrier Analysis of Hydrogen Powered Maritime Vessels, International Conference on Ocean, Offshore, and Arctic Engineering (OMAE), in *ASME Transactions*, https://doi.org/10.1115/OMAE2021-60451
- Balestra L., Schjølberg I. (2021) Energy management strategies for a zero-emission hybrid domestic ferry, *International Journal of Hydrogen Energy*, 10.1016/j.ijhydene.2021.09.091
- Balestra L., Schjølberg I. (2021) Modelling and simulation of a zero-emission hybrid power plant for a domestic ferry, *International Journal of Hydrogen Energy*, 10.1016/j.ijhydene.2020.12.187

  Balestra L. (2022) Design of Hybrid Fuel Cell/Battery Systems for Maritime Vessels, PhD thesis, NTNU, https://ntnuopen.ntnu.no/ntnu-xmlui/handle/11250/3028532

Summary

The H2Maritime project has investigated and studied different models and methods have been developed for the bunkering of liquid hydrogen (LH2) and gaseous hydrogen (GH2). The project has provided new insights into how to refuel or bunker hydrogen in a safe and efficient manner and how to design and operate fuel cells for maritime propulsion systems. The methods and simulation tools developed in the project have been applied and validated against experimental data and system designs for real-world use cases. The knowledge gained in the H2Maritime project has been and will continue to be transferred to many maritime applications and industries in Norway.

Detailed simulation tools have been developed for use by the three research partners, the five industry partners and the Norwegian Maritime Authority. Documentation on these simulation tools can upon request be made available from IFE, NTNU, and USN. The results of the H2Maritime project show that cooling of the hydrogen gas may be required for the GH2 bunkering. Fast fuelling of gaseous hydrogen will increase the temperature in the tank, which will be a major challenge if the maximum temperature is to be kept below 65 °C.

The research activities in the H2Maritime project on the fast fuelling of pressurised hydrogen tanks are relevant for several of the latest hydrogen projects currently being developed along the coast of Norway. Several companies have shown interest for the work carried out in the H2 refuelling project. The research activity on hydrogen bunkering systems continues at IFE in the Rail4EARTH project.

Safety strategies must be implemented to ensure safe operation during refuelling and bunkering of hydrogen. Depressurisation of gas during emergency situations must, for instance, ensure the lowest risk possible. The research activities on hydrogen safety in human operations were already implemented in a study (use case) of an actual liquid hydrogen bunkering process for a ship. The knowledge built up on liquid hydrogen storage will also be further pursued in new research projects at IFE and USN.

The research activity on low-temperature PEM (proton exchange membrane) fuel cells systems is highly relevant for several maritime fuel cell systems suppliers and power system integrators in Norway. The research activity on fuel cell systems continues in the MoZEES and HYDROGENi projects. Two key persons from the H2 Maritime project (one from IFE and one from NTNU) have started working in a relevant maritime company (Teco2030).

In autumn last year, the Norwegian government announced a more ambitious goal of reducing emissions by at least 55 percent by 2030. To achieve this goal, several projects have been initiated, in which hydrogen and fuel cells are used on ships. The NMA is involved in several of these projects.

More research is needed in areas addressed by the *H2Maritime* project, both linked to human, technological and organisational aspects.