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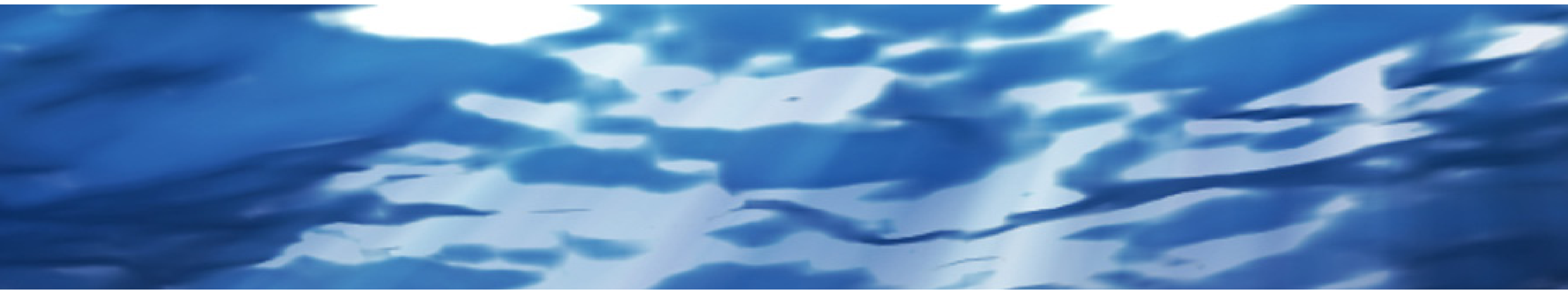

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Safe Hydrogen Installation on-board

A pre-study carried out within the Swedish Transport Administration's industry program Sustainable Shipping, operated by Lighthouse, published February 2022

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Safe Hydrogen Installation on-board

A pre-study focusing on the possibility to create a retrofit installation of a fuel cell propulsion system on-board a vessel

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In cooperation with

A large reference group, described in the report

A pre-study carried out within the Swedish Transport Administration's industry program Sustainable Shipping, operated by Lighthouse

Summary

In the search for a clean sustainable fuel alternative for the maritime sector, hydrogen has gained a lot of interest during the latest years. One key advantage of hydrogen is that it can be produced in a sustainable manner trough renewable energy, and it doesn't emit any greenhouse gases (GHG) when used. However, even if the interest from the industry is increasing and a number of pilot-projects are announced, several barriers to overcome still exist. Primarily the remaining issues are linked to safety regulatory aspects, in summary a need for more knowledge and practical experience of using hydrogen in marine applications.

In this pre-study, the area of using hydrogen for fuel cells on-board a ship is further investigated. The overall object of this study is to contribute to a heightened knowledge regarding the use of hydrogen and in particular aspects related to safety and regulatory issues.

The goal of this study was to start the development of a roadmap for a full-scale installation of a hydrogen-powered fuel cell drivetrain in an existing ship (so-called retrofit installation). To achieve this, the study was built around Ventrafiken's passenger ferry Uraniborg, which operates between Landskrona and Ven in the south of Sweden. By analysing data from the ships power management system and conducting a hazard identification analysis, a potential fuel cell/battery concept was formulated.

The result shows that it is possible through retrofit to install a fuel cell-based propulsion system in combination with batteries, which also are aligned with safety concerns. However, in the case of Uraniborg it would involve extensive alterations on-board, and several areas still exist where further studies are needed before taking on such an endeavour. In summary, the conclusion is that the suggested design is a conceivable concept that could be implemented. But in the case of Uraniborg it would be easier to build a new vessel adapted for hydrogen operation than to make a retrofit. This, due to the alterations that would be needed in the ships interior design in order to store and manage hydrogen in a safe way, for example to keep it separated from areas where personnel are present as well as spaces where electrical installations are present.

In addition to the theoretical concept, the project has also created an industry network for hydrogen in maritime applications with a total of 47 industry members at the time of writing. The network will continue to support the implementation of hydrogen in maritime applications through knowledge sharing and support the creation of new research and development projects, even after the end of this study.

During the project, several areas where identified where further research is needed. E.g.,

- Research regarding different storage options of H2 and connected piping systems. Differences in safety, cost, and operational aspects.

- Further assessment of the bunkering procedure of hydrogen and the associated safety aspects.
- Full-scale pilot installations and assessments of real hydrogen projects in various ship types and operational profiles. Both in form of new builds, retrofits on existing ships and in combination with local hydrogen production, distribution of hydrogen and hydrogen storage.

Sammanfattning

I strävan efter att hitta ett hållbart bränslealternativ för den maritima sektorn har intresset kring vätgas vuxit snabbt under de senaste åren. En viktig fördel med vätgas är att det kan produceras på ett hållbart sätt genom förnybar energi och att det inte blir några växthusgasutsläpp (GHG) när det används. Men även om intresset från branschen växer och ett ökat antal pilotprojekt annonseras finns det fortfarande flera hinder att övervinna. Främst är det frågor kopplade till en säker hantering av bränslet och osäkerheter i befintliga regelverk som återstår att lösa. Inom dessa områden finns ett stort behov av mer kunskap och praktisk erfarenhet av att använda vätgas för framdrift ombord fartyg.

I denna förstudie undersöks möjligheterna att använda vätgas till bränsleceller ombord på ett fartyg. Det övergripande syftet med denna studie är att bidra till en ökad kunskap om användningen av vätgas och i synnerhet aspekter relaterade till regelverk och säkerhetsfrågor.

Målet med denna studie var att lägga grunden för en ”guide” till en fullskalig installation av en vätgasdriven bränslecellsdrivlina i ett befintligt fartyg (så kallad retrofit-installation). Studien är fokuserad och uppbyggd kring Ventrafikens passagerarfärja Uraniborg som trafikerar sträckan Landskrona och Ven i västra Skåne. Genom att analysera data från fartygets energiuppföljningssystem och genomföra en riskidentifieringsanalys utformades ett hypotetiskt bränslecells-/batterikoncept.

Resultatet av studien visar att det är möjligt att genomföra en retrofit-installation av ett bränslecells- och batteribaserat som samtidigt tar hänsyn till säkerhetsaspekter ombord. I Uraniborgs fall skulle det dock innebära omfattande ombyggnationer ombord, och det finns fortfarande flera områden där ytterligare studier behövs innan ett sådant arbete skulle kunna genomföras. Sammanfattningsvis är slutsatsen att den föreslagna designen är ett genomförbart koncept men att det skulle vara lättare att bygga ett nytt fartyg anpassat för vätgasdrift istället för att göra en retrofit-lösning. Detta på grund av de förändringar som skulle behöva genomföras i fartygets utformning för att lagra och ventilera vätgasen på ett säkert sätt och hålla det avskilt från gemensamma utrymmen samt utrymmen där elektriska installationer finns.

Utöver det teoretiska konceptet har projektet även skapat ett industrinätverk för vätgas i maritima applikationer med totalt 47 industrimedlemmar (i skrivande stund). Nätverket kommer att fortsätta att fokusera på implementeringen av vätgas i maritima tillämpningar även efter studiens avslut genom kunskapsdelning och stödja skapandet av nya forsknings- och utvecklingsprojekt.

Under projektets genomförande identifierades flera områden där ytterligare forskning behövs, exempelvis:

- Utredning angående olika lagringsmöjligheter av vätgas med tillhörande rörsystem ombord. Skillnader i säkerhets-, kostnads- och driftsaspekter.
- Ytterligare bedömning av bunkringsförfarandet för vätgas och tillhörande säkerhetsaspekter.
- Fullskaliga installationer av vätgasprojekt i olika fartygstyper och operativa profiler. Både i form av nybyggnationer, ombyggnader på befintliga fartyg och i kombination med lokal vätgasproduktion, distribution av vätgas och vätgaslagring.

Contents

1 Introduction

1.1 Project background

The need for clean sustainable fuel alternatives in the shipping industry has intensified during the latest years. The maritime shipping industry accounts for approximately one-quarter of all emissions from the global transport sector, corresponding to nearly one billion tons of CO2 per year. It is crucial for the future of shipping to find viable measures to decarbonise the industry. The International Maritime Organization (IMO) has set the target of a 50 percent reduction in greenhouse gas (GHG) emissions by 2050, compared to 2008 levels, in order to align the industry with the objectives of the Paris Climate Agreement. (CSIS, 2021)

Hydrogen, in particular green hydrogen, has the potential to play a crucial role in the journey towards sustainability. The label "green" indicates that the hydrogen has been produced trough electrolysis with electricity that stems from a renewable energy source. As a marine fuel, hydrogen can be used either in liquid form, as a gas or as an enabler for synthetic electrofuels. However, the implementation in a marine context holds several barriers that need to be addressed before a broader use can be achieved. Apart from the financial aspects, the biggest concerns for hydrogen-use in shipping is related to regulatory aspects as well as safety issues. (DNV, 2021)

Based on its physical properties, hydrogen can be considered quite a tricky fuel alternative when safety is concerned. As described, on a ship, pure hydrogen might be stored either in its liquid or gaseous state. Stored as a liquid, hydrogen requires a storage system that can handle low temperatures (-253°C). As a gas on the other hand, the fuel needs to be compressed to a very high pressure (typically 250–700 bar). Seeing the fact that hydrogen is the smallest of all molecules, it poses more challenges to be stored in a gas state compared to other, already existing gaseous marine fuels. It has a wider flammability range, ignites easily and due to its small molecule size, it has higher tendency penetrate through materials and seals that are usually considered leak-proof. In summary, the properties of hydrogen may lead to an increased overall risk on-board ships compared to other fuel types unless applicable safety measures and practices are implemented. Today, an increasing number of technology suppliers are focusing on creating components that meets the safety aspects of marine hydrogen applications. However, a knowledge gap exists in the maritime industry at large due to a shortage of real-life adaptations, which slows down the implementation process. This becomes clear when the second threshold for marine hydrogen is considered, namely the regulatory aspects. (DNV, 2021)

Even though the interest and the number of investments in hydrogen as a marine fuel has increased, the regulatory framework is lagging. The international guidelines developed by IMO, the IGF Code, points to a demanding approval process for the adaptation of alternative fuels and power systems. There is a requirement for demonstration that the new power system holds an equivalent level of safety compared to conventional solutions. In addition, neither the IMO, Flag States, nor Class Societies have satisfactory rules and/or requirements for hydrogen-powered ships. However, this is a work in progress. The IMO have initiated a process to complement the IGF Code with rules for fuel cells. Bureau Veritas has Class rules, but these do not cover the storage of hydrogen. In summary, a shipowner that wants to consider hydrogen is more or less left on its own to navigate between the questions of design-options, technology set-ups and safe integrations in order to get a safe and approved hydrogen installation. To come to terms with this issue, more practical experience of hydrogen on-board ships is needed.(DNV, 2021)

In this feasibility study the question of safety and regulatory aspects of the implementation of hydrogen and fuel cells as a power system in a marine context are in focus. The main objective is to develop a roadmap for a retrofit installation of a hydrogen-powered drivetrain. At the centre of the study is Ventrafiken's RoPax ferry Uraniborg, which operates the Landskrona-Ven route in Skåne.

The project aims to develop a theoretical concept and at the same time investigate safety aspects for a hydrogen-based propulsion system. The goal is to create guidance for shipowners who are considering switching to hydrogen operation. In addition to the hydrogen concept, a secondary goal of this study is to create and launch an industry-network regarding hydrogen-related questions in maritime environments. This network will serve as a platform for knowledge sharing, both when it comes to practical experiences and research insights.

The study has been carried out by RISE, Research Institutes of Sweden, IVL Swedish Environmental Research Institute and CLOSER/Lindholmen Science Park. The project is part of the Swedish Transport Administration's industry program Sustainable Shipping, which is managed by Lighthouse.

1.2 Reference group and stakeholder involvement

To support the feasibility study, a diverse reference group (RG) was connected to the project, with representatives from different areas of the maritime industry. All in all, it consisted of 16 organisations, ranging from shipowners, technology suppliers, administrative and regulatory parties. In Table 1, the reference group is presented.

Table 1. Reference group for the project.

Organisation/Company	Business area
Bureau Veritas	Classification society
Euromekanik	Technology supplier
Ingmarsö Sjötjänst	Ship-owner
Kraft Powercon	Technology supplier
Swedish Coast Guard	Coast authority
Port of Landskrona	Port authority
PowerCell	Technology supplier
Scania	Technology supplier
Swedish Maritime Administration	Maritime authority
Swedish Sea Rescue Society	Non-profit organisation
Skärgårdsredarna	Trade organisation
Stena	Ship-owner
Swedish Transport Agency	Regulatory authority
Vattenfall	Energy supplier
Ventrafiken	Ship-owner
Volvo Penta	Technology supplier

Throughout the project, the RG has provided input and support, by participating in 3 reference group meetings and in specific theme workshops: one about the disposition of the hydrogen power system and one regarding hazard-identification. This was done to secure that result was reviewed and carried out in accordance with the latest insights in the field as well as applicability in real-life conditions, as the participants represent leading experts from the industry and relevant end-users.

In addition to these events, several representatives from the RG have been consulted continuously throughout the project to secure the quality of end-result, especially regarding the subject of risk management connected to hydrogen storage tanks and the conditions of on-board Uraniborg.

All in all, the RG has been highly involved in the work carried out in this project and has been crucial for the quality of the end-result.

1.3 Industry network

As described in the background, one of the expected outcomes of this feasibility study was to establish an "Industry Network" about hydrogen applications in the maritime industry. The purpose of this network is to serve as a platform for knowledge sharing and to share new insights related to the subject. Moreover, the network will support the creation of new research and development projects related to hydrogen in maritime applications. Throughout the project, industry partners were given the opportunity to announce their interest in the network and by the end of the study, 47 representatives from the maritime value chain have subscribed.

The network officially launched in October by hosting a webinar together with the American company Zero Emission Industries, which is behind the world's first 100% hydrogen powered high-speed ferry which started to operate during the late summer of 2021 in the San Francisco Bay area.

After the end of this project, the network will continue to support the implementation of hydrogen in maritime applications.

2 General overview and stakeholders

Looking back a couple of years, most hydrogen initiatives in shipping have been plans and drafts, and in case the projects have been conducted, it has mostly been conventional diesel engines converted to run on a mix of hydrogen and diesel. But now the first pilot projects are being built and delivered, where propulsion is fully fuelled with hydrogen and the energy transformation happens in fuel cells. Most of the projects where information is publicly available are in the planning stage, but there are examples showing that the technology for hydrogen and fuel cells are now at a stage where ships are being built. See in section 2.1.

The development of fuel cells has accelerated and companies like Gothenburg based Power Cell are foreseeing a growing interest from the marine sector. Furthermore, the technical development converting diesel engines to make them able to run on 100 % hydrogen seems to move forward. Two different engine suppliers claim that they are close to market for such hydrogen fuelled engines, Dietz and Keyou (Diesel Motor Nordic AB, 2021, Dietz, 2021 and Keyou, 2021).

2.1 Relevant marine hydrogen installations on-board ships

The project *Getting to Zero Coalition* (2021) has mapped relevant projects related to alternative fuels and found that before 2020 only two hydrogen ship projects above 5 000 DWT were initiated but since 2020 six new projects have started. This indicates that hydrogen now starts to be interesting as a fuel for larger ships.

Below, some examples are given of planned respectively built hydrogen powered ships. The examples have been selected to show which kind of vessels that is recently built and for the moment planned for. The examples are not meant to give an overview of all, the still very few, hydrogen vessels being built and planned for but is instead selected, and discussed with the reference group, as they are interesting and represent different vessel sizes and types, being built for commercial purposes.

2.1.1 Norled- MF Hydra ferry

The shipping company Norled has just taken delivery of a hydrogen powered ferry built by Westcon shipyard, design by LMG Marin. The ferry (see figure 1) is the world's first liquid hydrogen powered ferry and will only have to be refuelled every third week due to a tank capacity of approximately 4 tonnes hydrogen. The ferry commenced its service during 2021 and will operate on a route near Stavanger. Regarding capacity, the ferry is designed for 299 passengers and 80 cars. The speed is about 10 knots. (Norled, 2021)

Figure 1. From: Norled/LMG Marin.

The ferry (see figure 1) is at present (January 2022) operating in the Jøsenfjorden sailing between Hjelmeland, Porsberg and Haustavika with a daily operational distance of about 80 Nautical Miles (NM). Furthermore, the ferry will be able to operate on 100% battery. The fuel cell system consists of two Ballard FCWave PEM units of 200 kW each.

2.1.2 Hydrogen-electric workboat for the aquaculture industry

The initiative stems from fish farms being identified as an area of interest as different fish farms have many similar needs regarding transportation. An emission free work boat for the Norwegian fishing industry is therefore under development to meet the needs of the industry. The fish farm vessel has been named Moen Marin NABCAT 1480.

The development of the vessel is made within the Norwegian Renewable Energy Cluster, RENERGY, which creates an entire value chain of actors within the field of renewable energy by connecting energy companies, suppliers of technology, experts, and end-users. RENERGY has together with collaborators identified hydrogen as an important energy carrier for transportation in the aquaculture and shipping industry (Renergy, 2021).

The project has been grated NOK 28 million to develop the hydrogen-electric vessel from Pilot-E, a funding body established by the Research Council of Norway (Fishfarmingexpert, 2021). Development of the boat will be undertaken by several project partners and the Swedish company PowerCell is being assessed as supplier of fuel cells for the project.

The work boat is designed to manage one day of operation without refuelling. The vessel is estimated to be taken into operation 2023/2024. (Renergy, 2021)

2.1.3 Green city ferries

The Swedish company Green City Ferries is specialised on high-speed ferries powered by electricity (battery) or hydrogen (fuel cells) and are developing a passenger ferry suited for serial production (see figure 2). The first vessel is planned to be delivered in 2023. The concept for a battery or hydrogen vessel is similar, where battery is deemed the best solutions for a distance below 15 NM and hydrogen for longer range. The vessel under development will carry approximately 150 passengers and operate at a speed of 25-30 knots. The hull is a foil-supported catamaran with expected energy consumption of some 30 kWh per NM. In the hydrogen / fuel cell version the range is expected to be some 100-150 NM with associated daily consumption of around 200 kg of hydrogen, stored in pressure tanks at 350 bar.

Green City Ferries was also participating in developing Båtplan Stockholm 2025, an initiative including a plan to transform the commuter ferry traffic in Stockholm and surrounding archipelago to zero emission.

The sister company to Green City Ferries, Echandia, develops and delivers batteries and fuel cell solutions for maritime applications. Echandia will also deliver batteries and fuel cells to the Green City Ferry high speed vessels. (Green City Ferries, 2021)

Figure 2. From: Green City Ferries. Concept ferry BB Green 24.

2.1.4 ZEMShips

The Zero Emissions Ships (ZEMShips) project was initiated in 2006 and has in collaboration with project partners developed the FCS Alsterwasser; a Hamburg stationed passenger ship powered by hybrid fuel cell technology. The vessel started to operate on inner city waterways in Hamburg Germany in 2008. The ship has not been operational since 2013.

The ship, FCS Alsterwasser, is powered by a hybrid unit using fuel cell systems from Proton Motor and a lead-gel battery. To achieve a high fuel efficiency, an energy management system coordinates the power output from the fuel cells and the battery. The vessel could accommodate up to 100 passengers. (Proton Motor Fuel Cell GmbH, 2021)

2.1.5 Sea Change

During 2021, All American Marine, Inc. and SWITCH Maritime launched the world's first commercial hydrogen fuel cell-powered high-speed ferry, Sea Change (See figure 3). The ferry, which now operates in the California Bay Area is 70-foot and have a capacity of 75-passengers. The vessel is equipped with a hydrogen fuel cell power package provided and designed by Zero Emissions Industries, which includes 360 kW of Cummins fuel cells and Hexagon hydrogen storage tanks with a capacity of 246 kg. Additionally, the system is integrated with 100 kWh of a lithium-ion battery provided by XALT and a 2x 300 kW electric propulsion system provided by BAE Systems.

Figure 3 Sea Change lanuched in 2021

Sea Change is a result of a multiply step project which stated as a feasibility study named Water-Go-Around with the amin of investigating the viability of using hydrogen as a marine fuel seen from all aspects of suitability. i.e., social, economic, and environmental perspective. After a successfully theoretical concept the project developed into the fully scaled pilot which now been launched and taken in operation. The purpose of Sea Change is to demonstrate a pathway to commercialization for zero-emission hydrogen fuel cell marine technologies. Even though some wok remains when it comes to permits regarding hydrogen fuel systems for maritime vessels with the US Coast Guard, the completed ferry will exhibit the viability of this zero-carbon ship propulsion technology for the commercial and regulatory communities. (gcaptain, 2021).

2.2 Actors in the maritime hydrogen sector in relation to the hydrogen value chain

Water as the almost only residual product makes hydrogen as a fuel very attractive in shipping of the future. A strong government commitment has initiated a momentum in decarbonising the transport industry in Sweden where hydrogen might play a role. According to McKinsey (2021), the expected deployment support for hydrogen infrastructure towards the development of large-scale hydrogen projects will drive scale through the equipment value chain which is expected to reduce the cost of hydrogen production. One type of clusters that McKinsey (2021) mention as interesting to support deployment within, with potential large-scale hydrogen users, are port areas for fuel bunkering, port logistics, and transportation.

There are however many uncertainties in how the infrastructure for production, storage, transport, and the use of hydrogen in shipping ultimately will play out. This report emphasises on potential value chains of hydrogen in shipping and on involved stakeholders.

Hydrogen's low density makes it considerably harder to store than most other fuels. Low density also makes hydrogen expensive to transport (BloombergNEF 2020). If and when hydrogen production costs are falling, costs for hydrogen distribution will become increasingly more important (McKinsey 2021). An additional cost-effective option for large-scale transport is through pipelines. (BloombergNEF 2020)

The complete value chain for hydrogen in the maritime sector needs further development in all aspects ranging from production, transportation, storage, bunkering, and certification and regulations.

Without the purpose to provide a full overview, but to highlight the width of the value chain, the following section will simplify the value chain as production & distribution, storage & supply and operations with relevant actors.

Example of local solution:

As a supplier of green hydrogen, one possible solution for Swedish ports can be to establish hydrogen production from offshore wind farms and local electrolysers, and then compress the hydrogen for storage at the port area. Either at ground level, underground or in rock caverns. Pipelines to nearby fuelling stations for ships and land vehicles make the fuel accessible.

Production & Distribution

Most reports predict a limited but steady growth of hydrogen demand until 2030 (PWC, 2021) in a wider context than maritime sector. For production and distribution, three types of value chains are emerging. Large-scale hydrogen plants that are in close proximity to favourable renewables. Smaller users, for example refuelling stations where a regional distribution will be required. And regions without optimal resources, where both large- and small users may rely on hydrogen import. (McKinsey, 2021).

Here, actors as Oy Woikoski Ab, Kraft Powercon, Preem and Statkraft focus on production of hydrogen. And actors as NEL and ITM Power provide electrolysers for renewable energy i.e. Green Hydrogen. Focusing on renewably produced of hydrogen, actors as Svea Vind and Nilsson Energy has emerged. Together with more experienced actors such as Linde Gas and Euromekanik that provides knowledge of system design and installation, the industry has a comprehensive knowledge base.

Storage & Supply

Pinpointed as large-scale hydrogen clusters, port areas have the possibility to establish a strategic role in the transport system of the future regarding production and storage of hydrogen as a fuel, enabling the availability for use of the fuel for land and sea transports. Many ports have already identified a demand in and around the port to use vehicles that are powered by hydrogen and has started to act: Göteborgs hamn, Gävle hamn, Trelleborgs hamn, Landskrona hamn, Luleå hamn, Stockholms hamnar. Additional actors focus more on the filling stations by distribution or local production of hydrogen e.g. Circle K and Oazer.

Operations

New-building or converting a ship to run on hydrogen is a challenging task which includes development of new components and the process of getting the installation approved without the existence of clear rules and regulations. Classification societies as Lloyd's Register, DNV and Bureau Veritas are currently developing guidelines for the use of hydrogen as fuel in ships. . Here, suppliers as PowerCell, ZEM AS and Volvo Penta are in the frontline when converting and developing components and systems for the use of hydrogen together with ship-owners such as Färjerederiet, Green city ferries, Ingmarsö sjötjänst, Kustbevakningen, Sjöfartsverket, Sjöräddningssällskapet, Skärgårdsredarna, Stena and Ventrafiken.

Knowledge

Knowledge development and knowledge transfer is of major importance to facilitate the transition. Here, actors as IVL, RISE, KTH, Chalmers, Swedish Solar HydroGenesis and others are a vital part of the Swedish competence cluster. Together with topic-specific discussions supplied by organisations as Vätgas Sverige, Lighthouse, SMTF knowledge transfer can be achieved.

3 Possible potential and benefits using hydrogen as bunker fuel

The potential of hydrogen in shipping as well as an energy carrier in other parts of the society is large. Countries and regions have ambitious strategies and hydrogen programs. Hydrogen seems to be a potential fuel for a part of the shipping sector, but it is still too early to say if hydrogen and fuel cells on-board vessels are going to be a widely spread solution.

3.1 Production and availability

Hydrogen has for many years been discussed as an interesting fuel alternative for reducing greenhouse gases, but the technology is still expensive. In line with the EU hydrogen strategy, adopted in July 2020 (European Commission, 2020), EU aims to accelerate the development of clean hydrogen with the target to increase todays 2 % of the EU's current energy consumption originating from hydrogen towards some 14 % by 2050. The strategy also states that for inland waterways and short-sea shipping, hydrogen have the potential of becoming an alternative low emission fuel.

Origin of hydrogen gas is often referred to in colours. Grey hydrogen gas is produced from natural gas in a process called steam reforming. It is the most dominant production method today. Blue hydrogen is produced from fossil fuels (natural gas, coal) but with carbon dioxide emissions minimised using CCS (Carbon Capture Storage) technology. Blue hydrogen could contribute to increase hydrogen economy. Today it is used as a step between the grey and green hydrogen. Green hydrogen is produced by electrolysis of water and power from renewable energy sources.

Hydrogen is most likely to be produced renewably either by electrolysis of water with electricity or via reforming of biomethane (biogas).

The production of hydrogen can be carried out either close to where the fuel is used if electricity, clean water, and a suitable site are available, or it can be produced elsewhere and transported to bunkering sites. Either way of production will need a storage unit which can be a mobile container, or a permanent storage at site.

The hydrogen fuelled heavy trucks, that truck manufacturers such as Volvo Trucks and Scania are developing, are expected to have a role in the future market due to the foreseen longer range than similar battery-electrical heavy trucks. (Scania 2021, Volvo Trucks 2021). Heavy hydrogen trucks will run on compressed hydrogen as the liquification process requires significant amount of energy.

For storage of hydrogen on-board ships, it is less expensive with hydrogen in compressed form. To manage longer voyages or less frequent bunkering, storage in liquid form might be required.

The hydrogen demand from the transport sector is however still low. Hydrogen filling stations are still rare but exist in few numbers, making hydrogen available for the so far very limited number of hydrogen powered vehicles. Renewable hydrogen is produced and available at a limited number of places in Sweden such as:

- In Sandviken, Linde Gas has an electrolyser to produce hydrogen. The capacity of the electrolyser is 2x 275 Nm^3/h, which corresponds to a production capacity of about 1 ton per day. In Sandviken, there is also a hydrogen filling station connected with a pipeline directly from Linde Gas.
- Linde Gas operates the production facility in Halmstad, which was built for the former Pilkington glass factory. A production with 2 x 250 Nm^3/h electrolyser corresponds to a production capacity of approximately 1 tonne of hydrogen per day.
- In Mariestad, there is hydrogen production with electrolysis from locally located solar panels adjacent to the hydrogen filling station. The facility is operated by the municipal energy company VänerEnergi AB.
- There are also established hydrogen filling stations in Stockholm (Arlanda), Mariestad, and Umeå.
- Höganäs AB in the city of Höganäs has a 1,500 Nm^3/h reformer and 700 Nm^3/h electrolyser, which corresponds to a production of just over 4 tonnes per day.
- AAK in Karlshamn has a 2 x 600 Nm^3/h electrolyser, which corresponds to a production of just over 2 tonnes of hydrogen per day.

Recently several initiatives have emerged, where different organisations have expressed their plans for building renewable hydrogen production capacity and tank stations.

REH2 is a Gothenburg-based company, partly owned by Nilsson Energy (which built the hydrogen filling station in Mariestad). REH2 is working to build a national network of hydrogen filling stations with decentralised production and intends to establish hydrogen filling stations located together with existing diesel filling stations for heavy trucks. They have applied and received support for their planned construction of 24 hydrogen filling stations around Sweden. The support from Klimatklivet of 355 MSEK was granted in December 2021 (REH2, 2021 and Regeringskansliet, 2021, Naturvårdsverket, 2021).

Several Swedish ports such as Port of Gävle, Port of Stockholm and Port of Gothenburg aim to make hydrogen available in the port area for own equipment, trucks as well as for future demand from ships. Port of Gävle has for example signed an agreement with Svea Vind Offshore to establish hydrogen production in the port area with a preliminary start in 2023. At first, the hydrogen will be used by the region's industry and as fuel in the road transport sector (Svea Vind Offshore, 2021). Over time demand from the other sectors such as ships and terminal operations is expected to grow. Port of Gothenburg has announced the aim to establish hydrogen production in the port area. The plant, to be located at Risholmen, is planned to have a capacity of four megawatts, which will provide a production of up to two tonnes of hydrogen per day. The Norwegian energy company Statkraft is responsible for the investment while the port supports with the land area. (Göteborgs Posten, 2021).

There are also initiatives announced with plans for large scale hydrogen production from wind power electricity with the aim of producing electro-fuels such as methanol and potentially ammonia at a later stage, in Sweden as well as in neighbouring countries.

3.2 Pros and cons related to hydrogen as a marine fuel

Benefits with green hydrogen as a fuel used in fuel cells are that the system can be seen as almost emission free, creates very little noise and that hydrogen can be produced almost anywhere as long as there is access to electricity and water.

The **challenges** for the usage of hydrogen as marine fuel are mainly **cost**, **safety** and **storage**.

In relation to **safety** there are still only guidelines in place for usage and installation of hydrogen systems on-board ship available, for example the classification society Bureau Veritas guidelines for which a revised version is under way. In practice, this means that existing international regulatory framework states that hydrogen-fuelled ships must comply with the International Convention for the Safety of Life at Sea (SOLAS) and Part A of the IGF Code. Shipowners must therefore be able to prove the safety of their alternative designs for hydrogen-powered vessels to the relevant flag state administration or classification society and should work closely with a classification society during the design phase. A more desirable situation for the shipowners would instead be if the classification societies would present class rules developed for the safe and practical usage of hydrogen and fuel cells on-board with clear guidelines on how the installations and procedures should be conducted in order to meet necessary safety requirements. Class rules for hydrogen installations would make the design process for hydrogen fuelled ships less complex, like other fuels for which class rules exists. (Bureau Veritas, 2021a). See also section 5 for more detailed information on Regulations, Guidelines & Standards.

Related to **cost**, the general view is that hydrogen solutions for ships will be more costly than battery electrical solutions for cases where battery solution is an option, for shorter operational range and where it is manageable to access and charge the battery system. It seems also that the total costs of ownership for green hydrogen and fuel cells in general will be more costly than some of the other renewable solutions under discussion such as ammonia and methanol, especially for larger ships. Examples of such cost predictions has been made recently by Korberg (2021) where both fuel production and total costs for vessel operations has been assessed. But there are still many uncertainties on future cost predictions for production, storage, bunkering and usage of hydrogen as well as cost levels of fuel cells, same as the case for other renewable fuels under development. Prices are expected to decrease with larger production volumes and the development of technology and processes linked to the use of hydrogen. There are for example predictions made by McKinsey that points out hydrogen fuel cell trucks to be able to compete economically with diesel trucks for specific flexible and demanding long-haul trucking with a break even around 2027. (McKinsey, 2021).

Handling and **storage** of hydrogen is straight forward even if it takes up significantly more space than conventional fuels used on-board ships today. It seems manageable for most ship solutions but will act as an added cost for cases where the pay load in form of cargo or passenger needs to be decreased.

The International Council on Clean Transportation (ICCT 2020) have modelled energy demand and fuel storage space requirements for a container ship operating between US and China if powered by liquid hydrogen and fuel cells. According to the report, it is stated that despite hydrogens lower energy density compared to heavy fuel oil, they found no major bunkering barriers to power containerships with hydrogen. With only minor changes to fuel capacity or operations, 99 % of the voyages along the modelled routes could be managed by replacing 5 % of cargo space with more hydrogen fuel or by adding one additional port of call to refuel.

All in all, it seems that it is too early to tell how competitive the hydrogen and fuel cell solutions will be in the future. But it is definitely a possible path that can contribute to the needed transformation of shipping towards sustainable operations.

3.3 Hydrogen as a retrofit

Analysis and description of needs and possibilities of retrofit on existing vessels for hydrogen operation has been one of the main objectives for this project. As per today’s costs levels for hydrogen and fuel cell installations, the driver for such installations including retrofit is still mainly to learn more and to find solutions to challenges. And with the rapidly growing interest for hydrogen as well as technology development, development in terms of regulations, safe handling practices and availability of hydrogen, as well as incentives coming up, it seems that hydrogen installations could make sense in many perspectives. At the time being it is however not possible to state if a significant share of retrofitted vessels will be powered by hydrogen.

3.4 Sustainability aspects with hydrogen compared to other fuel alternatives

There are several different sustainability aspects connected to the different alternative fuels for powering ships. Aspects that are important to look at includes greenhouse gases, noise, underwater noise, resilience in society, etc.

In a quick overview of the most relevant frequently discussed alternatives to conventional marine fuels, it becomes clear that all have drawbacks and positive prospects related to sustainability. For the time being, alternative fuels as liquefied natural gas (LNG), liquified petroleum gas (LPG), but also methanol, ammonia and hydrogen are produced from fossil feedstock and thus have limited sustainability potential, but they can also be produced as biofuels or electrofuels.

Ammonia, which also have gained a lot of interest during the later years is currently produced from fossil natural gas. Another issue with ammonia is its toxicity which gives rise to several safety issues when stored and used on-board vessels. Different biofuels, which are also strong contenders in the search for an alternative zero carbon fuel, are also in a varying degree connected to suitability challenges depending on production methods. Bio-alternatives are also facing challenges when it comes to high cost, but even more important when maritime applications are concerned, the availability is very limited. The sustainability potential (especially environmental) of all-electrical alternatives is dependent on how clean the energy mix is at the site where the vessel is charging, and battery applications are still limited to shorter distances.

And finally, as described in section 3.2, hydrogen is not an exception as it also faces a lot of challenges. However, with this complexity in mind the most likely future scenario is that all the alternatives above will be part of the transition to a more sustainable maritime sector and that they all serve a purpose in different areas of the industry. (DNV, 2021)

Many stakeholders consider hydrogen as a viable solution for zero emission coastal and short-sea shipping. From an environmental perspective, using hydrogen through fuel cell technology, the local emissions of carbon dioxide, nitrogen oxides and particles can be radically reduced. In addition, compared to battery propulsion, hydrogen can be a more flexible energy carrier, facilitate onboard storage of more energy, and it is also more suitable for transport to remote bunkering sites or places where the grid experience capacity issues. However, whether hydrogen is a truly zero-emission option depends on the value chain and whether it is produced from renewable energy sources as described in section 3.1. (DNV, 2021) (Vätgas Sverige, 2022)

Seen from an economic and social sustainability perspective, hydrogen has further advantages. However, they are highly dependent on the degree of integration of hydrogen in other industries and the society at large. One of the many benefits of hydrogen is its wide usage in different energy markets. Just as it can be used as a fuel, hydrogen can be used to store and produced electricity, heating and are a key in many industrial processes. This implies that by establishing a national hydrogen production industry, the resilience of the total societal infrastructure would increase, and the import dependence would be reduced. This can in turn contribute to increased values in other vital social functions such as secure food production and military defence. In this aspect, decentralised hydrogen systems can add important resilience values to existing infrastructure as, e.g., the electricity grid, the gas grid and infrastructure for refuelling / charging mobility. However, all these values are, as stated, dependent on a high implementation of hydrogen infrastructure at large. Seen from a maritime perspective only, these benefits could be applicable to port operations as hydrogen could create similar values seen to resilience and self-sufficiency if local hydrogen production and storages was established. (Fossilfritt Sverige, 2021)

Seen as a marine fuel, the economical sustainability is much dependent on a cost reduction in both hydrogen production and the components of the fuel cell system, and for this to happen, a continuous technical development and large-scale implementation is needed. A notable social benefit that hydrogen brings is the positive health impacts reduced local emission brings. However, the social sustainability of hydrogen as marine fuel is dependent on that the remaining issues regarding risk management on-board and during refuelling procedures are being resolved.

3.4.1 Cost comparison of hydrogen as a fuel seen to GHG-emissions

In relation to the case of potential fuel switch for the ferry Uraniborg, further described in section *4. Concept installation of hydrogen-powered fuel cell system Uraniborg* we will here present a simplified estimation in relation to effects on external cost differences connected to such a fuel switch. The calculations cover valuated external costs for air emissions and greenhouse gases for three operational alternatives:

- The ship uses conventional fuel (E10 fossil diesel fuel containing 10% renewable ethanol).
- The ship uses 100 % renewable HVO.
- The ship uses fuel cells running on hydrogen produced with electrolysers.

Based on calculated emissions per roundtrip, external costs for air emissions using the Swedish Transport Administration calculation tools, gives that present diesel operations generates approximately 10 times higher external costs versus 5 times higher if fuel were switched to renewable diesel fuel (HVO) compared to hydrogen operations.

The electricity source used for hydrogen production will influence the calculation results significantly, why the presented results shall be seen as an indication of changes in external costs. The socio-economic cost for hydrogen would for example be significantly lower in case 100 % renewable electricity such as wind power would have been used as a basis for the calculations instead of the Nordic electricity mix.

Calculations are based on:

- Present fuel consumption of 68 litres of fuel used per one way trip compared to the approximately 10 kg of hydrogen expected to be consumed if the vessel was retrofitted with a hydrogen propulsion system.
- Greenhouse gas performance fuel data for MK1 and HVO from Energimyndigheten (2021)
- Emissions generated from electricity production for Nordic electricity mix from Vattenfall (2019).
- Emissions generated from hydrogen production based on Vattenfall (2019) for Nordic electricity mix as well as hydrogen production described in Hjort (2021).
- Typical emission factors for the main engine installed on-board Uraniborg.
- Air emission valuations from *ASEK 7.0*[1], shown in Table 2 from Trafikverket (2020).

Table 2. Assessment of air pollution and greenhouse gases based on ASEK 7.0.

Air emission and effect (SEK/kg)	
Particulates PM2.5 - Exhaust particles	6 900
Nitrogen oxides - Environment effects Eutrophication	2
Nitrogen oxides - Ground-level ozone, Götaland	1.5
Carbon dioxide equivalents	7

---

[1] Effects from air pollution that are valued in ASEK (Trafikverket 2020) are, for example, local effects of air pollution in the form of negative health effects, such as increased ill health and symptoms in the respiratory tract and respiratory system, increased cancer risk, etc. Emissions of nitrogen oxides have effects in the form of eutrophication of soil and water and the formation of ground-level ozone. Ground-level ozone in turn causes damage to cultivated crops, forest damage, allergies, and respiratory problems, and can also contribute to climate effects. The methodological starting point for socio-economic valuation in ASEK is to start from damage costs. That the valuation is based on how air pollution actually affects people through various health and environmental effects.

4 Concept installation of hydrogen-powered fuel cell system Uraniborg

In this chapter a theoretical outline of a hydrogen-powered fuel cell system on-board Ventrafiken's Ro-Pax ferry Uraniborg is described. Based on the data obtained from the ships power management systems, ship drawings and existing propulsion system, the fuel cell system will be designed with associated infrastructure and subsystems such as hydrogen storage and battery systems.

4.1 Methodology

In order to conduct a first draft of a fuel cell concept on-board Uraniborg, data was collected from the shipowner in the form of ship drawings and fuel consumption. In addition, a visit on-board the vessel was arranged to see the appropriate installation areas.

The data regarding the fuel consumption was maintained from the installed BlueFlow system. The system has been in operation since the autumn of 2020 with the purpose of highlighting the energy demand on-board the ship. In total, 15 routes (30 single routs) were examined in this study to verify the necessary energy capacity of the new propulsion system. The data collection included routes from different departure times during the day as well as weekdays and weekends.

In parallel to this project, the shipowner has arranged seminaries on "green and efficient operations" for the crew members with the aim of creating energy aware operations with the support from the BlueFlow data collection and real-time visualisation of the energy demand. When selecting routes for the concept calculations in this study, data was collected both prior to and after this seminar. This was done to take in to account the effect it had on the operation. However, uncertainties exist of the long-time effects of that kind of energy saving measures which made it important to include routes before the seminar as well.

The data was gathered with a resolution of fuel consumption per second. By calculating the energy content of fuel (diesel), the energy and power demand could be determined. By taking in to account the efficiency and energy losses of the current combustion engine, the fuel cell and a potential battery support, and the needed installation capacity of the electrical propulsion system could be defined. In table 3 the expected efficiency rates of each component/energy conversion that have been used are presented.

Table 3 Expected efficiency rates of the components in the fuel cell propulsion system

Component/energy conversion	Efficiency rate η
Combustion engine	0,25
Electric motor + battery	0,92

Electric motor + fuel cell	0,45
FC + battery recharging	0,81

For each route, six design concepts where examined, ranging from 100% battery propulsion to 100% fuel cell propulsion. Technological advantages relate to the faster response time of batteries and that fuel cells systems allow faster refuelling and overall higher energy density. Hence, designing a system with batteries to handle power peaks, and fuel cells to provide a constant base power load will make the system more optimised. It is also possible that at mixed system is more economical as there are differences in investment cost and fuel/electricity price depending on how much of the propulsion system is fuel cells/batteries. A summary of each concept is shown in table 3. The percentage represent the installed power capacity for each component.

Table 4 Distribution of installed power capacity of batteries and fuel cells in each design case

Case design	Battery (%)	Fuel cell (%)
0	100	0
1	80	20
2	60	40
3	40	60
4	20	80
5	0	100

To calculate the amount of hydrogen that each case corresponded to, the fuel cell energy demand was used (1kg hydrogen = 33kWh). In case 0-1, the batteries are assumed to be charged externally by shore power, but as the fuel cell capacity increases (case 2-4) the batteries are being powered by the fuel cells.

In the first draft of the concept (before the hazard identification workshop, see chapter 5), the hydrogen tanks were selected based on the available space on-board and a desirable bunkering routine. Based on the result from calculations regarding the propulsion setup, the first draft also contained a suggested placement of batteries and fuel cells. A second set-up was later conducted based on the feedback from the safety review.

4.2 Technical summary and operational profile

In this section the technical specifications of Uraniborg are presented as well as the logged operational profiles.

M/S Uraniborg

M/S Uraniborg is a RoPax ferry that operates the route Landskrona-Ven at the south-west cost of Sweden. The ship dates back to 2012 and is constructed as a "double-ender" which allows efficient dockings when in port. The crossing between Landskrona and Ven takes approximately 30 minutes which corresponds to a distance of 4,2 nautical miles. In table 5 a technical summary of Uraniborg is presented.

Table 5 Technical summary of Uraniborg

M/S Uraniborg	
Ship dimensions	
Length	49,95 m
Width	12,0 m
Depth in water	2,85 m
Ship capacity	
Passengers	394 persons
Vehicles on car deck	14 cars
Max speed	10 knots
Energy data	
Fuel consumption (combustion)*	103 l/h
Energy content diesel	9950 kWh/m3
Energy consumption*	1025 kWh/h
Operational hours	4070 h/year
Number of single routes	19 routes/day

*At average speed

In figure 4 an overview of the engine deck is presented. The highlighted sections showcase possible installation areas for the components of the fuel cell system.

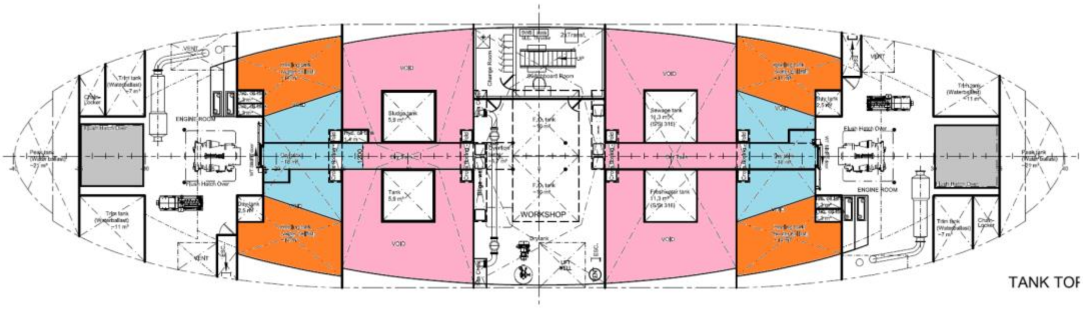

Figure 4 Overview of Engine deck of Uraniborg

4.3 Result - Fuel cell concept

In this section, the result from the concept evaluation is presented. In table 6 the energy demand calculations for each of the population setups are visualised. The result represents the energy and power demand for one round-trip (2 single routes).

Table 6 Energy and power demand for each battery/fuel cell distribution case

NR		**Battery Energy [kWh]**	**Max Battery Power [kW]**	**FC Energy [kWh]**	**Max FC Power [kW]**	**Hydrogen demand [kg]**
0	Max	335	847	0	0	0
	Mean	293	633	0	0	0
	Min	244	450	0	0	0
1	Max	130*	683	188	164	6
	Mean	128*	511	146	123	4
	Min	116*	363	81	87	2
2	Max	113	519	699	328	21
	Mean	92	388	615	245	19
	Min	74	276	513	174	16
3	Max	75	355	694	492	21
	Mean	**61**	**265**	**610**	**368**	**19**
	Min	49	189	508	262	15
4	Max	38	191	689	656	21
	Mean	**31**	**143**	**605**	**491**	**18**
	Min	25	101	503	349	15
5	Max	0	0	684	820	21
	Mean	0	0	600	613	18
	Min	0	0	498	436	15

*Based on time estimates regarding power load

As described in the previous section, the six cases represent different set-ups regarding the allocation of the installed power capacity of batteries and fuel cells. In case 0-1, the batteries are being charge externally by shore power, and thus the hydrogen demand remains low. However, in the cases when the fuel cells are used to power the batteries as well as the propulsion the hydrogen demand remains steadily at approximately 20 kg/round trip. The slight decrease that can be detected as the fuel cell capacity increases can be explained by the reduced losses between the fuel cell and battery recharging.

As described earlier, it is desirable to choose a set up where the batteries are used to cover power peaks due to the faster response time and let the fuel cells covers the base load, and thus the power distribution of the route must be considered. In figure 5, the average power demand of one round-trip is visualised.

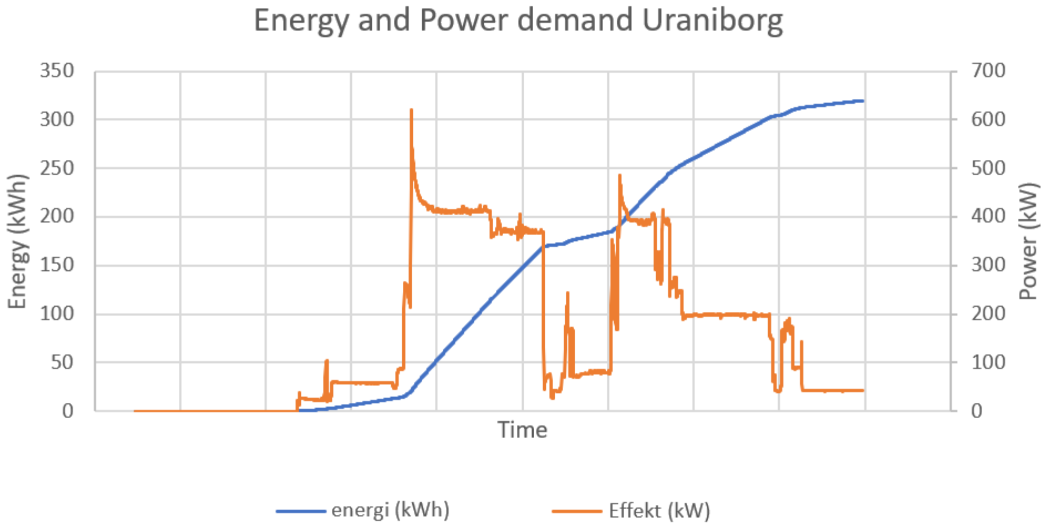

Figure 5 Average energy and power demand Uraniborg during 2 single routes

As shown, the energy demand varies depending on which direction the ship is heading. When heading from Landskrona to Ven, the energy consumption is higher than when traveling from Ven. As the data is gathered during different days and weather conditions, it is hard to find a conclusive reason behind this. What can be said however is that the ship experiences a peak in power when leaving the port areas, no matter the direction. As the energy demand varies depending on direction, it is difficult to determine a fixed base load, but looking at the operational pattern it could be approximated to 300-400 kW. Looking at the mean power consumption, case 3 and 4 appears most suitable. These cases correspond to propulsion systems with either 60 or 80 percent of the power demand covered by fuel cells.

In figure 6-7, the first draft of two potential propulsion system is presented based on case 3 and 4. Each case corresponds to a design that was considered before the Hazard Identification workshop. The dimension of the used components is presented in table 7.

Table 7 Technical summary of components just in the proposed design

Technical summery	
Battery features (per unit)	
Dimensions	2,4 x 0,7 x 0,5 m
Weight	436 kg
Power capacity	77 kWh
Fuel cell features (per unit)	
Dimensions	0.7 x 0.9 x 2.0 m
Weight	700 kg
Power capacity	200 kW

Hydrogen storage features (per unit)	
Dimensions	3,0 x 2,4 x 2,7 m
Storage capacity/Unit	165 kg

The first design, based on the energy calculation case 3, consist of two battery units, two FC stacks and six storage systems. This corresponds to a total hydrogen storage capacity of 990 kg which allows 5,5 days of operation. However, it is worth pointing out that a more frequent bunker practice is recommended to prevent the storage from running empty.

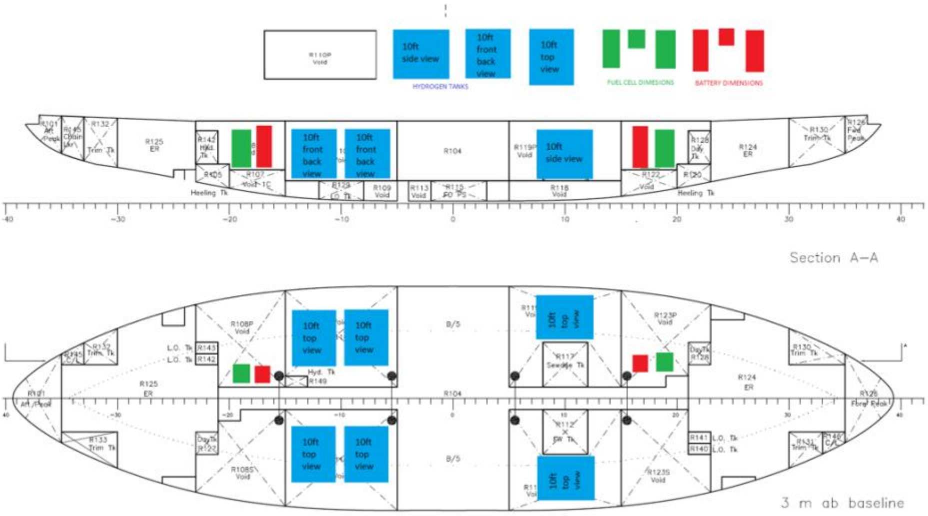

Figure 6 Suggested installation set-up before Hazard Identification workshop – showcasing case 3. The design consists of two FC units (green), two battery units (red) and six storage units (blue)

The second design, based on case 4, holds the same storage capacity as in case 3 but includes a third FC stack. As the fuel cells in both the designs are used to power the batteries as well as the propulsion, leaving combined power capacity unchanged, the hydrogen demand stays approximately the same in both cases and corresponds to 5,5 days of operations.

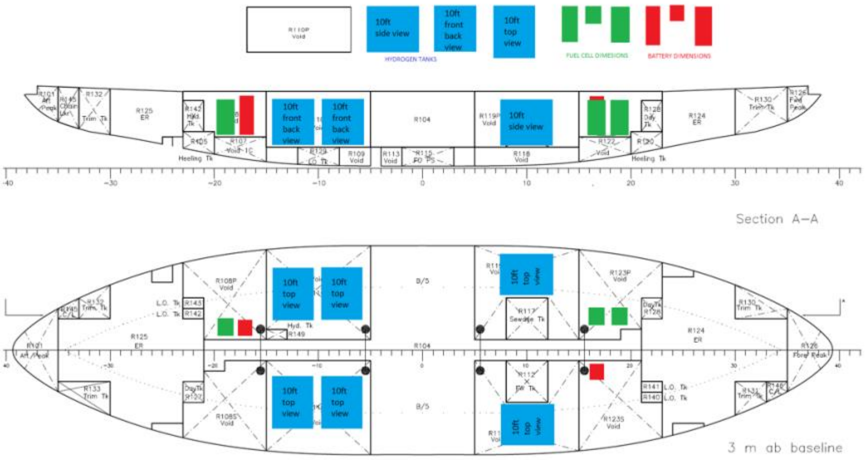

Figure 7 Suggested installation set-up before Hazard Identification workshop– showcasing case 4. The design consists of three FC units (green), two battery units (red) and six storage units (blue)

After the Hazard Identification workshop, alterations were made to the design. In chapter 6 the final set-up is presented along with a summary of the project findings.

5 Regulations and safety solutions for the concept installation

A screening of current relevant regulations was carried out to identify existing related regulations and guidelines for safe hydrogen installations on-board existing ships, and to highlight any regulatory gaps. In addition to this, a Hazard Identification (HazID) was carried out for the concept installation to identify risks and potential safety solutions. The focus of the HazID was on risks associated with storage of hydrogen and with the proposed fuel cell installation. Fire and explosion risks were emphasized during this work. A summary of general safety considerations for hydrogen is presented in Appendix A.

The output from the above-described work consists of an overview of relevant regulations and guidelines, identified risks for the concept installation, proposed safety measures and a list of areas where studies in greater depths are recommended to further specify the safety of the concept installation. It should be noted that the scope of this work only covered a HazID of the concept installation. A complete risk analysis or risk assessment was not performed as part of this work.

5.1 Regulations, Guidelines & Standards

A screening of regulations and guidelines was made to determine relevant regulations and guidelines regarding hydrogen fuel cell installations. In table 8 the documents that were considered in this screening are listed.

Table 8. Guidelines, regulations and standards for fuel cell installations and safe usage of hydrogen on ships. The three documents written in bold are the ones deemed most relevant to the concept installation.

Publisher (Year)	Title of document	Type of document
IMO (2016)	The International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code).	Regulation (IMO Code under SOLAS)
IMO (2016)	The International code for Ships using Gases or other Low-flashpoint Fuels (IGF Code)	Regulation (IMO Code under SOLAS)
IMO, under development	Interim Guidelines for the safety of ships using fuel cell power installations	Regulation (Interim Guidelines)

Bureau Veritas, (2009)*	Guidelines for fuel cell installations On-board Commercial Ships	Classification Society guidelines
Det Norske Veritas, (2021)	Handbook for Hydrogen-Fuelled Vessels	Classification Society guidelines
American Bureau of Shipping, (2019)	Fuel Cell Power Systems for Marine and Offshore Applications	Classification Society guidelines
ISO TR 16916, (2015)	Basic consideration of safety for hydrogen systems	International standard

* Bureau Veritas is currently developing a new version of these guidelines, planned to be published in the end of 2021.

5.1.1 Review of relevant regulations and guidelines

The screening of regulations showed that there are currently no internationally accepted maritime regulations for the use of hydrogen and fuel cells. However, there are regulations and guidelines that are of relevance for the concept installation. Based on the screening of regulations and guidelines, the following three documents were chosen for further review.

- IMO: The International code for Ships using Gases or other Low-flashpoint Fuels (IGF Code)
- Bureau Veritas: Guidelines for Fuel Cell Systems On-board Commercial Ships
- IMO: Interim guidelines for the safety of ships using fuel cell power installations (under development).

The IGF Code provides requirements for arrangement, installation, control and monitoring of machinery, equipment and systems using low-flashpoint fuel. The scope of the IGF Code includes fuel storage tanks on-board. However, the current version of the IGF Code only includes detailed requirements for natural gas as a fuel. For other low-flashpoint fuels, such as hydrogen, the IGF Code requires that the alternative design method is used to demonstrate compliance with the functional requirements. Chapter 2.33 of the IGF Code specifies that demonstration of alternative design shall be done in accordance with SOLAS II-1/55 (IMO, 2016). It provides a method for alternative design and arrangements for machinery, electrical installations and low-flashpoint fuel storage and distribution systems. As there are currently no prescriptive regulations specifically addressing fire safety of hydrogen fuel cell installations, any installation of hydrogen fuel cells may also need to be approved as an alternative design for fire safety in accordance with SOLAS II-2/17 *Alternative design and arrangements*.

In support of demonstration of alternative design involving low-flashpoint fuel, IMO has developed guidelines that provide requirements for usage of low-flashpoint fuel. There is currently on-going work to develop interim guidelines for the safety of ships using fuel cell power installations, and hydrogen in fuel cells is included in these Interim IMO Guidelines. Hydrogen storage tanks are however not covered by the Interim IMO Guidelines (IMO, n.d.). The interim guidelines are still under development and are expected to be made available during 2022.

Classification societies, like Bureau Veritas (BV), have also published guidelines for hydrogen installations. The guidelines published by BV apply to fuel cell system installations on-board. It should be noted that the reviewed guidelines were published in 2009. BV is currently developing an updated version of these guidelines that is planned to be published later in 2021. The updated version of the guidelines will cover fuel cell power installations, but unlike the current guidelines, the updated version will not cover fuel storage tanks (Bureau Veritas, 2009; Bureau Veritas, n.d.).

5.1.2 Comparison of relevant regulations and guidelines

Although prescriptive regulations for hydrogen as a fuel are currently missing, Part A-1 of the IGF Code, the Interim IMO Guidelines (under development) and BV's Guidelines for Fuel Cell Systems On-board Commercial Ships, constitute a good starting point for fire safety requirements for ship hydrogen installations. The following chapter gives a summary of the requirements relating to fire safety in the three documents and compares them to each other. The updated guidelines from BV, although still under development and subject to modification, have been considered as well and notable changes have been included in the comparison. The comparison indicates that the fire safety requirements of the current BV guidelines (2009) are consistent with the requirements of the IGF Code, whereas the updated version of the guidelines is consistent with the IMO Interim Guidelines. Note that the comparison does not give a complete account of the requirements, only an overview. A more detailed comparison is given in Appendix B.

Risk assessment
All three documents require some sort of risk analysis or risk assessment to be performed if using low-flashpoint fuel. The scope of the risk assessment and the required techniques vary, but fire and explosion risks are emphasised as important to address in all documents (Bureau Veritas, 2009; Bureau Veritas, n.d.; IMO, 2016; IMO, n.d.).

Fire Detection
All three documents require a fire detection system in compliance with the International Fire Safety Systems (FSS) Code. The Interim IMO Guidelines and the current BV guidelines specify that the detectors need to be suitable for hydrogen. The requirements for the detection system will change in the new

version of the BV guidelines, likely to require a detection system complying with NR467 Pt C, Ch 4, Sec 15, as well as to require flame detectors in fuel cell spaces. All three documents agree that smoke detection is not sufficient (Bureau Veritas, 2009; Bureau Veritas, n.d.; IMO, 2016; IMO, n.d.).

Control, monitoring & safety systems
All three documents all include several requirements regarding control, monitoring and safety systems for the spaces containing hydrogen. The most notable systems required are gas detection, pressure monitoring and monitoring of the ventilation (Bureau Veritas, 2009; Bureau Veritas, n.d.; IMO, 2016).

Containment
A-60 class divisions are required to provide fire integrity for the fuel cell spaces in all three documents. The hydrogen storage spaces must also be protected with A-60 class divisions, in accordance with the IGF Code. The Interim IMO Guidelines require fuel cell spaces to be gas-tight towards other enclosed spaces. The updated version of the BV guidelines also includes this requirement. All three documents require access to the hydrogen storage spaces and fuel cell spaces directly from open deck, or through an air lock. Alternatively, technical provisions should be made to confirm that the atmosphere is gas-free and to ensure that the equipment has been shut down, isolated from the fuel system, and drained from leakages. In addition to this, all documents require that spaces designed for hydrogen usage should be regarded as machinery spaces of category A for fire protection purposes (Bureau Veritas, 2009; Bureau Veritas, n.d.; IMO, 2016; IMO, n.d.).

Extinguishment
The IGF Code requires enclosed spaces containing equipment for fuel preparation to be provided with a fixed fire-extinguishing system complying with SOLAS II-2/10.4.1.1 and the FSS Code, while considering concentrations and the application rate needed to extinguish gas fires. The Interim IMO Guidelines require a fixed fire-extinguishing system that is suitable for the primary fuel and the fuel cell technology in fuel cell spaces. The current version of the BV guidelines has similar requirements regarding the fire-extinguishing system as the IGF Code. However, in the updated version of the guidelines the requirements are the same as in the Interim IMO Guidelines (Bureau Veritas, 2009; Bureau Veritas, n.d.; IMO, 2016; IMO, n.d.).

Explosion prevention and mitigation
Explosion prevention and mitigation is given much consideration in all three documents. The probability of formation of ignitable mixtures and the presence of ignition sources are to be minimised according to all three documents. Atmospheric control in the spaces with hydrogen-containing equipment is emphasised in all three documents. The Interim IMO Guidelines require that atmospheric control of fuel cell spaces should be made by either inerting or ventilation. This requirement is also included in the updated version of the BV guidelines. All three documents also require that if an explosion does occur, the

impact on other spaces should be limited. Emergency shutdown (ESD) arrangements and pressure relief valves or systems are suggested as mitigating measures in all three documents. The updated version of the BV guidelines also requires an explosion analysis to be performed for ventilated fuel cell spaces. This is to demonstrate that the maximum pressure build-up does not exceed the design pressure of the space (Bureau Veritas, 2009; Bureau Veritas, n.d.; IMO, 2016; IMO, n.d.)

5.2 Hazard Identification

A preliminary qualitative hazard identification (HazID) was carried out through a digital workshop performed September 2, 2021. The workshop was carried out by a team consisting of participants from varying disciplines and backgrounds. A list of the participants, their organisation as well as their profession and area of expertise can be found in Appendix C. The purpose of the workshop was to identify the most critical risks and safety measures of the concept installation on-board Uraniborg as well as potential safety measures.

5.2.1 Method

The concept installation was described as a system using six spaces: bunkering station, fuel transfer space, hydrogen storage space, fuel cell space, machinery space and battery space. The system is illustrated in figure 8. During the workshop, the spaces were analysed one by one. However, the two most pertinent spaces for the concept installation, namely “Hydrogen storage space” and “Fuel Cell space”, were prioritised during the workshop.

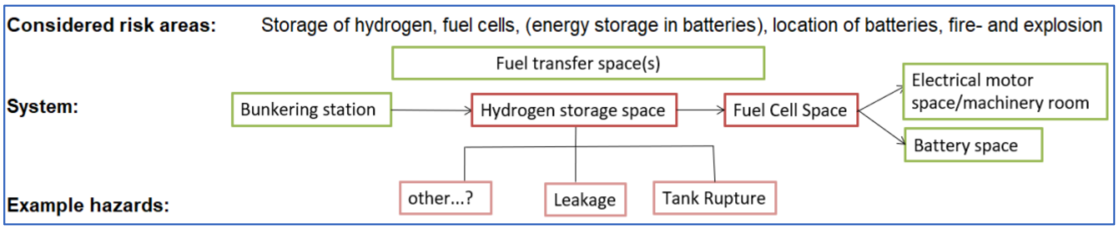

Figure 8 System description of concept installation.

An Excel workbook for the structure and documentation of the workshop was developed as part of the work.

First, potential ignition sources in each space were listed. Thereafter, hazardous events and their causes were identified. For each hazardous event, the probability of the event occurring (considering all possible causes), the potential consequences and their severities were discussed and documented. Critical factors for the hazardous events and current/known safety measures were also listed before identifying potential safety measures. Comments during the workshop were documented as well. A copy of the filled in Excel workbook can be found in Appendix C.

The workshop was followed by complementary meetings and email conversations to address questions that had not been resolved during the workshop. The most notable outcomes of the workshop are summarised below.

5.2.2 Result of the Hazard Identification Workshop

The resulting Excel worksheets from the HazID workshop are presented in Appendix C. The following is a summary of the most notable outcomes of the workshop.

- The batteries and the fuel cells should not be located in the same space. This to prevent the batteries from constituting an ignition source in spaces containing hydrogen.
- Several potential ignition sources were identified for the hydrogen storage space and the fuel cell space, such as electrical ignition sources, collision/mechanical damage, mechanically caused sparks, static discharge, heat sources and self-ignition of a hydrogen release. Several safety measures were identified to remove or minimise ignition sources in spaces containing hydrogen, reducing the probability of fire and explosions, for example choice of material, usage of explosion-classified equipment and maintenance routines for the on-board personnel. All identified measures are presented in Appendix C.
- Permeation is a hazard which occurs naturally due to the small size of the hydrogen molecule. The permeation rate through the material used for the hydrogen storage tanks should be understood and evaluated to ensure that the permeation rate is at an acceptable level. Metal lining can be expected to perform better in this regard in comparison with polymer lining. The ventilation system in the hydrogen storage space should be designed to manage the expected permeation. A measure to minimise permeation in the piping system could be to use double walled pipes and to use butt welded joints. Several other potential safety measures were identified to prevent and mitigate permeation (see Appendix C).
- Leakage is a hazard in both fuel storage spaces and fuel cell spaces. In a fuel storage space, leakage was assessed as a hazard that is known to occur, and even common if testing and maintenance of the tanks is not properly managed. Identified potential causes include corrosion of system components, weaknesses in connections and manufacturing errors. The consequences of a leakage may vary, with an explosion being the worst-case scenario which could result in major damage to the ship or fatalities. A-60 divisions, gas detection, suitable systems for fire-extinguishing and fire detection are safety measures expected in both fuel storage spaces and fuel cell spaces to prevent and mitigate the consequences of a hydrogen leakage. Either a ventilation system or an inerting system will also need to be implemented in the spaces as a safety measure. Examples of potential safety measures for the fuel storage space and

the fuel cell space that were identified during the workshop are listed below (the complete list of safety solutions are presented in Appendix C):
    - Shut-off valves between the cylinders in the hydrogen storage space.
    - Pressure relief valves for the hydrogen storage tanks, ensuring relief in a "safe" direction.
    - Having the hydrogen storage tanks enclosed in a box, which is ventilated or has an inert atmosphere (with over-pressure) with a release valve to the outside of the ship. Such a box could also be mounted on rubber feet to mitigate vibrations.
    - Operational safety procedures for operation and maintenance, as well as training of the crew to know the particulars of hydrogen fire safety.
    - Hand-held leakage detectors/sniffers, to be used during maintenance.
    - Use of explosion-classified equipment and choosing materials that minimise the probability of static discharge and rust (to avoid the need for rust grinding).
- Other hazards identified for hydrogen storage spaces and fuel cell spaces were storage tank rupture, loss of power and flooding. However, these hazards were not prioritised during the HazID and were thus not further reviewed.
- Procedures for testing and classification of components, such as hydrogen storage tanks and fuel cells, were brought up during the workshop as important aspects of a fuel cell power installation. The components used in this type of installation should be adapted to usage in the maritime environment. Vibrations and exposure to salt water were also aspects identified as needed to consider. Components should be tested and certified in to demonstrate performance in a maritime environment.

The risks identified during the HazID and how they relate to each other in terms of severity of consequences are illustrated in Figure 9. Note that the estimates of the severity of consequences are qualitative and associated with uncertainties. The estimates were made without considering the potential safety measures identified during the HazID workshop. The numbers of the scale do not correspond to a certain risk criterion or pre-defined acceptable risk level. Rather, figure 9 is for illustrative and comparative purposes of the HazID result only.

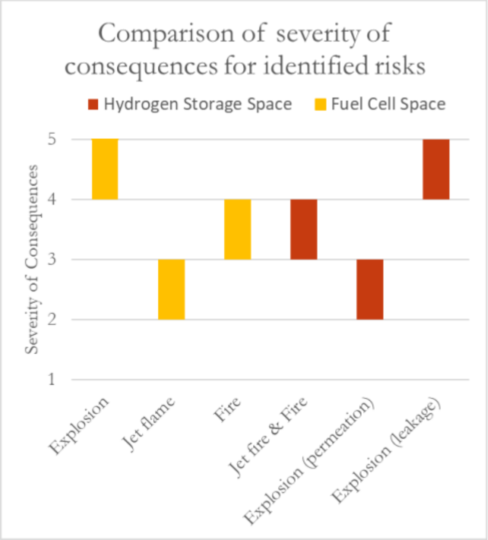

Figure 9 Illustration of the severity of consequences for the identified risks during the HazID, not considering potential safety measures.

The scale used to estimate the severity of consequences is presented in table 9.

Table 9. Scale of severity of consequences.

	1	2	3	4	5
Severity of Consequence	Minor service/ component replacement	Major service / material damage OR minor risk of injury	Major repair requiring downtime OR major risk of injury	Loss of propulsion OR risk of fatalities	Major damage to ship OR high risk of fatalities

5.3 Discussion of regulations and safety solutions for the concept installation

5.3.1 Regulatory gaps

There are currently no internationally accepted maritime regulations for the use of hydrogen and fuel cells on-board an existing ship. IMO is currently developing interim guidelines covering fuel cell power installation, which will be a step closer to having such maritime regulations. However, storage of hydrogen on-board does not seem to be covered by the current regulation or the regulations being developed. Bunkering of hydrogen is another area of using hydrogen and fuel cells on-board where the regulation screening did not give any results.

5.3.2 Safety solutions for the concept installation

Based on the HazID and the regulatory overview, several areas where further analysis is needed were identified for the concept installation. These areas are discussed below. It is to be noted that the output constitutes a hazard identification of the concept installation, and the results should be viewed as a basis for further assessment. A risk assessment is needed to establish the levels of risk and to determine required measures to make the risks acceptable.

Collision and grounding were identified as possible causes to a leakage in the fuel cell spaces and hydrogen storage spaces in the HazID. Chapter 5.3 of the IGF Code include requirements about the location of natural gas tanks to protect the tanks from external damage caused by collision or grounding (IMO, 2016). The location of the hydrogen storage tanks was therefore updated in the concept installation to adhere to these requirements to protect the hydrogen storage tanks from collision and grounding.

In the concept installation, the hydrogen storage spaces, and fuel cell spaces are located in enclosed spaces under deck. On the contrary, risk management strategies for hydrogen are generally based on "open-air" installations to ensure quick dispersion and lesser probability of pressure build-up. The placement of the hydrogen storage tanks and fuel cells in the concept installation means that an explosion or fire will most likely affect the spaces above the hydrogen storage space and fuel cell spaces. An "open air" installation might be the most feasible solution for fuel cell installation when considering fire and explosion risks. Therefore, the explosion integrity of the proposed spaces should be analysed. The consequence of an explosion or fire should also be analysed and assessed to see how other spaces on-board are affected, and to determine the level of risk as well as necessary safety measures to make it acceptable.

In accordance with the Interim IMO Guidelines and the IGF Code, access to hydrogen storage spaces and fuel cell spaces should preferably be directly from open deck. If this is not possible, access to the hydrogen storage spaces and fuel cell spaces should be through air locks. Alternatively, technical provisions could be made so that access to the spaces is only possible after it has been confirmed that the atmosphere is gas-free and after the equipment has been shut down, isolated from the fuel system and drained from gas. Access to the spaces was not covered by the HazID, and technical provisions to access the hydrogen storage space and fuel cell spaces in the concept installation, as required by the regulations, is an area to be further addressed.

There are areas where the configuration and design of an existing ship such as Uraniborg might affect the possibility to comply with current regulations and the possibility to implement safety measures. For example, integrating new safety systems such as a suitable ventilation system, or creating a safe way to access the hydrogen spaces, might be more challenging on an existing ship compared to a newbuild.

The fuel transfer system for the hydrogen (piping system) was not covered by the HazID workshop. Due to the configuration of the hydrogen storage spaces and fuel cell spaces in the concept design, pipes containing hydrogen would most likely have to cross spaces that are currently not designed to contain hydrogen and where personnel may be present. The piping system will therefore need further assessment to establish an acceptable level of safety. One possible solution is to put the pipes containing hydrogen in gas-tight enclosures where the pipes are led through such spaces. The gas-tight enclosures could be fitted with detection systems to detect a leakage as well as an inerting system to prevent creation of a flammable mixture.

Bunkering was raised as an important safety aspect during the HazID workshop of a fuel cell power system installation. However, bunkering was only discussed briefly during the workshop. Compared to existing bunkering procedures, bunkering of hydrogen will result in new risks that have yet to be identified for a maritime application. Further consideration of the bunkering process in general, and especially the safety aspects is therefore recommended.

6 Concept results and conclusions

In this chapter the final, remodelled, concept design of the potential fuel cell/battery system on-board Uraniborg is presented. Alterations has been made in order to better align the set-up according to existing regulations and the findings in the Hazard Identification workshop. The chapter also includes conclusions from each work package as well as suggestion on further research areas.

6.1 Final concept design

In order to adapt the suggested designs in chapter 4 to the regulations and safety aspects that were highlighted in the previous chapter, a number of alterations have been made. In summary, the propulsion set-up was set to “case 3”, the placing of all included components was rearranged, and lastly the storage capacity was reduced.

The following safety aspects has affected the original design:

- The batteries and the fuel cells should not be located in the same space. (HazID WS)
- The fuel tanks should be protected from external damage caused by collision or grounding by being located at a minimum distance of B/5 measured from the ships side to the centreline. (IGF)
- The fuel cells and battery packs should be evenly distributed (if possible) regarding weight. (HazID WS)

In figure 10 the original design for case 3 is shown with the violations to the rules and recommendations highlighted. In the figure, the B/5 distance is marked in red.

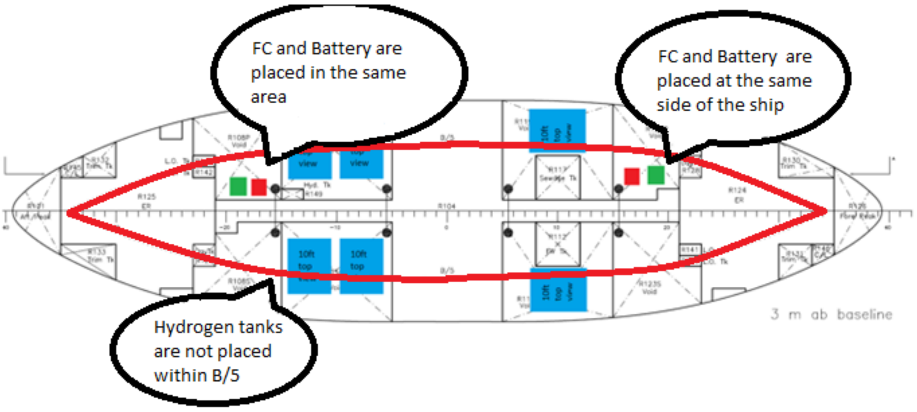

Figure 10 The original design proposal for case 3 is showcased with highlighted regulations violations. The B/5 distance is marked in red.

To accommodate the recommended safety aspects, the fuel cells and battery units were separated and placed in individual voids. In order to spread the weight of the installation evenly, the case 3 design was selected as it contains an even number of units, which in turn was placed at opposite sides to each other. Thus, the installed power capacity of the installation remained unchanged to the original design. However, to adjust the design in accordance with the IGF code, the hydrogen storage capacity needed to be reduced due to a lack of available space within B/5.

In figure 11-12 two possible new designs are presented. In the first set-up, the hydrogen storage consists of three units with a combined capacity of 495 kg hydrogen. This corresponds to 2,8 days of operation. With a safety margin this would indicate that Uraniborg needs to bunker every second day. The second design is based on the assumption that the hydrogen storage tanks are modular and allowed to be divided in smaller units. In this scenario, the storage tanks could be installed in the remaining area close to the sewage tanks and add to a total hydrogen capacity of 907,5 kg. This corresponds to 5,0 days of operation but with a recommendation of a bunkering sequence every fourth day.

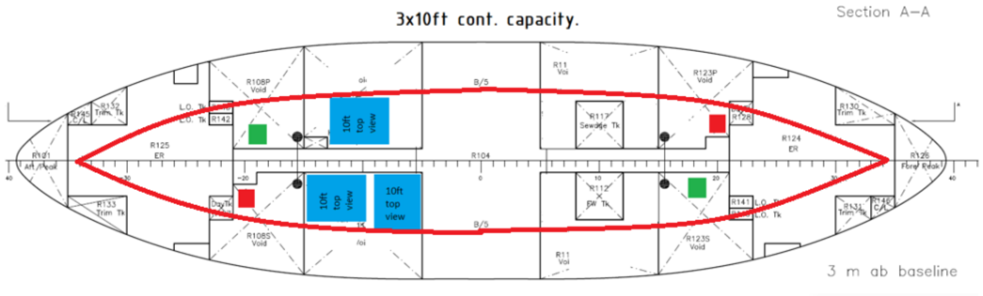

Figure 11 The improved design proposal of the electrical FC/battery drive train on-board Uraniborg. The fuel cells (green) and battery units (red) have been replaced and separated and the hydrogen storge have been reduced to 3 units and replaced to fit inside the B/5 distance.

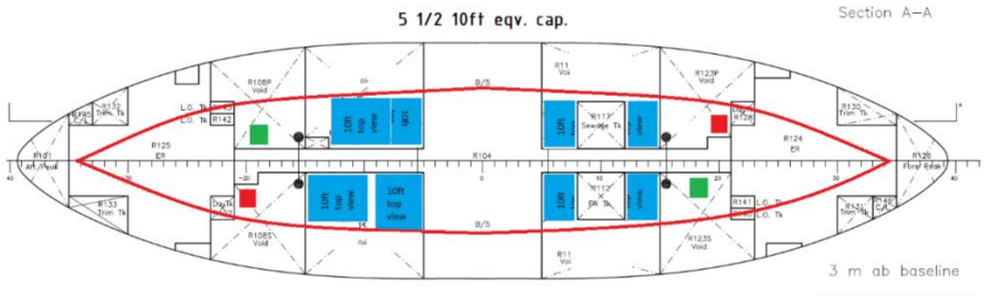

Figure 12 The improved design proposal of the electrical FC/battery drive train on-board Uraniborg. The fuel cells (green) and battery units (red) have been replaced and separated and the hydrogen storge have been reduced to 5,5 units (assuming modular design) and replaced to fit inside the B/5 distance.

In table 10 the two design proposals are summarised.

Table 10 Summery of final FC/Battery design on-board Uraniborg

Technical summery			
Redesign 1		**Redesign 2**	
Battery features		**Battery features**	
Number of units	2	Number of units	2
Power capacity	154	Power capacity	154
Fuel cell features		**Fuel cell features**	
Number of units	2	Number of units	2
Power capacity	400kW	Power capacity	400kW
Hydrogen storage		**Hydrogen storage**	
Number of units	3	Number of units	5,5
Storage capacity	495 kg	Storage capacity	907,5

6.2 Project conclusions

In this section the conclusion from each chapter is presented.

6.2.1 Present status of marine hydrogen installations and actors in the maritime hydrogen sector

The first pilot projects with 100% fuel cell propulsion, described in section 2.1, are now being built and delivered. This being both new-built fuel cell installations and retrofit installations from conventional diesel engines.

As described in section 2.2, different stakeholders with special importance to the development of maritime hydrogen applications have been identified within this project. Pinpointed as large-scale hydrogen node, port areas are foreseen to establish a strategic role in the transport system regarding storage & supply of hydrogen as a fuel. But equally important are shipping companies, manufacturers of different kind equipment, energy companies, authorities, classification societies, researchers etc.

6.2.2 Aspects using hydrogen and as bunker fuel

Renewable hydrogen will most likely be produced either by electrolysis or via reforming of biomethane (biogas). Due to support from society and interest from the industry such as steel and truck manufacturing as well as chemical plants, it is likely that the renewable hydrogen production will grow in the coming years, as discussed in section 3.1.

Benefits with green hydrogen as a fuel used in fuel cells are that the system can be seen as almost emission free, creates very little noise and that hydrogen can be produced almost anywhere as long as there is access so electricity and water. The challenges for the usage of hydrogen as marine fuel are mainly costs, safety and storage.

Related to costs, estimates from research projects and predictions from organisations like the classification societies as well as companies that develops ship concepts based on alternative fuels is that hydrogen solutions for ships will be more costly than battery electrical solutions for cases where the battery solution is manageable, for shorter operational range and where it is manageable to access and charge the system.

6.2.3 System design and hydrogen applications

The use of hydrogen as a marine fuel is still in its early stages of adaptation and there is a great need of knowledge build-up. This in turn makes it impossible to solely rely on the traditional actors in the value-chains, such as shipyards, when it comes to retrofit procedures that includes hydrogen installations. Support and insights from third parties with previous experience of practical installations is needed to succeed. In other words, there is a need for a knowledge transfer from other parts of the transport and energy industry. E.g., a potential hydrogen installation endeavour on-board Uraniborg would need to consult companies outside the maritime industry with knowledge in areas such as piping for hydrogen, installation, inspection, and testing. And all of these in combination and integration with hazardous electrical installations, high pressures systems or cryogenic temperatures and high voltage DC power.

In the case of Uraniborg, we look at a retrofit installation which is a complicating factor compared with installing the hydrogen propulsion system in a new built vessel. Firstly, the design of Uraniborg is made with regards to a conventional drive train and surrounding systems, both from a technical, a regulatory and an operational perspective. To install a completely new and in many ways different system into an existing design will be a challenge from all above three aspects and demands new innovative solutions. The installation will affect most of the vital system on-board and large interventions needs to be carried out in the ships structure and systems. These interventions will also affect the safety and operation of the ship and needs therefore to be compliant with rules and regulations as well as with the standard operating procedures, such as e.g., bunkering, firefighting, maintenance etc.

The interaction between the new system and components of the old systems will need to be addressed, since this might affect the total efficiency of the system. Due to the complexity off a retrofit installation, the cost can be assumed to be higher than the same system in a new build. Adding to the cost for a retrofit is also the time span that the ship will be off-hire and the possible need for a replacement ship. However, with new technology such as digital tools for modelling and simulation of the installation, time can be saved. It should be noted that every ship and its operational profile is different and that of course affects the complexity and cost of the installation.

6.2.4 Regulatory inventory and safety solutions for the concept installation

The regulation screening shows that there are currently no internationally accepted maritime regulations for the use of hydrogen and fuel cells. Interim guidelines for fuel cell installation on-board are currently being developed at IMO, and there are also classification society regulations currently being developed that will address installation of fuel cells. However, the regulation screening has not been able to show existing regulations that covers the storage of hydrogen tanks on-board, or any ongoing work with this type of regulations. Bunkering was emphasised as an important aspect for the use of hydrogen and fuel cells on-board during the HazID. However, the regulation screening did not show regulations addressing bunkering of hydrogen. Therefore, hydrogen storage on-board and bunkering of hydrogen are considered regulatory gaps.

6.2.5 Hazard Identification workshop

The HazID showed that testing and certification of fuel cells and hydrogen storage tanks for use in the maritime environment does not seem well refined. More clarification about requirements of testing and certification is needed.
The following list presents the overall conclusions of the HazID:

- Batteries, fuel cells, and hydrogen storage tanks should be separated. This is to avoid batteries constituting a fire hazard for the fuel cells and hydrogen storage tanks.
- Ignition sources in the fuel cell space and hydrogen space is an important safety aspect to take into consideration, and potential ignition sources should be eliminated or minimised. Choice of material, usage of explosion-classified equipment and maintenance routines for the on-board personnel were identified as potential safety measures for this.
- An explosion in the fuel cell spaces or the hydrogen storage spaces constitutes the largest risk according to the HazID results. As described in chapter 5.2.2, a leakage in the hydrogen storage space was rated as an event that is "common" (4 out of 5 on the likelihood scale, refer to Appendix C). An explosion following a leakage in the hydrogen storage space or fuel cell space might cause major damage to ship or high risk of fatalities. It should be noted that a leakage does not necessarily lead to an explosion.
- The HazID of the concept installation should be viewed as a basis for further assessment. A full risk assessment of a fuel cell installation on-board is needed.

6.3 Future initiatives and research

A list of areas where further studies and work are recommended is presented below:

- Further assessment of the identified risks, especially the risk of explosion connected to leakage of hydrogen.
- Further assessment of the cost of the identified safety measure and a detailed review of their effect on the risks.
- Research regarding different storage options of H2 and connected piping systems.
- Establish a knowledge and development centre regarding clean fuel alternatives for the maritime industry, including hydrogen applications.
- Further assessment of the bunkering procedure of hydrogen and the associated safety aspects.
- Further assessment on cost development for hydrogen installation taking both technical development and development of policies into consideration (internalisation of external costs).
- Pilot installations and assessments of real hydrogen projects. Both in form of new builds, retrofits on existing ships as well as tank stations, local hydrogen production, distribution of hydrogen and hydrogen storage.

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Appendix A General Hydrogen Safety Considerations

Like any other energy carrier, hydrogen poses risks of accidents. The risks depend on the properties of hydrogen in combination with how the system is designed, run, and maintained. The surroundings also affect the risks.

This summary is based on ISO/TR 15916:2015 *Basic considerations for the safety of hydrogen systems* Chapter 6. Please note that the summary does not reflect all hazards of hydrogen that needs to be taken into consideration.

Hydrogen is a very **small molecule** (smallest of all gases), making it more likely to penetrate through materials and seals that are usually considered leak-proof. In unventilated spaces, even the smallest leak can eventually create combustible concentrations. Materials must be selected with this in consideration.

The **low relative density of** hydrogen (14 times lighter than air) causes hydrogen to rise rapidly, and the high diffusion coefficient causes it to quickly mix (in all directions) in air. This can cause small undiscovered leaks to accumulate in ceilings, for example, and combustible concentrations to occur on levels below the point of release. The propensity to mix can be an advantage when emitted outdoors, making hydrogen to relatively quickly dilute.

Hydrogen can cause **hydrogen embrittlement** in some metals by intruding and altering the properties of the metal so that it becomes brittle as cast iron, which can lead to cracks and leakage.

Hydrogen is **odourless** and without **toxic effects** on humans and the environment, but at high concentrations it can cause **asphyxiation**. Gaseous hydrogen is **colourless,** and an emission is difficult to detect (possibly a wheezing sound is heard), while liquid hydrogen has a blue colour. Hydrogen burns with a virtually invisible flame, which is why even an ignited emission can be difficult to detect.

Gaseous hydrogen is stored under high pressure, equal to high concentration of potential energy. Under the right conditions, as with other pressurized gases, a sudden release of this energy can have major pressure effects even without ignition.

Hydrogen can ignite in the presence of an oxidizing agent (e.g., oxygen) if t an ignition source is present. Compared to other combustible gases, hydrogen has a wide **flammability range** (4-77 % by volume in air) and low minimum ignition energy. Therefore, the probability of an emission igniting is higher than that of other gases. Hydrogen has also been shown to **ignite without an ignition source** present in the event of sudden releases from a pressure vessel into air. Because of these properties, many safety measures are based on separating hydrogen from oxidising agents.

Depending on the conditions (type of emissions, mixture, ambient), **combustion** of hydrogen may be non-premixed (e.g., at point emissions such as jet fire), deflagration (flame speed <350 m/s) and detonation (flame rate >350 m/s). **Reaction front** in hydrogen is moving very fast relatively, therefore explosion vents may not have time to release over pressure. Obstacles in the environment (e.g., pipes and walls) increase the likelihood of **pressure build-up** during combustion.

Appendix B Detailed comparison of regulations and guidelines

Table 11 gives a detailed comparison of relevant regulations and guidelines for a hydrogen fuel cell installation on-board a ship. Notable changes in the updated guidelines from Bureau Veritas (under development) have been included in the rightmost column of Table 11. The updated guidelines from Bureau Veritas are still a draft and subject to modification. Note that the comparison does not constitute a full account of the documents, only an overview.

Table 11. Comparison of fire safety requirements for onboard hydrogen fuel cell installations in relevant regulations.

	IGF Code	**Interim Guidelines for the safety of ships using fuel cell power installations (under development)**	**Bureau Veritas: Guidelines for Fuel Cell Systems Onboard Commercial Ships**	**Bureau Veritas: NR 547 Ships Using Fuel Cells (notable changes)**
Purpose	To provide an international standard for ships using low-flashpoint fuel.		Providing criteria for the arrangement and installation of machinery for propulsion and auxiliary purposes, using fuel cell installations.	Providing requirements for using fuel cell power systems onboard ships.
Application	Ships to which Part G of SOLAS chapter II-1 applies. This means that the IGF Code applies to ships using low-flashpoint fuels.		Fuel cell systems installations in ships.(1.1.1) Applicable to new ships. Application to existing ships to be decided by the Society. (1.1.4)	Design and installation of fuel cell power systems onboard. Does not cover hydrogen storage onboard. (1.2)
Status	2016 edition	Planned to be published during 2021.	Published 2009	Planned to be published during 2021.
Type of substance covered	Natural gas (LNG & CNG)	Hydrogen as fuel in fuel cells. Does not cover reformed fuel.	Hydrogen and other light gases, both in compressed and liquid state.	
Risk Assessment	A risk assessment to be made to address risks arising from the use of low-flashpoint fuels affecting persons onboard, the environment, the structural strength, or the integrity of the ship. The risk assessment should as a minimum consider: • Loss of function • Component damage • Fire • Explosion • Electric shock (4.2)	Risk arising from the use of fuel cells affecting the integrity of the ship should be analysed using recognized techniques. The risk analysis should as a minimum consider. - Mechanical damage - Operational and weather-related influences - Electrical faults - Unwanted chemical reactions - Toxicity - Auto-ignition	Risk analysis should be made addressing risks affecting structural strength and integrity of the ships using acceptable and recognized risk analysis techniques. The risk analysis should as a minimum consider: • Loss of function • Component damage • Fire • Explosion • Electric shock (2.1.1-2.1.3)	Scope of risk assessment is extended to also address persons onboard and the environment. Risk assessment is specified to include an HAZID for the fuel cells spaces, an HAZOP for the fuel cell power system and a FMECA analysis (only if fuel cell power installation is used for essential services). Scope of risk analysis is extended to also include • operational and environmental-related influences • Unwanted chemical reactions

		- Fire and explosions - Blackout (4.3)	The risk analysis should identify spaces where explosive mixtures may form, their volume as well as probability of explosion and potential consequences. (2.1.6) A safety and reliability analysis of the fuel cell power system should be made to identify hazards. Risk of hazards should be estimated from a combination of probability and severity. (6.1.2)	- Toxicity - Auto-ignition of fuels Blackout (2.1-2.1.3)
Fire Detection & Alarm Systems	Fixed fire detection and fire alarm system in compliance with FSS Code in fuel storage spaces and other relevant spaces of the fuel gas system where fire is possible. Smoke detection is not sufficient (11.7).	Fixed fire detection and fire alarm system in compliance with FSS Code. (3.1.4). Suitable fire detectors should be provided in fuel cell spaces. Smoke detection is not sufficient. (3.1.6)	Approved fixed fire detection system in tank room and ventilation trunk for tank room below deck. Smoke detection is not sufficient. (3.4.1) Detectors should be adapted to the flame produced by the gas. (3.4.1)	New guidelines require a detection system complying with NR467 Pt C, Ch 4, Sec 15. Flame detectors are required in fuel cell spaces. (6.4)
Control, monitoring & safety systems.	Liquid level gauging device in each liquified gas fuel tank (15.4.1) High liquid level alarm in each liquified gas fuel tank (15.4.2) High/low pressure alarm for bunkering & fuel tank monitoring. Pressure indicator for: - each pump discharge line and each fuel manifold, - ship's manifold valves and hose connections to the shore, - Fuel storage hold spaces and interbarrier spaces without open connection to the atmosphere (15.4.5-8) Gas compressor monitoring: alarms shall as a minimum be provided for low gas input pressure, low gas output pressure, high gas output pressure & compressor operation (15.6.1). Gas detection in tank connection spaces, ducts around fuel pipes, machinery spaces, compressor rooms & fuel preparation rooms,	Permanently installed gas/vapour detection system should be provided for fuel cell spaces, airlocks, expansion tanks/degassing vessels in the auxiliary system of the fuel cell power system, and other enclosed spaces where primary/reformed fuel may accumulate. (5.2.1) Gas/vapor detection should be provided for fuel cell spaces, air locks, expansion tanks/degassing vessels in the auxiliary systems where primary fuel may leak directly into a system medium, and other enclosed spaces where hydrogen may accumulate. (5.2.1) A detection system of the ventilation flow and of the fuel cell space pressure should be provided (5.3.1) Level sensors should be provided in bilge wells in fuel cell spaces. (5.4)	Monitoring and control options according to result of risk analysis. (5.1.5) Pressure gauge should be fitted: - between stop valve & connection to shore at bunker pipes. - At gas pump discharge lines and bunkering lines. (5.1.1-2) A bilge well in tank room surrounding liquid gas storage tank should have level indicator and temperature sensor. (5.1.3) Gas tanks should be monitored and protected from overfilling. A local indicating instrument for pressure should be provided for each tank. (5.2.1-5.2.2) Gas compressor monitoring: alarms shall	*Not reviewed*

	airlocks, gas heating circuit expansion tanks, motor rooms, other relevant spaces. ESD-protected machinery spaces shall have redundant gas detection systems. (15.8) Alarm for loss of the required ventilation capacity (15.10)	Manual activation of emergency shutdown should be arranged: on navigation bridge, in onboard safety centre, in engine control room, in fire control stations, adjacent to the exit of the fuel cell space. (5.5) Fuel cell monitoring should be made in accordance with the manufacturer's recommendations. (5.1.2)	as a minimum be provided for low gas input pressure, low gas output pressure, high gas output pressure & compressor operation (5.3.1) Gas detection should be provided in relevant spaces. ESD-protected machinery spaces should have two independent gas detection systems. (5.5.1) Parameters to be monitored in fuel cell power system should be based on a risk analysis as described in (6.1.2). Cell stack or process fault, ground fault, low voltage fault and overcurrent fault are all faults connected to the fuel cell power system that may need monitoring.	
Containment	A-60 class divisions between fuel tanks on open deck & other spaces shall be provided. (11.3.2) Space containing fuel containment system shall be separated from the machinery spaces of category A or other rooms with high fire risk by using a 900 mm cofferdam with insulation of A-60 class. (11.3.3) Spaces containing fuel containment systems shall either be separated with a cofferdam of at least 900 mm or A-60 class division. (11.3.3) A-60 class division between bunkering station and other spaces. A-60 class division for emergency shut down (ESD)protected machinery. (11.3.6-7) Fire protection of fuel pipes needs special consideration by the Administration. (11.3.5)	A-60 class divisions in fuel cell spaces (3.1.2) Gastight boundaries should be provided between fuel cell spaces and other enclosed spaces. (2.2.7) The fuel cell spaces should be able to safely contain fuel leakages and be provided with suitable leakage detection systems. (2.2.9)	Tank room boundaries and ventilation trunks should be constructed to class A-60. (3.2.2) Gas pipes trough ro-ro spaces need special consideration by the Society. (3.2.3) A-60 class divisions should be used to separate bunkering station from other spaces. (3.2.4) Access to the tank room should be from open deck, or through an air lock. (2.4.4). The fuel cell power system enclosure should be able to safely contain a capacity of 110% of the maximum volume of fluid anticipated to leak (6.1.17).	Piping containing hydrogen that has been generated in a fuel reformer onboard should not be lead trough enclosed spaces outside of a fuel cell space. The piping should be butt-welded as far as practicable, designed to minimize the number of connections and fitted with hydrogen detectors. (5.3.10)

	Fuel tanks shall be separated from cargo in acc. with IMDG Code where the fuel tanks are regarded as bulk packaging. (11.3.2)			
Extinguishment	Enclosed spaces containing equipment for fuel preparation are to be provided with a fixed fire-extinguishing system complying with SOLAS II-2/10.4.1.1 and FSS Code while considering concentrations/application rate that is needed for extinguishing gas fires. (11.3.1) Water spray system covering exposed parts of storage tank located on open deck and providing coverage for boundaries facing the storage tank. The system should have an application rate of 10 l/min/m² for the largest horizontal projected surfaces and 4 l/min/m² for vertical surfaces. (11.5) Dry chemical powder system in bunkering station area (11.6) One portable dry powder extinguisher near the bunkering station (11.6.2) Fire dampers in ventilation trunk for the tank connection space (13.4.2)	A fixed fire-extinguishing system that is suitable for the primary fuel and the fuel cell technology is required in fuel cell spaces. (3.3) Fire dampers should be provided in air inlet and outlet openings (3.4)	Water spray system covering exposed parts of storage tank above deck (3.3.2) Dry chemical powder system in bunkering station area. (3.3.3) One portable dry powder extinguisher near the bunkering station. (3.3.3) Fire dampers in ventilation trunk for tank room. (2.10.2)	New guidelines only specify that the extinguishing system should be suitable for hydrogen and the fuel cell technology. (6.3) Fire dampers should be provided in inlets and outlets if the space is ventilated. (4.4.2).
Explosion prevention	The probability of explosion shall be minimized by reducing the number of sources of ignition and reducing the probability of formation of ignitable mixtures. (12.2) Explosion shall be prevented by minimizing electrical equipment and wiring in hazardous areas. Electrical equipment in an ESD-protected machinery spaces need to fulfil special requirements. (12.3)	Fuel cell spaces should have simple geometrical shape to avoid accumulation of hydrogen-rich gas (2.2.9) Atmospheric control of fuel cell spaces should be made by either inerting or ventilation (2.3.1.1) Probability of gas accumulation & explosions in fuel cell spaces should be minimized by strategies including one or more of the following: - Purging - Providing failure monitoring in fuel cell containment systems, - contamination monitoring of air into fuel lines/fuel into air pipes,	Gas fuel cell power system components, systems and subsystems should be designed to exclude any explosion at all possible situations (6.4.1) Within a fuel system/process that uses controlled oxidation reactions, reactors or thermal burners potential formation of flammables should be avoided by: - Purging - Air-to-fuel regulation - Reactant shutoff, purging/passivation as necessary after shutdown (6.4.5) Ventilation should be provided in tank rooms. (2.10.2)	A fuel cell space is either to be ventilated or inerted. (4.4.1)

		- pressure/temperature monitoring, - providing pre-programmed sequence to contain/manage propagation of reaction to other sections of fuel cell system or surrounding spaces. (3.2.3)	Fault monitoring in fuel processing systems should be provided. Possible formation of flammable mixtures due to failures in fuel containing systems should be addressed. Design of fuel processing system should consider air ingestion, cross-flow/back-flow of air into fuel lines or fuel into air lines. The fuel system should be able to contain or release pressure and temperature build-ups and manage the propagation of the reaction to other sections of the fuel system/external environment. Formation of flammables outside the fuel system should also be managed. (6.4.5)	
Explosion mitigation	An explosion shall not: - Impact proper functioning of systems/equipment in adjacent spaces - Cause flooding below main deck - Injure people - Disrupt control stations & switchboard rooms necessary for power distribution - Damage life-saving equipment - Damage firefighting equipment outside the space - Create chain reactions - Prevent access to LSA or impede escape routes (4.3)	Fuel cell spaces separated by a single bulkhead should have sufficient strength to withstand a local gas explosion without affecting the integrity and equipment of the adjacent space. (3.2.1) Suitable explosion pressure relief devices and ESD arrangements should be used to mitigate failures leading to dangerous overpressure, e.g. gas pipe ruptures or blow out of gaskets. (3.2.2)	An explosion should not: - Cause damage to any space other than that in which the incident occurs - Disrupt the proper functioning of other zones - Damage the ship so that flooding below the main deck or any progressive flooding occurs - Damage work areas or accommodation so that people are injured - Damage life-saving equipment or associated launching arrangements - Disrupt functioning of fire-fighting equipment located outside the explosion damaged space - Affect other areas so that chain reactions may arise. (2.1.6) If gas fuel cell power system components, systems and subsystems are not designed to exclude any explosion at all possible situations, they should be designed to allow explosions without detrimental	New guidelines also specifies that an explosion should not prevent access to life-saving appliances or impede escape routes. (2.2) An explosion analysis is to be performed for ventilated fuel cell spaces to demonstrate that the maximum pressure build-up does not exceed the design pressure of the space (2.2.2).

			effect and to discharge to a safe location. Explosions should not interrupt safe operation of fuel cell power system. (6.4.1) Pressure relief valves should be provided for storage tanks and for the storage space. (2.8.2, 2.8.4).	
Other	Spaces containing equipment for the fuel preparation shall be regarded as a machinery space of category A (11.3.1)	Fuel cell space should be regarded as a machinery space of category A for fire protection purposes. (3.1.1)	Compressor room should be regarded as a machinery space of category A for fire protection purposes (3.1.2)	Fuel cell space should be regarded as a machinery space of category A. (6.1.2)

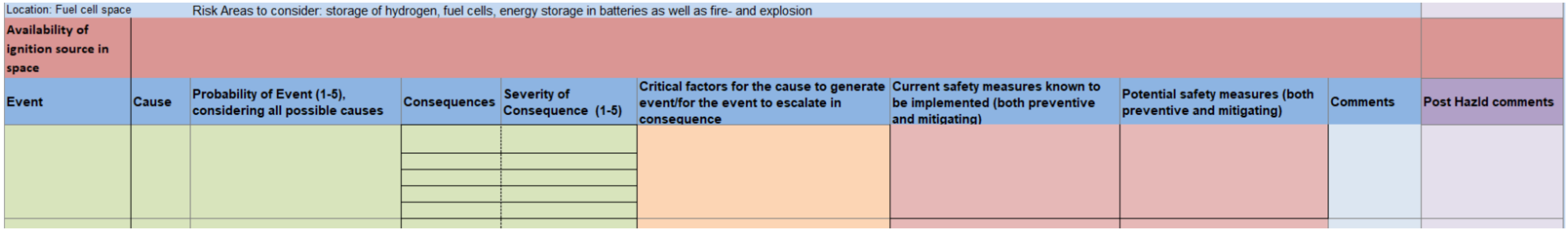
Appendix C HazID workshop

The participants of the workshop, their organisation and their profession and area of expertise are listed in Table 12. A representative from Euromekanik was also invited to the HazID workshop but was unable to attend. A complementary meeting was held with Euromekanik after the workshop to address questions about hydrogen storage tanks that were raised during the workshop.

Table 12. Participants of the HazID workshop.

Participant	Organisation	Profession / Area of expertise	Role in HazID
Stina Andersson	RISE	Research Engineer / Fire safety, risk management	Facilitator
Franz Evegren	RISE	Director of the Fire Safe Transport Unit / Risk assessment, ship fire safety	Co-Facilitator /Scribe
Andreas Bach	RISE	Project leader / Maritime operations	Project Owner
Paul Adams	RISE	Business developer / Vehicle hydrogen safety	Participant
Petra Andersson	RISE	Senior Researcher / Battery fire safety, explosion	Participant
Karl Samuelsson	PowerCell	COO &/ director of product development	Participant
Saeed Mohebbi	Transportstyrelsen/ Swedish Transport Agency	Marine engineer/ Senior advisor electrical safety and alternative fuel	Participant
Linus Olsson	Ventrafiken	Master Mariner/Managing Director	Participant
Patrik Appelgren	Vattenfall	Affärsutvecklare, Grön omställning	Participant
Bilal Malla	Vattenfall	Affärsutvecklare, Grön omställning / Marinexpert	Participant
Mariusz Maruszak	Bureau Veritas	Electrical Plan Approval Surveyor – Electricity matters	Participant
Jan Janzen	Bureau Veritas	Plan Approval Surveyor Machinery & Safety	Participant

The structure of the HazID is presented in Table 13. .



Location: Fuel cell space

Risk Areas to consider: storage of hydrogen, fuel cells, energy storage in batteries as well as fire- and explosion

Availability of ignition source in space

Event	Cause	Probability of Event (1-5), considering all possible causes	Consequences	Severity of Consequence (1-5)	Critical factors for the cause to generate event/for the event to escalate in consequence	Current safety measures known to be implemented (both preventive and mitigating)	Potential safety measures (both preventive and mitigating)	Comments	Post HazId comments

Table 13. Structure of HazID.

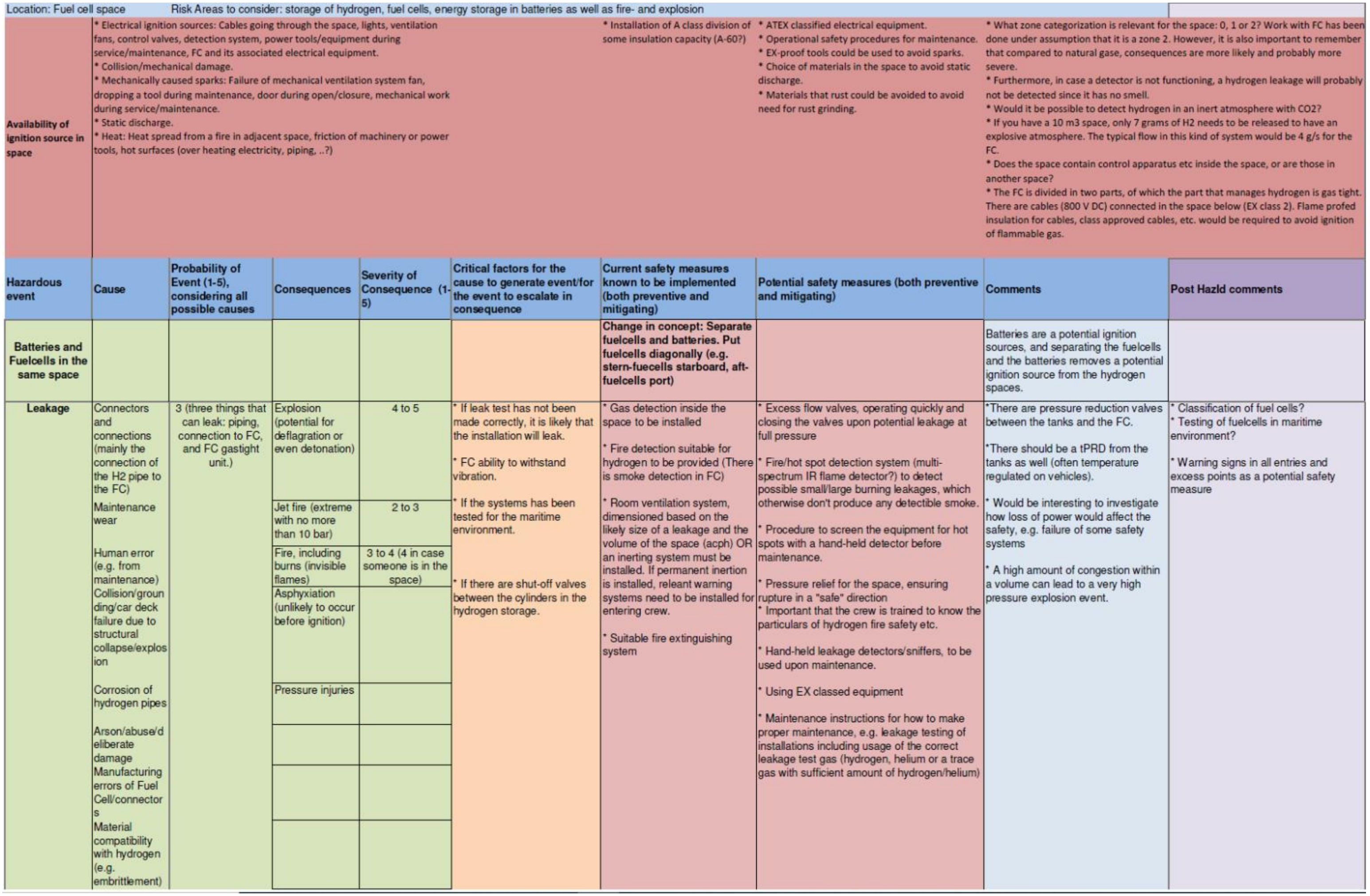
The probability of a hazardous event and the severity of each consequence was estimated using a scale from 1 to 5. The numbers correspond to a probability and severity as presented in chapter 5.

Table 14.Scale for estimating probability and severity of consequences.

	1	2	3	4	5
Probability of Event	Practically impossible	Not likely/ heard of it	Known to occur	Common	Very common
Severity of Consequence	Minor service/component replacement	Major service / material damage OR minor risk of injury	Major repair requiring downtime OR major risk of injury	Loss of propulsion OR risk of fatalities	Major damage to ship OR high risk of fatalities

The resulting Excel spreadsheets from the HazID workshop are presented below.

Resulting Excel spreadsheet from HazID workshop for Fuel Cell Space



Location: Fuel cell space	Risk Areas to consider: storage of hydrogen, fuel cells, energy storage in batteries as well as fire- and explosion								
Availability of ignition source in space	* Electrical ignition sources: Cables going through the space, lights, ventilation fans, control valves, detection system, power tools/equipment during service/maintenance, FC and its associated electrical equipment. * Collision/mechanical damage. * Mechanically caused sparks: Failure of mechanical ventilation system fan, dropping a tool during maintenance, door during open/closure, mechanical work during service/maintenance. * Static discharge. * Heat: Heat spread from a fire in adjacent space, friction of machinery or power tools, hot surfaces (over heating electricity, piping, ..?)					* Installation of A class division of some insulation capacity (A-60?)	* ATEX classified electrical equipment. * Operational safety procedures for maintenance. * EX-proof tools could be used to avoid sparks. * Choice of materials in the space to avoid static discharge. * Materials that rust could be avoided to avoid need for rust grinding.	* What zone categorization is relevant for the space: 0, 1 or 2? Work with FC has been done under assumption that it is a zone 2. However, it is also important to remember that compared to natural gase, consequences are more likely and probably more severe. * Furthermore, in case a detector is not functioning, a hydrogen leakage will probably not be detected since it has no smell. * Would it be possible to detect hydrogen in an inert atmosphere with CO2? * If you have a 10 m3 space, only 7 grams of H2 needs to be released to have an explosive atmosphere. The typical flow in this kind of system would be 4 g/s for the FC. * Does the space contain control apparatus etc inside the space, or are those in another space? * The FC is divided in two parts, of which the part that manages hydrogen is gas tight. There are cables (800 V DC) connected in the space below (EX class 2). Flame profed insulation for cables, class approved cables, etc. would be required to avoid ignition of flammable gas.	
Hazardous event	**Cause**	**Probability of Event (1-5), considering all possible causes**	**Consequences**	**Severity of Consequence (1-5)**	**Critical factors for the cause to generate event/for the event to escalate in consequence**	**Current safety measures known to be implemented (both preventive and mitigating)**	**Potential safety measures (both preventive and mitigating)**	**Comments**	**Post HazId comments**
Batteries and Fuelcells in the same space						**Change in concept: Separate fuelcells and batteries. Put fuelcells diagonally (e.g. stern-fuecells starboard, aft-fuelcells port)**		Batteries are a potential ignition sources, and separating the fuelcells and the batteries removes a potential ignition source from the hydrogen spaces.	
Leakage	Connectors and connections (mainly the connection of the H2 pipe to the FC)	3 (three things that can leak: piping, connection to FC, and FC gastight unit.)	Explosion (potential for deflagration or even detonation)	4 to 5	* If leak test has not been made correctly, it is likely that the installation will leak. * FC ability to withstand vibration. * If the systems has been tested for the maritime environment. * If there are shut-off valves between the cylinders in the hydrogen storage.	* Gas detection inside the space to be installed * Fire detection suitable for hydrogen to be provided (There is smoke detection in FC) * Room ventilation system, dimensioned based on the likely size of a leakage and the volume of the space (acph) OR an inerting system must be installed. If permanent inertion is installed, releant warning systems need to be installed for entering crew. * Suitable fire extinguishing system	* Excess flow valves, operating quickly and closing the valves upon potential leakage at full pressure * Fire/hot spot detection system (multi-spectrum IR flame detector?) to detect possible small/large burning leakages, which otherwise don't produce any detectible smoke. * Procedure to screen the equipment for hot spots with a hand-held detector before maintenance. * Pressure relief for the space, ensuring rupture in a "safe" direction * Important that the crew is trained to know the particulars of hydrogen fire safety etc. * Hand-held leakage detectors/sniffers, to be used upon maintenance. * Using EX classed equipment * Maintenance instructions for how to make proper maintenance, e.g. leakage testing of installations including usage of the correct leakage test gas (hydrogen, helium or a trace gas with sufficient amount of hydrogen/helium)	*There are pressure reduction valves between the tanks and the FC. *There should be a tPRD from the tanks as well (often temperature regulated on vehicles). * Would be interesting to investigate how loss of power would affect the safety, e.g. failure of some safety systems * A high amount of congestion within a volume can lead to a very high pressure explosion event.	* Classification of fuel cells? * Testing of fuelcells in maritime environment? * Warning signs in all entries and excess points as a potential safety measure
	Maintenance wear		Jet fire (extreme with no more than 10 bar)	2 to 3					
	Human error (e.g. from maintenance)		Fire, including burns (invisible flames)	3 to 4 (4 in case someone is in the space)					
	Collision/grounding/car deck failure due to structural collapse/explosion		Asphyxiation (unlikely to occur before ignition)						
	Corrosion of hydrogen pipes		Pressure injuries						
	Arson/abuse/deliberate damage								
	Manufacturing errors of Fuel Cell/connectors								
	Material compatibility with hydrogen (e.g. embrittlement)								

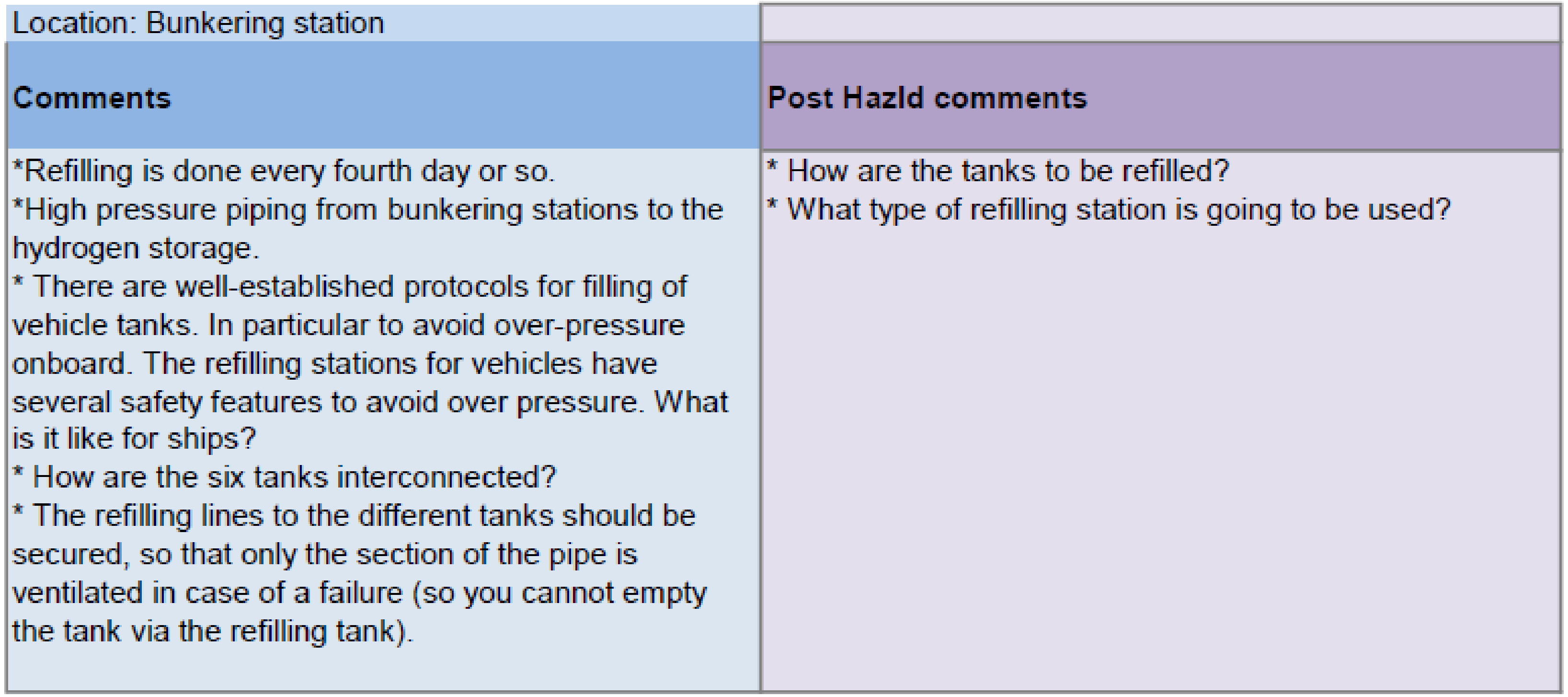
	FC not designed for a maritime environment (corrosion) Vibration								
Loss of power							*Hydrogen valves would close, but the ventilation would prefferable be kept open *Auxiliary machinery engines could be keept for redundancy.		
Flooding							*Flooding could potentially cause electrical faults in FC module		

Resulting Excel spreadsheet from HazID workshop for Hydrogen Storage Space

Location: Hydrogen Storage Space Risk Areas to consider: storage of hydrogen, fuel cells, energy storage in batteries as well as fire- and explosion									
Availability of ignition source in space	* Electrical ignition sources: Cables going through the space, lights, ventilation fans, control valves for storage tanks, detection system, power tools and equipment during service/maintenance/HOT WORK * Collision/mechanical damage. * Mechanically caused sparks: Failure of mechanical ventilation system fan, dropping a tool during maintenance, door during open/closure, mechanical work during service/maintenance. * Static discharge. * Heat: heat spread from a fire in adjacent space, friction of machinery or power tools, hot surfaces (over heating electricity, piping, ..?) * Self-ignition of a hydrogen release.					* Installation of A class division of some insulation capacity (A-60?)	*ATEX classified electrical equipment. *Operational safety procedures for operation and maintenance. *EX-proof tools could be used to avoid sparks. *Choice of materials in the space to avoid static discharge. *Materials that rust could be avoided to avoid need for rust grinding. * Putting the tanks in a box, which is ventilated and avoids external ignition sources. * Having an inert atmosphere inside the box (with over-pressure) with release valve to the outside of the ship. *A box could also be mounted on rubber feet (vibrations) etc.	* What zone categorization is relevant for the space: 0 or 1? Likely zone 1, since the tanks are not supposed to leak, even if they can potentially leak. However, it is also important to remember that compared to natural gas, consequences are more likely and probably more severe. * Furthermore, in case a detector is not functioning, a hydrogen leakage will probably not be detected since it has no smell. * Would it be possible to detect hydrogen in an inert atmosphere with CO2?	*Other potential safety measures include: Warning signs in all entries and axcess points, heat detecting surveillance and CCTV, staff training.
Hazard event	**Cause**	**Probability of Event (1-5), considering all possible causes**	**Consequences**	**Severity of Consequence (1-5)**	**Critical factors for the cause to generate event/for the event to escalate in consequence**	**Current safety measures known to be implemented (both preventive and mitigating)**	**Potential safety measures (both preventive and mitigating)**	**Comments**	**Post HazId comments**
Batteries and Fuelcells in the same space						**Change in concept: Separate fuelcells and batteries. Put fuelcells diagonally (e.g. stern- fuecells starboard, aft- fuelcells port)**			
Permeation	No specific cause - it occurs naturally	5	Explosion (likely a flash fire rather than a deflagration)	3 (depends if someone is in the space)	* Tank material * Temperature in the space could potentially increase the permeation (not only the pressure), in particular if there is a prolonged 40-60°C temperature (yet another reason to separate the batteries from the hydrogen storage/FC spaces) * Tank pressure	*Room ventilation system * Gas detection system for gas release to be provided * Suitable fire extinguishing system	* Explosion relief from the void/storage space. * No usage of polymer lined tanks (negligible for metal-lined composite tanks). Otherwise tests need to be done to investigate the permeation and calculations on the consequences for the specific space. * Important issue particularly in case the ventilation system is not functioning, since this could cause hydrogen accumulating. It is therefore important to have some kind of warning system, letting you know if the ventilation is functioning * Warning if there is an explosive atmosphere in the space, before someone entering. * Pipes from tanks to the FC would be double walled. Assumed that the annular space between walls is monitored for leakage.	*Better to release H2 high up than under the water, since the gas is very light and will quickly rise. A pipe to a high point (over and away from the ship) * The void spaces are below the water line, and the temperature is therefore not very high even during summer	*Hight of ventilation pipe to release H2 must be calculated based on the amount of hydorgen that can be released an potential ignition sources. * Lining mterial: if polymer rather than metal is used, the permeation rate needs to be understood and evaluated against the application. * Tanks and piping should have documentation that proofs permeation is not occuring during operation. * It is not yet decided what material is to be used in the hydrogen storage tanks.

Leakage	Connectors and connections (weakeness in these) Maintenance wear (wearing out parts of the system) Human error (e.g. from maintenance) Arson/abuse/deliberate damage Corrosion of system components Collision/grounding/car deck failure due to structural collapse or explosion Manufacturing errors of tank/connectors Material compatibility with hydrogen (e.g. embrittlement) Tanks not tested for the maritime Vibration	4 (with the proper maintenance instructions and proper testing before installation, this should be reduced to 3)	Explosion (potential for deflagration or even detonation)	4 to 5	* If leak test has not been made correctly, it is likely that the installation will leak. * Tanks ability to withstand vibration. * If the systems has been tested for the maritime environment. SEE "POST HAZID COMMENT" * If there are shut-off valves between the cylinders in the hydrogen storage.	* Gas detection inside the space to be provided * Fire detection suitable for hydrogen to be provided * Room ventilation system, dimensioned based on the likely size of a leakage and the volume of the space (acph). * Suitable fire extinguishing system	* Shut-off valves between the cylinders in the hydrogen storage. * Excess flow valves, operating quickly and closing the valves upon potential leakage at full pressure * Fire/hot spot detection system (multi-spectrum IR flame detector?) to detect possible small/large burning leakages, which otherwise don't produce any detectible smoke. * Procedure to screen the equipment for hot spots with a hand-held detector before maintenance. * Pressure relief for the space, ensuring rupture in a "safe" direction * Important that the crew is trained to know the particulars of hydrogen fire safety etc. * Hand-held leakage detectors/sniffers, to be used upon maintenance. * Having the hydrogen storage enclosed in a box. * Using EX classed equipment * Maintenance instructions for how to make proper maintenance, e.g. leakage testing of installations including usage of the correct leakage test gas (hydrogen, helium or a trace gas with sufficient amount of hydrogen/helium)	*There are pressure reduction valves between the tanks and the FC. They should be located as close to the tanks as possible, so high pressure is dealt with only in one location *There should be a TPRD from the tanks as well (often temperature regulated on vehicles). "'*Thermally-activated pressure relief device (TPRD)' means a non- reclosing PRD that is activated by temperature to open and release hydrogen gas*." * Would be interesting to investigate how loss of power would affect the safety, e.g. failure of some safety systems? * A high amount of congestion within a volume can lead to a very high pressure explosion event. * Important question is if the cylinders are interconnected or if there are shut-off valves on each tank, the maximum quantity possible to release is then limited by a large factor. SEE "POST HAZID COMMENTS". * What is a suitable safety distance from the hull to the hydrogen tanks? B/5? * What material is used in the tank? Glass fibre or carbon fibre? What is the lining material of the tanks?	* Testing of tanks for maritime environment: how have the tanks been tested? Have the tanks in the project been tested for a maritime environment? Are there currently any testing/approving regulations and standards for using tanks in the maritime environment? *Glass fibre has not been used for compressed hydrogen in the road vehicle industry for a long time. If glass fibre is used as material in the tanks, this may mean more safety issues compared to using carbon fibre (stress rupture of fibres?) * Connectors and coupling should be of suitable type for hydrogen. Suitability should be based on documentation. * There are automatic shut-off valves on each "stack" (stack=several bundles, budle=several interconnected tanks)There are manuell shut-off valves one each "bundle". It is technically possible to provide automatic shut-off valves for each bundle. * Testing of tanks have been landbased, i.e. no specific testing for use in maritime operations.
			Jet fire	3 to 4 (4 in case someone is in the space). High probability of damage to the piping and cabling running through the space, which could also have consequences. Perhaps loss of steering?					
			Fire, including burns (invisible flames)	3 to 4 (4 in case someone is in the space)					
			Asphyxiation (unlikely to occur before ignition)						
			Pressure injuries						
Tank rupture									* Mechanical damage, fire exposure, corrosion and material fatigue are potential causes to tank rupture. * Tanks, pipes and couplings should be of suitable type for hydrogen. Suitability should be based on documentation.
Loss of power								* Would be interesting to investigate how loss of power would affect the safety, e.g. failure of some safety systems?	
Flooding								*Although not discussed in detailed during the workshop, the consequences due to flooding would probably not be very severe in the Hydrogen Storage Space.	

Resulting Excel spreadsheet from HazID workshop for Bunkering Station



Location: Bunkering station	
Comments	**Post HazId comments**
*Refilling is done every fourth day or so. *High pressure piping from bunkering stations to the hydrogen storage. * There are well-established protocols for filling of vehicle tanks. In particular to avoid over-pressure onboard. The refilling stations for vehicles have several safety features to avoid over pressure. What is it like for ships? * How are the six tanks interconnected? * The refilling lines to the different tanks should be secured, so that only the section of the pipe is ventilated in case of a failure (so you cannot empty the tank via the refilling tank).	* How are the tanks to be refilled? * What type of refilling station is going to be used?

Lighthouse samlar industri, samhälle, akademi och institut i triple helix-samverkan för att stärka Sveriges maritima konkurrenskraft genom forskning, utveckling och innovation. Som en del i arbetet för en hållbar maritim sektor initierar och koordinerar Lighthouse relevant forskning och innovation som utgår från industrin och samhällets behov.

Lighthouse – för en konkurrenskraftig, hållbar och säker maritim sektor med god arbetsmiljö



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