Aleksander Aira-Andersen

# Reliability-Centred Maintenance of Hydrogen-Fueled Coastal Fishing Vessel

Master's thesis in Marine Technology
Supervisor: Ingrid Bouwer Utne
June 2023

Master's thesis

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## Preface

This master's thesis is the final submission for the Master of Science degree in Marine Technology from the Norwegian University of Science and Technology (NTNU). The thesis was done during the spring semester 2023 and corresponds to 30 study credits. While studying Marine Technology, I developed a growing interest in renewable and zero-emission fuels for decarbonising ships. I also grew up in a place with close ties to the fishery industry. Combining these two interests motivated me for this master's thesis.

The thesis dives into using Reliability-Centred Maintenance (RCM) for a zero-emission coastal fishing vessel. The method is used to analyse the power generation system on a specific vessel. The outcome of the analysis is a proposed maintenance program for the technical system of the vessel, which promotes system reliability. Microsoft Excel has been used to structure the work for the thesis.

The student has struggled with finding relevant data for the analysis during the research. However, the supervisor, industry contacts and others have helped me guide me through this study to complete the task. A great deal of data and information was gained gradually during the semester. However, a turning point was during the Lofotfishing seminar in March, which helped me contact relevant partners.

I want to thank everyone who has contributed to the thesis. Thanks to PhD candidate Anna Sophia Hüllein for many interesting discussions and for providing useful help and advice for this thesis.

I want to thank my supervisor, Ingrid Bouwer Utne, at the Department of Marine Technology at NTNU, for guidance throughout the semester with the thesis.

Finally, thanks to my friends and family for their support during my time at NTNU; it has been some fantastic years.

Aleksander Aira-Andersen
Trondheim, 8th June 2023

# Summary

This master's thesis studies using the Reliability Centred Maintenance (RCM) method to establish a maintenance program for a hydrogen-fueled coastal fishing vessel. The vessel is a zero-emission coastal fishing vessel using hydrogen as fuel by utilizing fuel cells for power generation. This is due to the need to decarbonize the Norwegian Seafood Industry, which has a significant share of Norwegian greenhouse gas emissions. The experience of using fuel cells and hydrogen as a fuel for maritime vessels is limited, and several technical challenges concerning safety, availability, and operational ability occur. Norwegian-flagged ships using hydrogen as a fuel must follow the IGF code from The International Maritime Organization, which states that vessels using hydrogen as a fuel must have the same level of safety and reliability as ships using conventional machinery. By doing an RCM analysis on the power generation system, one can establish an overview of the risk picture for failures of this system and propose suitable maintenance tasks to reduce the probability and the consequence of a failure mode.

The RCM analysis is based on the perspective outlined in Moubray (1991). The focus remains on maintaining the system function safely and cost-effectively. The analysis studied the equipment of a system in a systematic order, including function descriptions, system failure modes, failure causes, criticality analysis and lastly, proposing maintenance tasks towards the failure modes. The criticality assessment used the shipbuilder's defined consequence and frequency parameters and risk acceptance criteria.

The outcome from the FMECA shows that the most critical failure modes were the failure of the air compressor and the failure of the input devices used for monitoring the fuel system. These failure modes were within an unacceptable risk area and had the highest risk index of 8. Only 3% of the failure modes from the FMECA were within an acceptable range and were therefore not assessed further in the maintenance task analysis. 62% of the failure modes were within the orange ALARP risk category, which generally should lower the risk level. However, a cost-benefit analysis should be done. 26% were within the yellow ALARP category, which are failures which can be accepted if a cost-benefit assessment is conducted.

The information from the FMECA worksheets was used to establish maintenance tasks to handle each evaluated failure mode. This resulted in a program of 33 maintenance tasks, where 24 were predictive, and nine were preventive. These maintenance tasks were further scheduled to maintenance packages with detailed descriptions of how and when maintenance should be conducted. The maintenance tasks are done in intervals from continuous maintenance to intervals of up to 5 years. Most of the tasks were scheduled condition-based maintenance tasks; however, scheduled restoration, scheduled replacement and failure-finding tasks are also in the maintenance plan for some failure modes. The results from this thesis can be implemented on the vessel to improve system reliability and availability.

# Sammendrag


Denne masteroppgaven studerer RCM metoden til å konstruere ett vedlikeholdsprogram for en kystfiskesjark som bruker hydrogen som drivstoff. Sjarken vil være et null-utslippsfartøy som bruker brenselceller til fremdrift ved hjelp av hydrogen. Den norske sjømatnæringen har en signifikant andel av Norges totale drivhusgass utslipp, og å gå over til null-utslippsdrivstoff vil være med å redusere utslippene innenfor denne sektoren. Foreløpig har vi lite erfaring med å bruke brenselsceller og hydrogen på skip, og mange tekniske utfordringer knyttet til sikkerhet, tilgjengelig og drift må løses før vi kan gå over til denne teknologien. Fartøyer som bruker hydrogen som drivstoff må følge IMO´s IGF-kode som krever at alle hydrogendrevne fartøy må kunne bevise samme sikkerhet og tilgjengelighet som fartøy med tradisjonelt propulsjonssystem. En RCM analyse danner en oversikt over risikobildet for en potensiell systemsvikt og brukes til å foreslå passende vedlikeholdsoppgaver for å redusere konsekvense og sannsynlighet av en svikt.

RCM analysen er basert på prosedyrer utviklet av Moubray (1991). Fokuset med analysen er å vedlikeholde systemfunksjonen på en sikker og kostnadseffektiv måte. Analysen har gått ut på å studere systemer på komponentnivå og blant det så inngår funksjonsbeskrivelse, sviktmoder, sviktårsaker, risikoevaluering og til slutt å foreslå vedlikeholdsoppgaver tilpasset sviktmodene. Risikoevaluering brukte skipsbyggerens egne konsekvens og sannsynlighetskategorier i tillegg til deres risikomatrise.

Fra FMECA analysen kom det frem at en svikt av luftkompressoren eller en svikt av tilstandsovervåkningssystemene for drivstoffsystemet var de mest kritiske sviktmodene. Disse sviktmodene var innenfor ett uakseptabelt risikonivå basert på risikomatrisen. 3% av sviktene var på ett akseptabelt risikonivå, disse ble ikke behandlet videre i vedlikeholdsanalysen. 62% av sviktmodene var innenfor det oransje ALARP området, som er sviktmoder som bør reduseres til ett lavere nivå, men dette må evalueres gjennom en kost-nytte analyse. 26% av sviktmodene var på det gule ALARP nivået, som også bør evalueres av en kost-nytte analyse, men risikoen på disse sviktene er lavere enn det oransje nivået.

Resultatene fra FMECA ble brukt til å etablere ett vedlikeholdsprogram rettet mot hver sviktmode. Vedlikeholdsprogrammet består av 33 vedlikeholdsoppgaver. 24 av vedlikeholdsoppgave er kategorisert som tilstandsovervåkning, mens de resterende 9 er preventive vedlikeholdsoppgaver. Disse ble senere sortert inn i vedlikeholdspakker basert på intervall og ga en detaljert beskrivelse av hvordan og når vedlikeholdet skal gjøres. Vedlikeholdsintervallene går fra kontinuerlig vedlikehold til ett vedlikeholdsintervall på 5 år. Majoriteten av vedlikeholdsoppgavene var tilstandsbasert vedlikehold, men andre vedlikeholdsoppgaver som planlagt reparasjon og planlagt erstatning og testing er også inkludert i vedlikeholdsprogrammet. Resultatene fra masteroppgaven kan bli inkludert i fiskefartøyets vedlikeholdsprogram for å øke systemets pålitelighet og tilgjengelighet.

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# Abbreviations

$CH_2$ Compressed Hydrogen

$H_2$ Hydrogen

$LH_2$ Liquefied Hydrogen

ALARP As Low As Reasonably Possible

CCUS Carbon Capture, Utilization and Storage

CLU Control Logic Unit

CM Corrective Maintenance

ESD Emergency Shutdown

F&G Fire and Gas

FC Fuel Cell

FMEA Failure Modes and Effects Analysis

FMECA Failure Modes, Effects and Criticality Analysis

GHG Greenhouse Gases

HAZID Hazard Identification

HFL Higher Flammability Limit

IACS The International Association of Classification Societies

ICE Internal Combustion Engine

IMO The International Maritime Organisation

LFL Lower Flammability Limit

MCFC Molten-Carbonate Fuel Cell

MGO Marine Gas Oil

MTA Maintenance Task Analysis

MTBF Mean Time Between Failure

P&ID Piping and Instrumentation Diagram

PAFC Phosphoric Acid Fuel Cell

PdM Predictive Maintenance

PEMFC Proton-exchange Membrane Fuel Cell

PFD Probability of Failure on Demand

PM Preventive Maintenance

RCM Reliability Centred Maintenance

RI Risk Index

SOFC Solid-Oxide Fuel Cell

SOLAS The International Convention for the Safety of Life at Sea

WTW Well-to-Waves

# 1 Introduction

The seafood industry in Norway plays a significant role in the country's economy. The seafood export from fisheries and aquaculture was approximately 10% of the total Norwegian export in terms of value in 2020 (Menon Economics (2021)) and is an important industry for Norway in terms of export, jobs and value creation. The seafood industry is responsible for roughly 4% of the Norwegian greenhouse gas emissions. According to Stakeholder (2022), the greenhouse gas emissions from the Norwegian seafood industry were about 1,5 million to 1,8 million tonnes of $CO_2$ which is higher than the country's commercial aviation industry with emissions of about 1,1 million tonnes. The Norwegian Environment Agency suggests that the total Norwegian greenhouse gases in terms of $CO_2$ equivalents in 2021 were about 48.9 tonnes. Reducing emissions in the seafood industry has, therefore potential to significantly reduce the total Norwegian greenhouse gas emissions. The Norwegian coastal fishing fleet is large and consists of several thousand fishing vessels (The Norwegian Fishery Directory (2023)) and is mainly using internal combustion engines running on conventional fuels (Stakeholder (2022)) which are a large source of these emissions. Replacing fossil fuels in fishing vessels and other vessels in the seafood industry with zero-emission fuels is a way to reduce the emissions from this sector. Several potential zero-emission or low-emission fuels exist, such as ammonia, hydrogen and methanol. All of these fuels will have no or low carbon dioxide emissions when used for propulsion; however, as good as this sounds, these fuels have other technical and economic issues which must be solved before they can be adopted as fuels. With limited experience in alternative fuels, it is difficult to know what energy carrier is the best option for shipowners. Adopting new technologies is expensive, and there is a risk of investing in the wrong technology. This is why many shipowners these days are reluctant to invest in new technology. In addition, the safety of these systems is unknown as we have little operational experience. With little to no regulatory framework for some zero-emission fuels, it can be a tedious process to get approval for the safe design of vessels with greener fuels. To kickstart the green shift within the coastal fishing fleet, the ZeroKyst project has decided to design and build a zero-emission fishing vessel using hydrogen as fuel.

The ZeroKyst project is a consortium and a collaboration between NTNU, Sintef and several industry partners for technology development to decarbonize the Norwegian Seafood industry. The goal is to provide a complete infrastructure to offer a zero-emission fuel chain for the vessels in the seafood industry. The project will also provide a zero-emission new build fishing vessel. From this consortium, infrastructure, experience and knowledge about decarbonizing the seafood industry can contribute to reducing the greenhouse gas emissions in the industry significantly so that the Norwegian goal to reduce emissions are reached.

When implementing new green technology, there are several technical and operational risks that have to be scrutinized. Hydrogen is a fuel with different properties than other fossil fuels, which gives other risks. A failure of some of the systems related to the new technology can therefore have large safety, environmental or operational consequences. One way to avoid failures is by designing a safe system. Safe system design is however difficult with limited experience and knowledge. Another way to avoid failures is by doing proper maintenance of the asset. A good maintenance plan can increase the reliability of an asset which means the probability of failure is reduced. In addition, it can also lead to a more cost beneficial solution for the ship owner. Therefore doing proper maintenance analyses should be in a ship operators mind.

This thesis aims to perform a Reliability-Centred Maintenance analysis of the hydrogen propulsion system on the ZeroKyst hydrogen-fueled coastal fishing vessel. A failure modes, effects and criticality analysis (FMECA) will be conducted before a maintenance task analysis (MTA). The result from the MTA gives a complete maintenance plan for targeting the failure modes of the system. A description of maintenance tasks, intervals and crew requirements is also provided. The results of this thesis can be used to understand what are the critical systems and failure modes in the hydrogen propulsion systems and what the best maintenance strategies are to target those failure modes. The result of the analysis is a maintenance plan which can be used for the fishing vessel, which shows how to maintain the different systems to avoid certain failure modes, which can increase the reliability and safety of the vessel. In addition, the framework from this analysis can be used to analyse other systems on the same vessel or used to analyse similar systems on alike vessels.

# 2 Background

## 2.1 The Norwegian Seafood Industry

The Norwegian seafood industry is one of the country's largest export industries. It consists of the fishery industry and the aquaculture industry. Fisheries have historically been an important and large industry in Norway. In contrast, the aquaculture industry is a relatively new industry, with the first-ever ocean-based salmon farm deployed in Hitra in 1970 (The Norwegian Seafood Council and Seafood Norway (2023)). Even though the aquaculture industry is new, it has had rapid growth and is today the second-largest export industry for Norway according to The Norwegian Ministry of Trade, Industries and Fishery (2023). The seafood industry is important, as it contributes to a lot of the export income and provides many jobs along the Norwegian coastline. Fishers, suppliers, banks, industry and many other stakeholders are involved in this industry to produce, catch, process and sell seafood domestically and abroad.

### 2.1.1 History of Norwegian Coastal Fisheries

The fishery industry has traditionally been important for Norway, especially with the yearly Lofoten Fishery in the late winter/early spring months every year when the cod comes back from the Barents Sea to Lofoten to spawn. The Lofoten Fishery is a known fishery, and many fishers from all over Norway have, throughout history, sailed to Lofoten to fish cod. The Lofoten Fishery is estimated to have been important for many hundred years.

Throughout the 1900s, fishing technology developed rapidly, especially with the introduction of the internal combustion engine for fishing vessels in the early 1910s, which industrialized fisheries. Rapid technology development has led to a large increase in catch from fisheries; this was, however, not sustainable and led consequently to the herring crisis in 1969 and the cod crisis in the 1980s (Dørum, Knut (2023)). A consequence of this has led to the Norwegian fishery management policy called the individual vessel quota policy, which was introduced in 1990. This means that every fishing vessel has an individual quota on how much fish they can catch yearly. This has the objective of ensuring a more sustainable fishery policy.

In the last ten years, the Norwegian fishing fleet has seen a reduction in approximately 600 vessels and consists mainly of small fishing vessels below 11m in length, according to The Norwegian Fishery Directory (2023). These types of small-scale fishing vessels are common for coastal fisheries such as the Lofoten Fishery. These vessels mostly use fishing gear such as Danish seine, long lines, gillnets and jigging machines. These types of vessels are small because they usually go out fishing in the morning, catch fish and then return to port in the evening. This reduces the need for storage capacity and for complex and energy-demanding freezing technology.

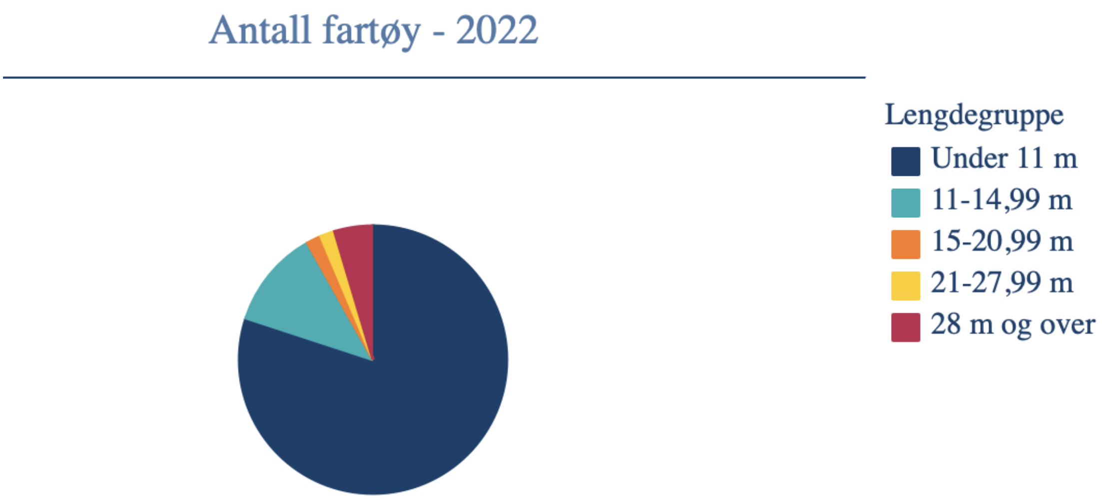


Figure 1: Size distribution of the Norwegian fishing fleet. From: The Norwegian Fishery Directory (2023).

An example of a small fishing vessel below 11m in length is the fishing vessel M/S Elvine shown in Figure 2.


Figure 2: M/S Elvine fishing vessel. Photo used with a permit from the photographer.

There are no number on how many vessels in the fishing fleet use other energy carriers than purely fossil fuels, however, Stakeholder (2022) estimates that the large majority of the vessel uses internal combustion engines with diesel as a fuel. Many fishing vessels are owned by the fishers themselves according to The Norwegian Ministry of Trade, Industry and Fisheries (2023), meaning it is not expected that the fleet is up to date with the newest technology. Changing the energy mix of the coastal fishing fleet is a challenge as it is a rather capital-intensive investment to either build a new vessel or retrofit an older vessel to use alternative energy carriers.

## 2.2 Stakeholders in the fishing industry

When looking at the Norwegian coastal fisheries and how they can be more sustainable, it is important to understand who the stakeholders that are involved in the industry are. Hüllein et al. (2023) suggests that there are three levels of stakeholders that are involved in the Norwegian Coastal Fisheries. The stakeholders that are directly dependent on the fisheries are ship owners, fishers and the fish processing industry. They are dependent as their income is dependent on the catch of the fish catch and the fish price. The second level of stakeholders is at the infrastructure level, which means that the fishers are dependent on harbours, fuel suppliers, shipyards and local communities, which are important for the fishers in the fisheries. The last level of stakeholders are insurance companies, relevant authorities which decides the rules and regulations, banks which provide financing for the vessels, society, etc. All the stakeholders will play an important role in the seafood industry in reducing greenhouse gas (GHG) emissions.

## 2.3 Decarbonization of the Seafood Industry

The seafood industry is important for Norway; however, the GHG emissions from this sector are significant, and the emissions must be reduced if the national emission goals should be reached. Due to the individual vessel quota system for the fisheries, it is not expected that the total fishing fleet will grow substantially in the future, however, numbers from The Norwegian Fishery Directory (2023) indicates that even though the fishing fleet has stabilized in the number of vessels, the installed power on the boats has increased. This means that if the trend continues, the emissions from the Norwegian seafood industry are expected to grow in the future as well. Stakeholder (2022) estimates that the total greenhouse gas emissions from the industry were in the range of 1550 - 1850 thousand tons of $CO_2$ equivalents in 2021, which is in the range of 3.2-3.8% of the total Norwegian greenhouse emission according to Statistics Norway (2023). The Norwegian Government aims to reduce emissions by at least 55% by 2030 (The Norwegian Government (2023)), and to do this, emission reductions must happen in the seafood industry as well.

Since the majority of the vessels in the seafood industry use fossil fuels, there is a significant potential to reduce the emissions from this sector by changing propulsion systems to hybrid, electric or to use zero-emission fuels as energy carriers. Adopting hydrogen as a marine fuel for vessels in this industry could be a way to address this environmental challenge. Pratt and Klebanoff (2018) suggests that using hydrogen fuel cells on a vessel can significantly reduce the total greenhouse gas emissions of a vessel. Hydrogen ($H_2$) is a potentially renewable energy source that has the potential to significantly reduce emissions from propulsion, as the only byproduct of its combustion is water vapour. Depending on the production method, hydrogen can potentially be a zero-emission fuel which can contribute to the objective of reducing the emissions from the industry. Gabrielii and Jafarzadeh (2020) suggests that hydrogen fuel cells for coastal fishing vessels are technically feasible. Having a hybrid electric system with a battery pack was also suggested as technically feasible and a possible way to decarbonize the coastal fishery fleet.

Despite the potential benefits, several technical challenges still need to be addressed before hydrogen can be widely adopted as a marine fuel. These include issues related to fuel storage, distribution, and maintenance. However, investing in research and development to address these challenges can pave the way for the wider adoption of hydrogen as a marine fuel in the seafood industry in Norway. Which will help to reduce emissions and promote sustainable energy in the sector.

## 2.4 ZeroKyst

The ZeroKyst project is one of the initiatives from industry partners and researchers such as NTNU and Sintef to decarbonize the seafood industry, with Selfa Arctic shipyard as the project manager. The consortium aims to contribute to 50% reduction of the emissions in the seafood industry by 2030 and wants to develop infrastructure for zero-emission vessels and a new-build zero-emission vessel. The main focus is to do this by using electric engines or hydrogen as a zero-emission fuel.

This collaboration between shipowners, shipyards, energy companies and local authorities can lead to a complete value chain for hydrogen fuel for vessels for the aquaculture industry.

The new-build zero-emission coastal fishing vessel is meant to be the world's first zero-emission coastal fishing vessel on hydrogen. It will lead to operational experience, development of notations and rules of this fuel. It is meant to run using hydrogen as fuel. The vessel is discussed further during the analysis of this thesis.

# 3 Objectives, scope and limitations

The purpose of this master's thesis is to perform a Reliability Centred Maintenance (RCM) analysis of a hydrogen-fueled coastal fishing vessel. First of all, an introduction to the RCM method and relevant literature is given, before the analysis is done on the vessel to recommend a suitable maintenance plan for the analysed systems.

The scope of the thesis is to use the RCM method to construct a maintenance program on the power generation system on a hydrogen-fueled fishing vessel. This will be done by conduction a Failure Mode, Effect and Criticality Analysis (FMECA) and a Maintenance Task Analysis (MTA) on the systems. Failure modes, consequences, and probabilities are assessed for every failure mode for every system. From this, a maintenance task analysis proposes a maintenance program to target the failure modes. The maintenance tasks are decided using the RCM decision logic with background in criticality, failure data and costs. A description of the proposed maintenance task with crew requirements, necessary equipment and maintenance intervals are also included in the analysis. Results from this thesis can be used to understand how the power generation system on the vessel can fail and what types of maintenance tasks would be appropriate to target the failure modes of this system. This creates a framework that can be used for other systems on the vessel or for analysing similar vessels.

Since this is a relatively new technology introduced to the maritime industry, it is difficult to obtain data regarding failure modes, probabilities and consequences. The analysis is based on information provided by the ZeroKyst partners, information found online from research papers and manufacturers and also from other stakeholders in the industry. Sometimes data has been used from the offshore oil & gas industry for similar components, and for the hydrogen systems, some information has been obtained from the aviation and land-transport industry, as hydrogen is at a more developed stage in these industries.

## 3.1 Thesis structure

This thesis is structured into several parts. An introduction to hydrogen and hydrogen propulsion systems is given in Chapter 4 before the method is covered in Chapter 5. Chapter 6 gives an introduction to the data collection for this analysis. Typical fishing vessel characteristics, operational profile and operational assumptions are given in Chapter 7 . The system and the vessel description is in Chapter 8, and the analysis description is in Chapter 9. The results and discussion is presented in Chapter 10, and a conclusion in Chapter 11. Lastly, recommendations and further work is presented in Chapter 12.

# 4 Introduction to Hydrogen

Hydrogen is the first chemical element in the periodic system with the symbol H and atomic number 1. Under normal temperature and pressure conditions, hydrogen is a gas which is an energy carrier with the chemical formula of $H_2$. It is a colourless, odourless gas that is highly flammable and can be used as fuel. Due to no carbon containment in hydrogen, it is a potential fuel with zero carbon emissions. When hydrogen is utilized in a fuel cell, the only by-product is water vapour. Depending on the production method of hydrogen, it can be a fully zero-emission fuel. This makes it a promising alternative to fossil fuels, which are a major contributor to air pollution and climate change. The following subsections gives an introduction to hydrogen and how hydrogen can be utilized as a marine fuel.

## 4.1 Hydrogen Production

Hydrogen production today can be split into four categories, as seen in Figure 3, according to Sürer and Arat (2022). Green, blue, turquoise and grey hydrogen:

- Green hydrogen: Hydrogen produced based on electrolysis using renewable energy. No GHG emissions are produced during the production of green $H_2$.
- Blue hydrogen: Blue hydrogen is produced using fossil fuels, however, most carbon dioxide emissions are captured and stored using carbon capture, utilization and storage (CCUS) technology.
- Turquoise hydrogen: Hydrogen produced using pyrolysis instead of steam methane reforming (SMR) or coal gasification. This gives the carbon as a solid waste, which can be more easily stored or re-used. This is mostly in the pilot phase (Sürer and Arat (2022)).
- Grey hydrogen: Hydrogen produced using fossil fuels as feedstock. Leads to significant greenhouse gas emissions during the production of the $H_2$. This is mainly done by SMR or coal gasification.

According to The International Energy Agency (2022), most hydrogen production today would fall into the grey hydrogen categorization. Around 62% of all hydrogen production worldwide uses natural gas as feedstock through SMR without CCUS technology. Around 19% of production utilizes coal as feedstock through coal gasification. In 2021, low-emission hydrogen production was about 0.7% of all production, with the vast majority being hydrogen produced on fossil fuels with CCUS technology (blue or turquoise). Green hydrogen production using electrolysis was very small; however, it increased by 20% compared to 2020. However, green and blue hydrogen production is developing at an impressive pace. The International Energy Agency (2022) suggests that green and blue hydrogen production could reach 24 MT $H_2$ by 2030, which is about 25% of the total hydrogen production in 2022. The advantage of blue and green hydrogen is that there will be zero or close to zero greenhouse gas emissions during the production of the $H_2$. When the hydrogen is used later as an energy carrier, it will not emit greenhouse gases either due to no carbon containment. Even though hydrogen will not emit greenhouse gases during fuel cell use or combustion, the hydrogen production method is important to reach any of the zero-emission goals.

There are several barriers which must be solved to increase the production of hydrogen through electrolysis:

- Cost: The current cost of producing hydrogen through electrolysis is two-three times higher than for grey hydrogen on average, according to The International Energy Agency (2022). This can be reduced by further scaling up production and developing more efficient and cost-effective technology.
- Insufficient infrastructure: There are hydrogen pipelines of around 2600 km in the United States and around 2000 km in Europe, which is very low compared to the worldwide natural

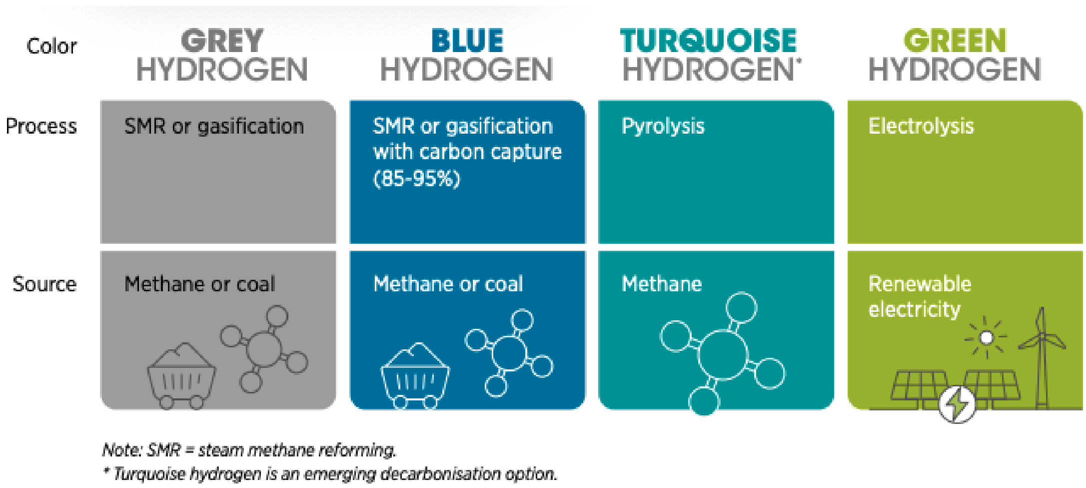


Figure 3: The four types of hydrogen production. From Natalie Marchant (2023).

gas pipelines above 1.1 million km (The International Energy Agency (2022). In addition, more refuelling stations and a larger spread in production areas is necessary to develop a complete hydrogen infrastructure.

- Energy losses: According to Chi and Yu (2018), one can expect energy losses through water electrolysis of around 20-30%. Further energy losses for storage (compression or liquefaction) and transportation are also expected, in addition to energy losses in the fuel cell when converting to electrical energy.

## 4.2 Hydrogen Storage

Despite the fact that hydrogen has a high power density compared to other fuels, it has a low volumetric energy density (DNV (2020)). Low volumetric energy density means that one needs more volume of fuel to get the same power output, and this is critical onboard a vessel with limited capacity. Therefore the storage method of hydrogen is important. There are three common storage methods of hydrogen: compressed hydrogen, liquid hydrogen or converting it to other energy carriers. Other energy carriers can be easier to handle and store before reconverting to hydrogen at a later stage. An example of this is converting the hydrogen to ammonia with a lower liquefaction temperature and compression temperature and a higher volumetric energy density according to DNV GL (2019). According to DNV (2020), compressed hydrogen has between 12-13 times lower volumetric energy density than Marine Gas Oil (MGO) and around four times lower volumetric energy density than ammonia. Liquefied hydrogen has a much higher volumetric energy density than compressed hydrogen; however, it is still four times lower than MGO and slightly lower than ammonia.

There are several challenges and advantages of all the common storage methods of hydrogen. Liquefied hydrogen has to be cooled down to a temperature of 20K (-253 °C). Liquefied hydrogen has a higher volumetric energy density than compressed hydrogen, which is a significant advantage (DNV GL (2019)); however, it requires around 25-35% of the original energy content to cool down the hydrogen for liquefaction according to The Commonwealth of Australia (2018). Another disadvantage of the liquefaction of hydrogen is that it is expensive to liquefy the substance. In addition, this will also lead to loss of boil-off gas of around 0.1-0.5% per day according to The International Energy Agency (2022). For vessels, the boil-off gas can however be used for propulsion, which is standard for Liquefied Natural Gas (LNG) carriers (McKinsey  Company (2023)). For weight issues, liquefaction is advantageous because the tank weight is significantly reduced by using liquefied hydrogen.

The second storage method for hydrogen is to compress it by increasing the pressure to 200-700 bar, depending on the desired density level. Reaching these pressure levels will have a demand of 8-12% of the original energy content (DNV GL (2019)). This method is simpler and more economical than other technologies. One disadvantage of compressed hydrogen is that the volumetric energy density is lower than for liquid, and one must select the right material for the storage tank, for instance, composites, which can increase the weight of storage significantly according to Sürer and Arat (2022).

Converting the hydrogen to ammonia or other hydrogen carriers for storage is the last method possible. This can be done for ammonia synthesis using the Haber-Bosch process (DNV (2020). The advantage of ammonia is the lower liquefaction temperature or compression temperature required. The chemical properties of ammonia are similar to Liquefied Petroleum Gas (LPG), which we have experience in handling. The downside of doing this is that the energy efficiency of the value chain will be reduced to only 55% by converting it (DNV GL (2019). In addition, ammonia is a highly toxic substance, so extra safety measures must be considered.

## 4.3 Hydrogen As a Marine Fuel

Hydrogen is among the several fuel types currently being researched as fuel for maritime vessels. In order to reach the GHG targets set by IMO to decarbonize the global fleet, fuels with lower emissions or zero-emission fuels are gaining more interest from ship owners, charterers and other stakeholders in the industry. Fuels such as ammonia, hydrogen (liquefied or compressed) and methanol are among the most discussed alternatives for zero or near-zero emission fuels.

The largest advantage of adopting hydrogen as a marine fuel is that zero or near-zero greenhouse gases are emitted during combustion or power generation using a fuel cell due to no carbon containment in hydrogen. It also has a high power density compared to other fuels and is relatively straightforward to produce. Figure 4 from Al-Breiki and Bicer (2021) shows that blue and green hydrogen from well-to-wake and during transportation has low GHG emissions in terms of $CO_2$ equivalents compared to other fuels such as methanol and ammonia.

However, hydrogen also has various challenges and disadvantages. One large disadvantage is that due to the low liquefaction temperature and boiling pressure, storage of the fuel is difficult. As mentioned, it can either be stored in a liquefied way at a low temperature of -253 °C or compressed to a pressure of 200-700 bar. The low temperature requires a lot of energy and costly tanks to store, and compressed hydrogen requires a high pressure which may potentially be an explosion hazard (ABS (2021)). In addition, the volumetric energy density of hydrogen is lower than for comparable fuels such as ammonia and much lower than MGO, according to DNV (2020), which leads to an increase in the CAPEX. High production costs of hydrogen produced using renewable energy and a strict regulatory framework are also barriers for shipowners who would potentially use hydrogen. There are also some safety concerns about hydrogen, which will be covered later.

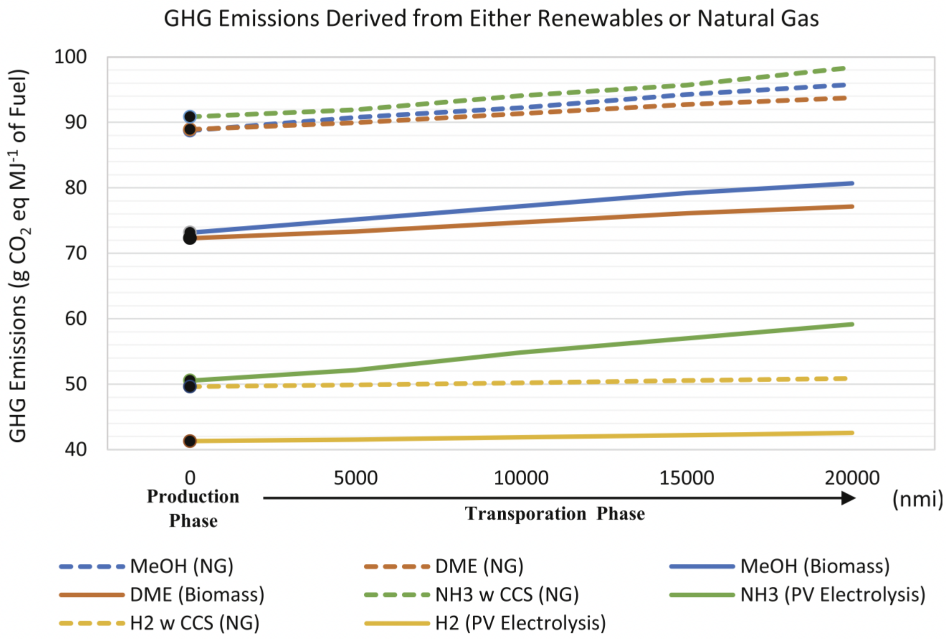


Figure 4: Life cycle GHG emission analysis on various potential marine fuels, from Al-Breiki and Bicer (2021)

## 4.4 Safety Challenges

Since hydrogen has special chemical and physical properties, some challenges exist in using and storing hydrogen as a fuel. One of the main hazards of storing compressed hydrogen is the high pressure. These high pressures mean that explosions can be a hazard with large consequences. For example the explosion of a hydrogen fueling station in Sandvika, Norway 2019, where a leak of hydrogen under high-pressure led to ignition and an explosion of the station. There were no casualties or human injuries; however, material damages occurred according to Henning Carr Ekroll, Aftenposten (2019).

Hydrogen has a wide flammability range from a Lower Flammability Limit (LFL) of 4% to a Higher Flammability Limit (HFL) of 75% according to ABS (2021). This means that if the hydrogen volume fraction in the air is between 4% and 75%, it can ignite. This range is significantly larger than for other fuels such as diesel, ammonia and methanol. This means that even though a leak of hydrogen can dissipate quickly due to the low density, it is a serious fire hazard due to the quick formation of flammable gas. Properly designed storage tanks, pipes, and safety systems are essential when handling compressed hydrogen.

Other hazards related to hydrogen as a fuel are electrical hazards, combustion hazards, and crash hazards which can be problematic when using hydrogen as a fuel according to the FMEA for hydrogen FC vehicles by Stephens et al. (2009). Embrittlement, corrosion and large burning velocities are other safety challenges as named by DNV and MarHySafe (2021).

## 4.5 Hydrogen Propulsion Systems

The following subsections briefly overview the two propulsion systems that can use hydrogen as a fuel. The two most common ways to use hydrogen for propulsion power are the internal combustion engine (ICE) and the fuel cell. The main difference is that fuel cell technology uses an electrochemical reaction to produce energy, while ICE converts energy through combustion.

### 4.5.1 Fuel Cell Technology

Fuel cells produce electrical energy by a process that converts chemical energy from the fuel to electric energy. This is done by reacting hydrogen and oxygen together in a catalyst which gives electricity and water as a byproduct. The chemical components pass through a negative anode and a positive cathode which are separated by a membrane. The chemical reactions happen at the anode and the cathode, while electrically charged particles are carried from the anode to the cathode producing electricity. The proton exchange membrane fuel cell (PEMFC) has been popular in marine vehicle projects due to its high energy efficiency and antipollution impact, according to Sürer and Arat (2022). PEM FC uses polymer electrolyte membranes with an anode and a cathode where the hydrogen is oxidized and an electron is then freed for electricity according to DNV and MarHySafe (2021). A principal sketch of a PEM FC is illustrated in Figure 5.

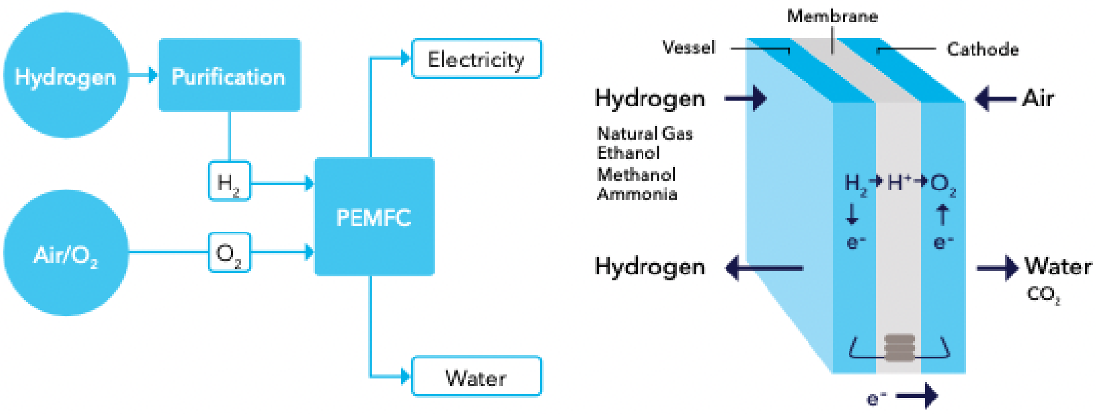


Figure 5: Principal sketch of a PEM Fuel Cell system, adopted from DNV and MarHySafe (2021).

Sürer and Arat (2022) lists several advantages of applying hydrogen FCs compared to ICE:

- **High efficiency and near-zero-emission**: Fuel cells have a higher fuel efficiency because the chemical energy is converted straight to electrical energy. There are fewer losses such as heat losses or mechanical losses. Since water is the only by-product of the chemical reaction, power generation has zero carbon dioxide emissions.
- **Low noise**: Due to no mechanical or moving parts, the noises during operation are expected to come from auxiliary equipment
- **Low operation temperature**: Preferred for marine vessels.
- **Low maintenance costs**: It is expected that having an electric motor with few/no moving parts will lead to less wear and tear, which can reduce maintenance costs.
- **Good modularity**: Fuel cells are modular and better at partial loads compared to ICEs.

However, there are also some challenges for applying fuel cells compared to ICE according to DNV and MarHySafe (2021):

- **Capital and operating cost**: Costs of a fuel cell power stack is significantly higher than conventional diesel engines. The catalysts in the FC are a high factor in the high cost of a fuel cell.

- **Technological maturity**: Compared to ICEs which have been the standard propulsion system in shipping for many years, there has been little technological development on fuel cells.
- Fuel cells are sensitive to impurities in the hydrogen. Suitable filtration is needed before entering the fuel cells.
- Requirement of a complex water management system for cooling the fuel cell and handling the excess water from the reaction.

In addition to the PEM fuel cell, there are also other types of fuel cells, such as alkaline FC (AFC), phosphoric acid FC (PAFC), molten carbonate FC (MCFC) and solid oxide FC (SOFC). However, only a few of these fuel cells are suitable for maritime applications. Inal and Deniz (2020) compares various fuel cell types for ships with different fuels and concludes that the PEM FC is the best option for using hydrogen as fuel. Sürer and Arat (2022) also suggests that PEMFC and MCFC/SOFC are the best options for hydrogen fuel cells. The vessel in this thesis is intended to use a PEM fuel cell system.

### 4.5.2 Internal Combustion Engine

An internal combustion engine (ICE) is an alternative energy converter to fuel cells. While fuel cells produce electrical energy by an electrochemical reaction, will the ICE burn hydrogen through combustion. ICEs are traditionally used for vessels today using conventional fuels such as diesel or heavy fuel oil. Traditional spark-ignited engines can be slightly modified to be adapted to hydrogen for combustion. The most important changes for these kinds of systems would be to enable them to handle high-pressure hydrogen or cryogenic temperatures if liquefied. In addition, NOx emissions can also be generated from the combustion of hydrogen due to the high operating temperatures. This can, however, be handled by technologies such as selective catalytic reduction (SCR). The advantage of adapting ICEs is that we have vast knowledge and experience in operating and maintaining ICEs, as this is the state-of-the-art propulsion system for many vessels today. Design and parts are assumed to be cost-effective due to the knowledge of this technology. The wide flammability range and the low ignition energy of hydrogen make it easy to start the engine using hydrogen. According to EY (2023), due to the low manufacturing costs and established supply chain for ICEs, economies of scale with ICEs can be reached faster than for fuel cells.

Currently, no commercially available $H_2$ internal combustion engines exist, and there seems to be little development, especially for ICEs for marine vessels. JCB has developed a hydrogen ICE concept for trucks which could be available. The commercial and technical readiness of the technology is far behind the FC technology for hydrogen. The first fuel cells for marine vessels have already been delivered. The vessel in the analysis in this thesis is based on a fuel cell propulsion system; therefore, ICEs will not be further covered in this thesis.

## 4.6 Other Projects With Hydrogen Fuel Cell-Based Maritime Vessels

There are several projects for vessels using hydrogen as fuel. One of the most notable ones is the MF Hydra ferry by Norled, the first ferry in the world to use liquefied hydrogen as fuel (Norled (2023)). The Hydra ferry uses liquefied $H_2$ as fuel and is expected to start sailing on $LH_2$ between Hjelmeland and Nesvik in Norway during 2023.

However, other projects use hydrogen as a fuel, such as the riverboat FCS Alsterwasser in Hamburg, which was the first ever fuel cell hydrogen-fueled vessel. The ship was developed in 2009 and has operated on hydrogen. Even a separate hydrogen fueling station was built for the vessel, according to Bassam et al. (2016). The ship is equipped with two PEM fuel cells and a battery system to court for load variations.

The Japan Fisheries and Research Agency (FRA) has, together with Toyota and Yanmar developed a fishing vessel with a length of about 12m using hydrogen fuel cells for propulsion. The first sea tests were, according to Plugboats (Jeff Butler) (2023) conducted in April 2021. It is unclear, however how far they are from commercializing the vessel.

Moen Marin has agreed with Salmar, Marin Design, and the Moen group to deliver a compressed hydrogen fuel-cell-based service vessel for the fish farming industry called the Pilot-E project. The expected delivery is at the start of 2024. This vessel will be hydrogen-electric and be around 15 meters in length.

## 4.7 Infrastructure

If one is going to transition to hydrogen-fueled fishing vessels, it is essential to have sufficient hydrogen infrastructure to fuel the vessel. The lack of infrastructure is one of the largest barriers for shipowners to invest in zero-emission vessels. Vice versa, no one wants to build infrastructure for hydrogen production if no vessels use it. In addition, to ensure zero-emission, hydrogen should be produced from renewable energy. H2 Marine, one of the partners in the ZeroKyst consortium, will provide a bunkering facility in Vannøya in Troms for green hydrogen. The fishing vessel in this thesis is intended to bunker hydrogen at this facility in Troms. The production facility will be able to produce 45 kg of $H_2$ per day and store up to 420 kg at a pressure of 350 bar (Zerokyst (2023)). This is essential for the vessel to be able to operate and fulfil its functions. According to H2 Marine, they are supposed to be able to provide $H_2$ on 5-year long-term contracts with a price of between 60-80 kr per kg. Having long-term prices makes it possible to do long-term investments in hydrogen projects, as it gives certainty in what can be expected in terms of fuel costs.

## 4.8 Regulatory Framework

In the following chapter, the regulatory framework regarding hydrogen as a fuel for a fishing vessel is presented in addition to general fishing vessel rules. As discussed, using hydrogen gives some additional safety concerns, and the regulatory framework is not yet complete due to a lack of experience with the fuel. Under control from IMO, the flag states have the responsibility to ensure that vessels registered in the ship registers have the necessary safety onboard. When it comes to hydrogen safety, these notations have not yet been completed, and the classification societies are important in this context to form the regulatory framework for the next generation of fuels.

### 4.8.1 Framework for Small Coastal Fishing Vessels

Norwegian coastal fishing vessels below 15 meters in length are not obliged to many regulatory frameworks. These vessels are small, and often only a single fisher operates the entire vessel. There are specific rules for inspections depending on the vessel's length. Vessels below 10.67 m in length are not required for periodic inspections from an external company, according to The Norwegian Maritime Authority (2023). However, vessels from 10.67 meters to 15 meters in length must be controlled every 30 months by companies approved by the Norwegian Maritime Authority. These types of fishing vessels also have vessel instructions which set requirements for the use of the vessel after a control.

### 4.8.2 SOLAS, The IGF-code and the Norwegian Regulation

The International Convention for the Safety of Life at Sea (SOLAS) defines the minimum requirements for vessel design, construction, equipment and operation. It is the responsibility of flag states to control that the requirements are reached. In addition to meeting the requirements of SOLAS, vessels must comply with the requirements of a classification society recognized by the flag state. Classification societies inspect, set requirements and guide shipowners, yards and other partners with their requirements. Some of the largest classification societies are the American Bureau of Shipping (ABS), DNV and Bureau Veritas. SOLAS is often more relevant to larger vessels than smaller coastal vessels, usually governed by the Flag states national rules. However, in some special cases, such as some fuel types, the Norwegian Maritime Administration requires all vessels to follow SOLAS rules regardless of size.

SOLAS originally stated that low flashpoint fuels, fuels with a flashpoint lower than 60°C, are prohibited. However, when introducing other more environmentally friendly fuels, such as LNG, ammonia and hydrogen, SOLAS added another set of rules for such fuels called the International Code of Safety for Ships using Gases or other Low-flashpoint Fuels (IGF) code. The IGF code is a standard for ships using gases or low flashpoint fuels other than gas carriers. The IGF code requires that the safety, reliability and dependability be similar to new conventional oil-fueled machinery. The IGF code provides developed proper specifications for LNG-fueled vessels, while other fuels are not yet covered. This means that it is not specified a regulatory framework for using hydrogen as a marine fuel from the IGF code at this stage. However, there is a way to get approval for hydrogen as a marine fuel by a process known as the "Alternative Design Process". The alternative design process aims to prove that the level of safety and reliability of the system is equivalent to a conventional system. This is often a rather time-consuming process as it requires much work to prove that the design is good enough. This is a barrier to adopting new fuels such as hydrogen. A minimum requirement for the alternative design approach is a risk analysis and an explosion analysis of the alternative fuel used. According to DNV and MarHySafe (2021), work has begun to include fuel cells as a part of the IGF code and will be included in future parts of the IGF code. These revisions take part within the four-year cycle of SOLAS revisions. The IGF code only applies to ships with or above 500 gross tonnage, which actually excludes the vessel for this thesis. However, Norwegian-flagged ships must also follow the Norwegian Maritime Regulation for low-flashpoint fuels: "Forskrift om skip som bruker drivstoff med flammepunkt under 60 grader C (FOR-2016-12-27-1883, 2017)". The regulation states that ships and vessels (fishing vessels included) should fulfil a recognized classification society's rules for ships using low flashpoint fuels below 60 °C. This means that the fishing vessel in this thesis is required nevertheless to follow the IGF code after Norwegian law. It also states that the safety level should be equivalent to a new diesel-fueled ship, which should be documented through a recognized risk and explosion analysis.

According to the DNV and MarHySafe (2021), the alternative design approach required by the IGF code has the five following milestones before the design can be approved:

1. Development of preliminary design
2. Preliminary design approval
3. Final design development
4. Final design testing, analysis
5. Final approval

Several iterations may be needed in this process to prove an equivalent safety level to get the final approval from the Flag State. In EU member flag states, members of the International Association of Classification Societies (IACS) can also approve on behalf of the flag state.

### 4.8.3 Classification Societies

DNV and MarHySafe (2021) published a handbook for hydrogen-fueled vessels, which is a road map towards safe hydrogen operations for ships using fuel cells. It offers specific design requirements to ensure safety and mitigate risk and is a result of a consortium of 26 companies in the MarHySafe industry project. The classification societies are important to drive requirements for new technology when the notations from IMO are not yet developed.

In addition to the hydrogen handbook, DNV has a class notation "FC", mandatory for all classed vessels with fuel cell power installations on board. Lastly, on order from Trøndelag Country Municipality, DNV produced applicable rules for hydrogen FC high-speed passenger vessels in Norway in 2018. This document shows many of the similar regulations as in their hydrogen handbook. Some of the most notable class requirements from DNV are shown below:

The system arrangement must follow the DNV FC notation for fuel cell systems. DNV has two different class notations for fuel cells, one notation for power generation for propulsion (Power) and the other notation (Safety) where the fuel cell is used for other essential or emergency services. For compressed hydrogen storage, there are no specific standards yet. DNV suggests, however, using the existing DNV rules for compressed natural gas as a starting point for a more specific evaluation. The most crucial consideration for hydrogen storage is the tank type. The material choice is essential concerning weight, structural integrity and corrosion. DNV also suggests several safeguards to reduce the risk of hydrogen leaks by utilizing double pipes, relief valves, proper ventilation, safe locations of hydrogen systems and gas detectors.

Bureau Veritas has also developed class notations for ships using fuel cells. They do not have specific rules for hydrogen as a fuel; however, they fall under the category of other low flashpoint fuels. Some of the most important notations are that the fuel storage system and fuel cell space should be physically separated. Fuel cell spaces should be gastight to boundaries and other enclosed spaces. Ignition sources are to be minimized. Fuel cell spaces should be accessible from an open deck or through an airlock if accessed through another enclosed space. They have several regulations regarding ventilation for fuel cell spaces. Bureau Veritas also requires a reliability assessment of the FC power system to ensure an equivalent level of power availability for ships equipped with an ICE. Fuel piping in a ventilated fuel cell space is to be double-walled or a leakage-containing casing to act as a barrier against leaks. Safety systems for gas detection, overpressure and other events are required.

American Bureau of Shipping (ABS) has also developed fuel cell design guidelines and required deliverables when applying for approval of a hydrogen fuel cell system on a vessel.

The rules and recommendations from the classification societies can ease the alternative design process for shipowners as they give more detailed instructions on how the hydrogen fuel cell systems can be designed to obtain an equivalent level of safety. They can also be important drivers for IMO when developing the IGF code for other types of low flashpoint fuels than LNG.

# 5 Method

## 5.1 Introduction to Maintenance

Maintenance is a critical aspect of the maritime industry, as the failure of assets can have significant safety, environmental or economic consequences for the stakeholders. To ensure that assets are performing as intended, the right maintenance strategy is important. Maintenance is defined as the set of activities required to keep physical assets in the desired operating condition or to restore them to this condition (Pintelon and Parodi-Herz (2008)).

To optimize the total life cycle of an asset and meet production requirements within the intended time frame, cost-effectively and complying with environmental and safety standards, various strategies and theories have been developed for maintenance management. There are several ways to manage maintenance, including the following strategies from Pintelon and Parodi-Herz (2008):

- Corrective Maintenance (CM): Maintenance is performed after the asset has failed.
- Preventive Maintenance (PM): Maintenance activities are performed at pre-determined intervals to reduce the probability of asset failure. Intervals may be based on the number of operating hours or uses, for example.
- Predictive Maintenance (PdM): Maintenance actions are based on inspections and condition monitoring, and are performed to predict and prevent potential failures.

## 5.2 Maintenance Regulations for Maritime Vessels

IMO sets maintenance regulations for shipping in its International Safety Management (ISM) Code. According to the ISM Code, ship operators are responsible for ensuring the safe operations of the vessel, which includes maintaining and operating the hull, machinery, and equipment in compliance with rules and regulations. However, the code does not prescribe specific maintenance management strategies for operators to follow, leaving it up to the operator. While classification societies may establish guidelines for vessel maintenance, such as dry dock requirements, they do not dictate a specific maintenance management specification. For fishing vessels, there are even fewer regulations. The Norwegian Maritime Authority usually have no requirements for conventional coastal fishing vessels, however for hydrogen-fuel cell vessels, it is possible that maintenance plans would be required to get approval in accordance with the IGF code.

## 5.3 History of RCM and Maintenance

With the world evolving and changing and assets are becoming more complex, maintenance has changed significantly over the years. According to Moubray (1991), one can define three generations of maintenance since the 1930s. The first generation covered the period up to World War II when the equipment was not mechanised, and downtime did not matter. No systemic maintenance strategies were used in this period; fixing equipment when it broke was normal. During World War II, this changed significantly with increased mechanisation and technological development. This led to the concept of preventive maintenance, mostly by doing fixed overhauls which increased equipment life and lowered costs. Since the 1970s, new expectations, research and techniques within maintenance management were developed. Availability, safety, quality and better cost-effectiveness were in focus, which led to several new maintenance strategies, such as RCM. RCM was first documented in a report by Nowlan and Heap (1978) for the aircraft industry to reduce the number of accidents and increase availability. RCM has ever since been developed further to fit it other industries, such as the maritime industry.

## 5.4 Introduction to RCM

There are several management strategies to improve the availability, safety and operation of assets. One of those methods is called Reliability-Centred Maintenance (RCM) which is a maintenance management strategy. RCM is defined in Moubray (1991) as a process used to determine the maintenance requirements of any physical asset in its operating context. To specify the definition of the RCM even further, Moubray (1991) suggests that an RCM analysis intends to answer each of the following seven questions for every asset:

1. What are the functions and associated performance standards of the asset in its present operating context?
2. In what ways does it fail to fulfil its functions?
3. What causes each functional failure?
4. What happens when each failure occurs?
5. In what way does each failure matter?
6. What can be done to prevent each failure?
7. What should be done if a suitable preventive task cannot be found?

The first question is the start of the RCM process, where the goal is to define all of the asset's functions and performance standards which must be done before the rest of the analysis can be conducted. After the functions are defined, the remaining research is to study what causes a functional failure and what the effects of these causes are. All the ways the assets functions can fail must be discovered, and these are known as functional failures. Functional failures are defined as the inability of the asset to meet the intended performance standard (Moubray (1991)). When all functional failures have been found, one must then investigate the causes of every functional failure. The causes of functional failures are defined as the failure modes and are researched in the third question that Moubray (1991) defined. When failure modes are defined, one can then assess the consequences of every failure mode, which can be done using a failure modes, effect and criticality analysis (FMECA). An FMECA assesses failure modes and the effect of the failure mode on a local level and on a system level. The FMECA gives a list of the most critical failure modes, and from that, a maintenance task analysis (MTA) is conducted, which leads to constructing a maintenance plan to target the failure modes for the asset.

## 5.5 Benefits and Drawback of RCM

Before conducting an analysis using the Reliability Centered Maintenance method, it is important to be aware of the potential outcomes and benefits that the analysis can provide. According to Moubray (1991), some benefits of using RCM on an organization's assets include:

- **Greater safety and environmental protection**: This is achieved by risk-reducing measures on the most critical failure modes derived from the FMECA.
- **Improved operating performance**: One of the goals of RCM is to ensure that the most efficient maintenance measure is performed for every function, which means that it is expected that the operating performance is increased.
- **Greater maintenance cost-effectiveness**: Maintenance actions which have the largest effect on the asset performance are chosen with RCM, which should reduce the overall routine workload. In addition, cost-benefit analyses are performed to study what are the most cost-effective maintenance tasks.
- **Longer operational life of critical and expensive items**: This is achieved due to a large focus on preventive and predictive maintenance.

- **A detailed and comprehensive maintenance database**: One of the outcomes of the RCM analysis is a detailed and extensive database of all maintenance requirements for the asset.
- **Better motivation & better teamwork**: Having done an RCM analysis makes it easier for the operators to take ownership of the maintenance plan and also gives a proper plan where the tasks are justified.

The RCM method also has some disadvantages that one should be aware of. The main drawback of the RCM method is that the process is resource intensive and time-consuming. One needs a team of different experts in the workshops, and performing the analysis is time-consuming if one wants to cover all systems. Data availability can be challenging, and in some cases, data must be gathered before one can proceed with the analysis. Some of these drawbacks can be reduced by reducing the scope of the RCM analysis to only include the most critical systems. This will, though lead to a less detailed analysis.

## 5.6 Asset Register

Many assets have an asset register or a plant register which shows the structures of the different systems and how the equipment in a system is related. One example of this is the tag number system in the offshore oil & gas industry. According to M. Rausand and Vatn (2008), a system is a grouping of subsystems that together perform a series of key functions, and the whole asset often has one summarized primary function. The systems can be grouped down to subsystems; the lowest point is an RCM analysis item. An RCM analysis item is a group of components that performs at least one function. The component is the lowest level at which equipment can be disassembled without damage to the involved items. Often, the asset register will be established at the beginning of the RCM process to understand the system if it is not yet established. The asset register is important to have before conducting the FMECA, as it is essential when structuring the failures and systems in the FMECA worksheets.

## 5.7 Functions

When the system register is defined, the next step in the RCM process is to research the asset's functions and performance standards. The purpose of an asset should be clearly defined, and the intended function should be understood. Different types of equipment and systems can have multiple functions. According to M. Rausand and Vatn (2008), the following checklist can be used to identify and define all the functions of a system:

1. Essential functions: Functions which are required to fulfil the purpose of the system.
2. Auxiliary functions: Functions needed to support the essential functions.
3. Protective functions: Functions intended to protect people, equipment and environment from damage and injury.
4. Information functions: Functions intended to give data and information about the system.
5. Interface functions: Functions intended to be for interfaces between the item and other items, may be active or passive.
6. Superfluous functions: Items or equipment which are superfluous, for instance, if it has been frequently modified over the years.

The functions of a system should be clearly outlined and the checklist above can assist in identifying these functions.

## 5.8 Functional Failures

When all the functions for the asset are defined, the next step is to find out how the functions can fail. Not all failures lead to a total loss of function and that is why it is useful to have classifications. This means that the primary function can still be performed even if there is a functional failure in the system. This is the answer to the second of the seven RCM questions. A functional failure is defined as an inability of any physical asset to meet the desired performance standard according to Moubray (1991). M. Rausand and Vatn (2008) have divided functional failures into the three following categories:

1. Total loss of function: When the asset function is not achieved at all.
2. Partial loss of function: When the asset function is achieved only to a certain degree, for example, if a pump can only compress a certain percentage of the flow intended.
3. Erroneous function: When the asset acts in a way that is not expected.

## 5.9 Failure Modes, Effects and Criticality Analysis

The RCM analysis includes several questions related to the failure of components. The Failure Mode, Effect, and Criticality Analysis (FMECA) is a key part of the RCM process. The FMECA evaluates the failure modes and the impact of those failure modes on a local level and then evaluates the criticality of the failure mode on the system level. Once all failure modes have been analyzed, it is important to determine if the criticality meets the desired performance standards and identify ways to meet those standards. The effects of the failure modes can be evaluated in terms of safety, availability, and cost to determine criticality. The next step is determining each failure mode's consequence and frequency. Finally, the FMECA analysis is completed by evaluating the Risk Index (RI), which can be defined according to M. Rausand and Vatn (2008) if the frequency index is logarithmic:

$$RI = CI + FI \tag{1}$$

where CI is the consequence index and FI is the frequency index. FI and CI are integers in a given range depending on the consequence and frequency categories used, to describe the probability of a failure and the consequence of the failure. This gives a Risk Index in a certain range where a high RI means that the risk is higher and should be checked towards the risk acceptance criteria. A Risk Priority Number (RPN) is sometimes used also instead of RI. The consequence index, frequency index and risk acceptance criteria varies depending on the standard and categorisation for each specific FMECA case.

FMECA analyses potential failures in a system by breaking it down into its individual components. The analysis is typically done using standardized worksheets that contain information about the component, including its tag number, function, and operational mode. An illustration of such FMECA worksheet is shown in Figure 21. The worksheet also includes details about potential failures, such as the failure mode, failure detection, and failure cause, as well as an analysis of the effect of the failure on the component and the system as a whole. Additionally, a quantitative assessment of the frequency and consequence of the failure is calculated, which is used to determine the risk index of the failure mode. Once the failure modes have been ranked by criticality, risk-reducing measures can be implemented to reduce the risk of those failures. This can be done by redesigning the system or designing suitable maintenance tasks to target the failure modes. According to M. Rausand and Haugen (2020) there are eight objectives of an FMECA:

1. Identify how each of the system components can fail.
2. Determine the causes of these failure modes.
3. Identify the effects that each failure mode can have on the rest of the study object.

4. Describe how the failure modes can be detected.
5. Determine how often each failure mode will occur.
6. Determine how serious the various failure modes are.
7. Assess the risk related to each failure modes.
8. Identify risk reduction measures that may be relevant.

FMECA, have both advantages and disadvantages, the following suggestions are adopted from M. Rausand and Haugen (2020). One of the main benefits is that it is widely used in the industry and is easy to understand. Additionally, it is systematic and comprehensive, making it easy to identify relevant failure modes. It also allows for the breakdown of complex systems to understand how they can fail and what the consequences will be. However, there are some drawbacks to using FMECA. The quality of the analysis relies on the experience and skill of the FMECA analyst. If the analyst lacks knowledge or experience, important information may be overlooked. It can also be time-consuming, as it involves analyzing failures on the component level and complex systems can have many components. Additionally, it requires a hierarchical system drawing.

The RCM analysis should also be conducted in groups with participants of different skills and experiences from different functions to cover all failure modes, consequences and other things relevant to the analysis. FMECA is often performed in workshops with several experts.

## 5.10 Failure Consequences

When the functional failures and failures modes have been discovered, one must assess the consequences of the failure mode. If a failure mode can lead to severe consequences, it is increasingly important to see if something can be done to reduce the consequences or reduce the risk of the failure mode to occur. Moubray (1991) suggests the following four failure consequences:

- Hidden: Hidden failures are failure modes that, in normal conditions, would not be apparent to the operating crew. Hidden failures don't have any direct consequences in itself, but they raise the possibility of a multiple failure.
- Safety and environmental consequences: These consequences either cause harm or death to someone or result in a violation of any corporate, local, or federal environmental standards.
- Operational consequences: Consequences that have an impact on operations or production.
- Non-operational consequences: Consequences that don't fit into the three categories mentioned above, thus they simply involve the immediate expense of repair.

The consequence categorization of a failure mode is important later in the RCM analysis because the decision of maintenance tasks are dependent on the consequences of the failure mode.

## 5.11 Maintenance Plan Development

When the consequences of the failure modes are assessed, one can then develop an appropriate maintenance plan which should ensure optimal costs at an accepted level of risk in terms of the defined risk acceptance criteria in the task. In the following subsections, which maintenance tasks are worthwhile is discussed for every failure mode consequence category.

### 5.11.1 Hidden Failures

Hidden failures are failures that the crew would not normally notice under normal conditions. The crew may find it challenging to locate some equipment because it may have a variety of failure modes not evident for the crew. The increased likelihood of multiple failures is the only effect of a hidden failure, as was previously discussed. To determine whether trying to prevent numerous failures is worthwhile, we must first weigh the potential consequences of the hidden failure. According to Moubray (1991), a preventive task is only worth doing for hidden failures, if it secures the availability to reduce the probability of a multiple failure to an acceptable level. If a suitable preventive task cannot be found, it has to be examined if it is feasible and worth inspecting the hidden function periodically to ensure it is still working. There are certain levels of availability the asset operator needs to require when determining the frequency of a failure finding interval. To ensure an availability of 99.5% of the component, a failure finding frequency should be 1% of the MTBF according to Moubray (1991).

### 5.11.2 Safety and Environmental Consequences

As per Moubray (1991), a preventive activity is only worthwhile if it lowers the risk of the failure to an acceptable level. If this cannot be achieved, redesign is necessary to ensure that the risk is acceptable or that the failure mode no longer has an impact on safety or the environment.

### 5.11.3 Operational Consequences

Operational failure consequences refer to the negative effects that impact the operation or production of an asset, which can include production output, quality, service, and repair costs. Unlike safety and environmental failure consequences, operational failures are primarily related to the economic aspects of the asset. According to Moubray (1991), preventive maintenance tasks should only be implemented for failure modes with operational consequences if the cost of the preventive task is less than the cost of the operational consequence and repair costs over a given time period. If a cost-effective preventive task cannot be found, it may not be worth to perform any scheduled maintenance. Alternatively, a design change of the asset could be implemented to reduce costs by lowering the probability of failure, decreasing the severity of consequences, or reducing the costs of preventive maintenance.

### 5.11.4 Non-operational Consequences

Non-operational consequences refer to the consequences of a failure that do not affect the operations, safety, or environment of an asset. These consequences are directly related to the costs of repairing the asset. According to Moubray (1991), it is only worthwhile to perform a preventive maintenance task for non-operational consequences if the cost of preventive action is less than the cost of fixing the failure.

## 5.12 Maintenance Task Analysis

One of the last steps in the RCM analysis is to determine an optimal maintenance system. The FMECA results in a list of all failure modes within the system ranked on severity. These are used when determining necessary maintenance tasks.

### 5.12.1 Classification of Maintenance Tasks

As mentioned earlier, there are several maintenance strategies, and maintenance strategies can be, for instance, divided into corrective, preventive and predictive maintenance according to Pintelon and Parodi-Herz (2008). It is worth noting that both predictive and preventive maintenance have the same goal, which is to prevent, reduce or avoid the consequences of a failure, but with different approaches to the maintenance. Corrective maintenance, on the other hand, is performed after the object has failed.

From a human safety and environmental perspective, predictive and preventive maintenance can be a good choice because the goal is to prevent or reduce the consequence of a failure. It might, for example, detect equipment degradation at an early stage through inspection or condition monitoring. However, performing maintenance too often can increase maintenance costs and can even lead to a higher risk of failure. By increasing the general level of maintenance, the risk for human errors and inadequate maintenance increases also according to Vinnem (2014). It is, therefore, important to find the correct balance of maintenance tasks.

Moubray (1991) suggests that scheduled restoration tasks mean remanufacturing a component or overhauling an entire system at or before a specific time limit, regardless of the condition. This means the tasks are performed at a pre-determined time interval or point in time. The frequency of scheduled restoration tasks is decided by the time the component shows a significant increase in the conditional probability of failure. To do this, one needs historical failure or reliability data of the item. If this is lacking due to data unavailability or if the system is new, it is difficult to set a fitting interval or point of the time where scheduled restoration is suitable. In addition, one needs to know if there is a certain time when there is an increase in the probability of failure of the item. To determine if a scheduled restoration task is worth doing, the consequences of the failure must be assessed, and this can be done using an RCM decision tree.

Scheduled replacement tasks are, according to Moubray (1991), tasks that replace an item or component at a certain time limit regardless of its condition, and this item is replaced with a completely new item or component. The frequency of the scheduled replacement tasks also depends on the component's failure probability. The consequences of the failure decide whether or not a scheduled replacement task is worth doing or not. There are also some items with different failure patterns, such as electronic, hydraulic and pneumatic equipment. They have little increase in the probability of failure with time. In these cases, scheduled replacements can actually increase failure rates by introducing high infant mortality into the system (Moubray (1991)). For these types of failure patterns, other types of maintenance strategies can be considered. Predictive maintenance based on inspections and condition monitoring for failure prediction can be more suitable tasks for these items.

Scheduled on-condition tasks are in the predictive maintenance task category. On-condition tasks are feasible if it is possible to define a clear potential failure condition and if it is possible to do condition monitoring of the item at periods less than the P-F interval. A P-F interval is an estimate of of the time from detecting a potential failure to the failure has occurred. As with other maintenance tasks, the consequences of the failures decide whether on-condition tasks are worth doing. Moubray (1991) describes four categories of on-condition techniques:

- Condition monitoring techniques: for instance vibration monitoring.
- Product quality variation techniques: In some industries, a proper quality management function is important information about potential failures. This is however not that relevant for a vessel.
- Primary effects monitoring: Monitoring pressure, flow, current and other inputs from the process can inform whether the system is performing at a sufficient level and can give warnings of potential failures.
- Inspection based on human senses: Inspection based on human senses (look, listen, feel and smell). This requires that the inspector has knowledge about the system so that the inspector is able to spot deviations. In addition, this process gives highly subjective information.

One also has scheduled failure-finding tasks. These are tasks where the objective is to find whether the component has failed. This implies that the item will be in failed state until the failure is found. Scheduled failure-finding tasks only apply for hidden failures and should only be done if no other maintenance task is suitable. This is because one cannot prevent the failure from happening with a failure-finding task.

Whether preventive, corrective or predictive maintenance is more suitable and what kind of task is optimal is decided by the RCM decision tree, covered in Section 5.13. Often, the main objective when choosing a maintenance task is to reduce the failure rate to an acceptable level and choose the most cost-effective task depending on the context of the failure.

### 5.12.2 Failure Patterns

During the FMECA, the failure modes and failure causes for the system have been established. The failure patterns for the different equipment are also important for establishing maintenance tasks and understanding the failure rate for various equipment. An illustration of six different failure patterns from Nowlan and Heap (1978) are illustrated in Figure 6.

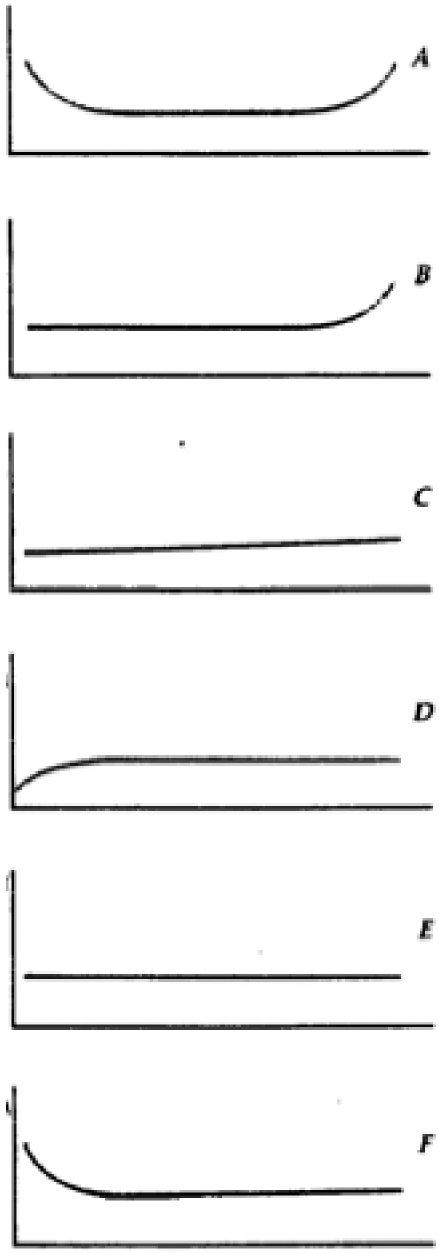


Figure 6: Six different failure patterns, from Nowlan and Heap (1978).

The failure patterns illustrated in Figure 6, shows how the probability of a failure for a certain type of equipment varies over time. Moubray (1991) defines the six different failure patterns in the following way:

- Pattern A: This is known as the bathtub curve. This failure pattern illustrates equipment with a larger probability for infant-mortality and for age-related wear out.
- Pattern B: This pattern shows age-related failures. As we can see, the failure rate is constant until a certain period where the failure probability increases significantly.
- Pattern C: This failure pattern also illustrates age-related failures, however it is challenging to identify a certain point of time where the probability of failure increases significantly.
- Pattern D: The break-in curve, the probability of failure is low in the early life of the component but increases rapidly before it is constant the rest of the lifetime.
- Pattern E: This pattern denotes random failures, the functional failure may occur at any time.
- Pattern F: This failure pattern shows infant mortality meaning that the probability of failure is higher in the early life time.

For this thesis, the failure modes have been divided roughly into four categories to make failure pattern categorization easier. This is due to lacking information and failure data. The four categories for the failure modes are mechanical, electrical, electromechanical and software.

Mechanical equipment or failures are often related to wear-out, fatigue and corrosion. These failures happen over time, which means that the equipment's failure probability increases with time. It is often found in equipment which is in direct contact with the product. These types of failures have been associated with failure pattern B. Failure modes related to fatigue have been associated with failure pattern C, which is related to cyclic loads or stresses over a time period. Electrical equipment has mostly been related to failure pattern E. These types of equipment are less exposed to wear-out, corrosion and fatigue and more exposed to random electrical faults such as short circuits or wrong installations. Electromechanical equipment, which is a combination of electrical and mechanical equipment, is assumed to have a failure pattern of A, which is a combination of failure pattern B and failure pattern F, meaning it combines high-infant mortality and wear-out. Other types of equipment have been given an individual assessment of the failure patterns.

### 5.12.3 P-F Interval

Condition monitoring for maintenance is based on the idea that failures develop over time. Failures can be spotted through signs of a potential failure, such as cracks showing fatigue, vibrations, corrosion, etc. Observing and monitoring the item over time could predict when a failure is about to occur. A P-F interval should be established to justify the use of such maintenance action. A P-F interval is an estimate of the time from detecting a potential failure to the point where it failed. On-condition tasks involve checking the item for potential failures so that an action can be taken to prevent the functional failure or avoid the consequences of the functional failure according to Moubray (1991). The frequency of the on-condition task must be less than the P-F interval to avoid a functional failure or reduce the consequences. If the task is done at intervals larger than the P-F interval, it is a chance that the failure is missed. However, it is also important to avoid too frequent intervals to avoid wasting resources and increasing the risk of human failures. A P-F curve is illustrated in Figure 7.

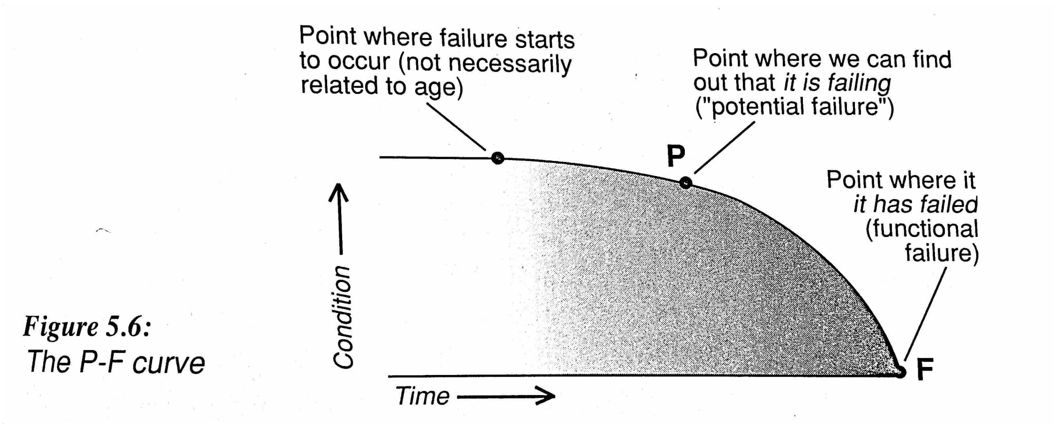


Figure 7: P-F curve where the P-F interval is the time from point P to point F. From Moubray (1991).

## 5.13 RCM Decision Diagram

Figure 8 presents a simplified version of the RCM decision process. The complete RCM decision diagram, which has been used for this analysis, is presented in Appendix E. It is divided into different consequence types and recommends a fitting maintenance activity to address the failure mode and its effects. The diagram offers a systematic approach to determining whether an activity is worthwhile. Using the RCM decision diagram, one can propose a maintenance plan based on the analysis results. Generally, the task should reduce the consequence or probability of failure or remove the hazard altogether. Also, the cost of the maintenance task should be assessed. As described earlier, if there are no safety or environmental consequences, a cost-benefit analysis of the task should be done.

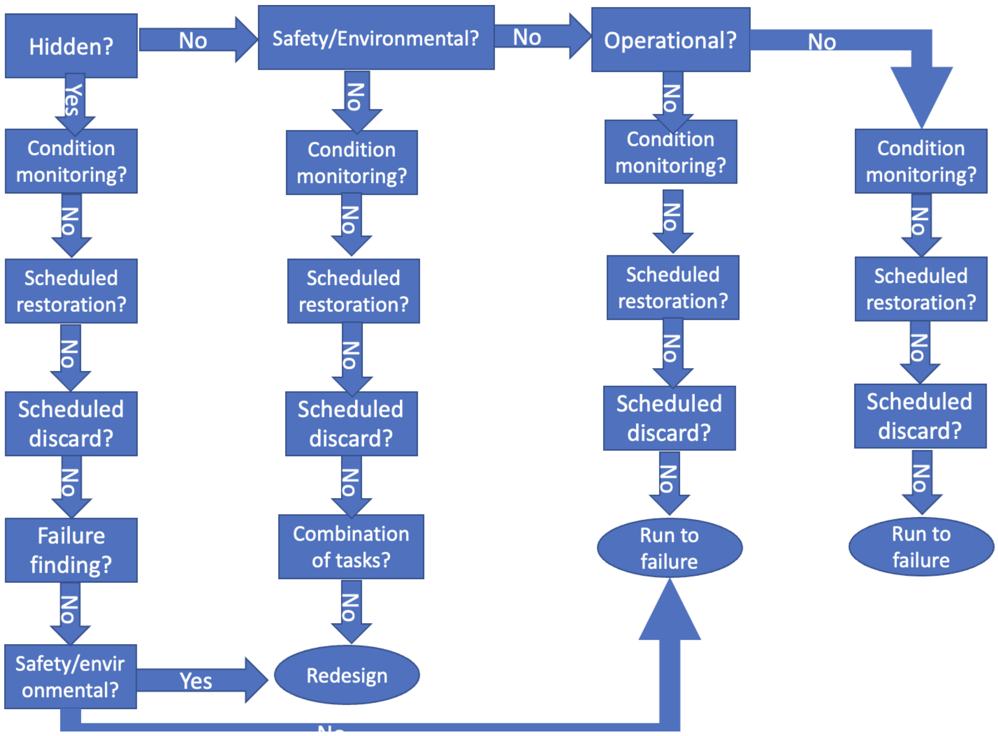


Figure 8: Simplified RCM Decision Diagram, adopted from Moubray (1991).

When conducting the RCM analysis and using the decision diagram, one starts in the top left corner for every failure mode. By working through the decision tree, the consequences of the failure mode are assessed, and a suitable maintenance task is found. Sometimes a suitable maintenance task is not found, the decision tree shows that a run to failure (corrective maintenance) or a complete redesign are suitable solutions.

## 5.14 RCM Framework

Many assets consist of complex systems and subsystems with many failure modes. It is critical to perform the analysis in a structured manner so that the results can be used and to get an overview of the process. Several frameworks can be used to structure the analysis, such as software, worksheets and tables. One can organize it to have a single framework for the FMECA and one for the total RCM with the maintenance tasks. Microsoft Excel or similar software are commonly used for structuring RCM worksheets. In this thesis Microsoft Excel was chosen as the RCM framework software. A separate sheet for the FMECA and the MTA has been made, with references between the two sheets. An illustration of the RCM framework for this thesis is shown in Figure 9. This framework followed the RCM decision diagram to show what maintenance tasks are the most suitable for each failure mode.

**RCM Decision Worksheet** Description: This worksheet follows the RCM decision tree presented in my Masters thesis, and is referencing to the FMECA worksheet for the failure modes

*System: H2 Propulsion System on Fishing Vessel* *Owner: Aleksander Aira-Andersen* *Page: 1 of 1*

| Failure referen | | Consequence evaluation | | | | Technical feasibility of tasks | | | Default action | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| System reference | Failure mode reference | Evident? | Safety? | Environmental? | Operational? | Is on-condition task feasible? | Is scheduled restoration feasible? | Is scheduled discard feasible? | Failure detection feasible? | Could the failure affect safety or the environment? | FP? | Proposed task | Interval | Comments |
| | | | | | | | | | | | | | | |

Figure 9: RCM Framework in Microsoft Excel.

## 5.15 Maintenance Costs

In addition to increase the safety and reliability of a system, one of the main objectives with an RCM analysis is to construct a cost-effective maintenance schedule. Comparisons of the maintenance tasks should therefore be done to ensure what maintenance tasks are the optimal for reduced costs.

### 5.15.1 Costs of Corrective Maintenance

The run-to-failure maintenance task are the events that would happen if there were no maintenance plan. Every failure would occur and then be repaired or replaced. The cost of corrective maintenance $C_{CM}$ is defined in the following manner:

$$C_{CM} = C_{DT} + C_S + C_R \tag{2}$$

where $C_{DT}$ is the downtime cost, $C_S$ is the cost of spare parts, and $C_R$ is the costs associated to the repair. Downtime costs are defined such:

$$C_{DT} = DT \cdot LI \tag{3}$$

where $DT$ is the downtime in hours and $LI$ is the loss of income per hour. The loss of income is assumed to be the cost of not operating the vessel, i.e. not doing any fishing activities.

Cost of repair $C_R$ is defined as:

$$C_R = C_L \cdot Duration \tag{4}$$

where $C_L$ are the labour costs per time unit. Costs related to travel time, weather window and preparation is assumed to be included in the repair costs.

### 5.15.2 Costs of Preventive Maintenance

The costs of scheduled restoration tasks are the following:

$$C_{SR} = C_R \tag{5}$$

The costs of scheduled replacement tasks are the following:

$$C_{SD} = C_R + C_S \tag{6}$$

The costs of on-condition tasks are:

$$C_{OC} = C_E + C_M \tag{7}$$

where $C_M$ is the cost of doing condition monitoring (manhours), and $C_E$ is the cost of the condition monitoring equipment.

## 5.16 Safety Instrumented Systems

Due to the hazards of using hydrogen as a fuel, the propulsion system will include Safety Instrumented Systems (SIS). A SIS is defined by Rausand (2014) as a safety system comprising at least three elements: sensors/input devices, logic solvers and a final element subsystem. The input devices detect a potential hazard and send a signal to the logic solver. The logic solver receives the signal from the sensor, which has triggered a specific limit. The logic solver then sends an activation signal to the final element subsystem. The final element subsystem is responsible for performing a safety function, for instance, closing a valve. The function of the SIS is to perform a Safety Integrity Function (SIF), which is a consequence-reducing barrier in case of a hazardous event. Certain standards and levels exist for a SIS to perform a SIF, called Safety Integrity Level (SIL). Four SIL levels are defined by IEC (2010), an international SIS standard. The four SIL levels are shown in Figure 10.

| **Safety integrity level (SIL)** | **Average frequency of a dangerous failure of the safety function [$h^{-1}$] (PFH)** |
|---|---|
| 4 | $\geq 10^{-9}$ to $< 10^{-8}$ |
| 3 | $\geq 10^{-8}$ to $< 10^{-7}$ |
| 2 | $\geq 10^{-7}$ to $< 10^{-6}$ |
| 1 | $\geq 10^{-6}$ to $< 10^{-5}$ |

Figure 10: Safety Integrity Levels as defined by IEC (2010).

### 5.16.1 Reliability Quantification for Safety Instrumented Systems

The SIS is vital to ensure the safety of the hydrogen propulsion system for the vessel. The SIS, such as emergency shutdown systems, process shutdown systems and fire and gas detection systems, are equipped to prevent deviations from normal operations to hazardous situations. SIS are also consequence-reducing barriers in case a hazardous event has already occurred. According to the PDS handbook by Håbrekke et al. (2013), SIS can have four types of failures with regard to system testing. Tests are done to ensure that the SIS is able to perform their SIF. The handbook provides an approach to understanding how SIS can fail and the probability of failure. Failures only detected by proof tests are called Dangerous Undetected (DU) failures and can lead to a failure of a SIS. Failures detected by built-in test functions and where the component is not operating on demand are called Dangerous Detected (DD) failures. Safe failures are failures where the equipment can operate in case of a failure and can also be detected (SD) or undetected (SU) safe failures. The most critical failures are dangerous undetected failures, as such failures of the SIS can be critical. Figure 11 defines the various failure categories and how the failure rates are defined according to Håbrekke et al. (2013).

| | Spurious trip failures | Dangerous failures | Sum |
|---|---|---|---|
| Undetected | $\lambda_{SU}$ | $\lambda_{DU}$ | $\lambda_{undet}$ |
| Detected | $\lambda_{SD}$ | $\lambda_{DD}$ | $\lambda_{det}$ |
| Sum | $\lambda_S$ | $\lambda_D$ | $\lambda_{crit}$ |

Figure 11: Failure rate definition for safe and dangerous, detected and undetected failures, from the PDS handbook by Håbrekke et al. (2013).

Rausand (2014) defined Probability of Failure on Demand (PFD) as the probability that a dangerous failure is present so that the SIS cannot perform the SIF at demand. PFD values are often categorized to certain SIL levels as shown in Figure 10. The PFD per hour and failure rates are used for determining some frequency indices of failure modes for SIS in the FMECA. For a 1-o-o-1 voting logic (no redundancy), the PFD per hour of testing period is approximated by:

$$PFD_{1oo1} \approx \lambda_{DU}/2 \tag{8}$$

where $\lambda_{DU}$ is the failure rate for a DU failure per $10^6$ hours. To obtain a desired level of safety, redundancy of SIS is often required to reduce the risk of a DU failure. The probability of failure on demand is dependent on the redundancy level. There are various types of redundancy, such as active and passive redundancy. Active redundancy means that several components are doing the same function continuously and simultaneously. Passive redundancy can be that a component is on standby and is activated if another component fails. Only active redundancy is assumed in this analysis. The PFD per hour of testing for a M-o-o-N voting logic ($M < N$) is approximated by:

$$PFD_{MooN} \approx \frac{N!}{(N-M+2)! \cdot (M-1)!} \cdot (\lambda_{DU})^{N-M+1} + C_{MooN} \cdot \beta \cdot (\lambda_{DU}/2) \tag{9}$$

where $C_{MooN}$ is a modification factor depending on the voting logic. The modification factor values are presented in Figure 12.

| M \ N | N = 2 | N = 3 | N = 4 | N = 5 | N = 6 |
|---|---|---|---|---|---|
| M = 1 | $C_{1oo2}$ = 1.0 | $C_{1oo3}$ = 0.5 | $C_{1oo4}$ = 0.3 | $C_{1oo5}$ = 0.21 | $C_{1oo6}$ = 0.17 |
| M = 2 | - | $C_{2oo3}$ = 2.0 | $C_{2oo4}$ = 1.1 | $C_{2oo5}$ = 0.7 | $C_{2oo6}$ = 0.4 |
| M = 3 | - | - | $C_{3oo4}$ = 2.9 | $C_{3oo5}$ = 1.8 | $C_{3oo6}$ = 1.1 |
| M = 4 | - | - | - | $C_{4oo5}$ = 3.7 | $C_{4oo6}$ = 2.4 |
| M = 5 | - | - | - | - | $C_{5oo6}$ = 4.3 |

Figure 12: Values of $C_{MooN}$, based on the PDS handbook from Håbrekke et al. (2013).

### 5.17 Literature Review

Madsen et al. (2020) did a concept study of the technical, regulatory and economic feasibility of a hydrogen fuel-cell coastal research vessel called Zero-V. This vessel uses an 1800 kW PEM fuel cell for primary propulsion and stores the hydrogen in a liquefied format in two separate $LH_2$ tanks, with a range of 2400 nm. From their complete well-to-waves (WTW) analysis, when using green hydrogen, it was estimated that the GHG emissions from this vessel would be approximately 91% less than those from an equivalent vessel on conventional diesel fuel. The capital costs were estimated to be similar for a conventional diesel-fueled research vessel of similar size. In contrast, the operations and maintenance costs were estimated to be 7.7% higher than the cost would be for an equivalent diesel fulled vessel using their assumed $LH_2$ prices. The vessel is significantly larger and more complex than a coastal fishing vessel, with higher costs; however, it shows the feasibility of adopting hydrogen using fuel cells on ships.

Brødrene Aa, Westcon Power & Automation and Boreal Sjø, together with Trøndelag Fylkeskommune, released a report from a conceptual design of a high-speed compressed hydrogen-fueled fuel cell ferry called Doffin in 2019. This report thoroughly describes the energy system and vessel particulars. A hazard identification (HAZID) of the hydrogen system was also conducted, with Gexcon as the facilitator. A risk matrix was not presented for the HAZID. However, the risks were ranked as Low/Medium/High. Some hazards identified are relevant to the vessel analysed in the thesis, while others are specific for the Doffin vessel.

Igder et al. (2021) studied emission-free ships' reliability and safety improvement using systemic reliability-centred maintenance (SRCM). An FMEA was performed, a simplified version of the FMECA for a hybrid MC fuel cell system. This was performed on a ship using liquid hydrogen, meaning some failure modes, such as $H_2$ boil-off gas increase, would not be relevant for a system using compressed hydrogen instead. However, other failure modes related to the fuel cells and batteries are relevant to the system in this thesis.

Ogbonnaya et al. (2021) performed an FMECA on a photovoltaic PEM fuel cell system for power generation for house loads, which shows some failure modes for fuel cell systems. A criticality assessment has also been done so that a comparison of some results can be made. This study was, however, not on a fuel cell designed for propulsion in the marine environment, so it should be noticed. Therefore it has some limitations with regards to using the results for this thesis.

Al-Douri et al. (2023) did a quantitative risk assessment (QRA) on a hydrogen-fueled fuel cell forklift and made a summary of frequency values for leaks from various components in an FC power system for the forklift. The forklift is not expected to operate in a marine environment which can be salty and moist, which should be taken into account.

Trivyza et al. (2021) also performed an FMECA of a fuel cell system with a corresponding criticality assessment. This was, however, for an ammonia-fueled fuel cell system. The results, especially related to storage and consequences of a leak, are assumed to be different due to the different properties of $NH_3$.

Stephens et al. (2009) performed an FMEA of a hydrogen PEM fuel-cell vehicle focusing on the fueling and fuel storage system, fuel delivery system and fuel cell system for a land-based vehicle. The focus was on compressed hydrogen in the 345 bar to 700 bar range. Despite not being on a marine vessel, many failure modes are assumed to be similar for the components.

Miller (2019) performed an FMECA for an aeroplane using PEM fuel cells with two options: either for emergency power and also as main power. Some fuel cell-specific failure modes can be relevant despite not being a maritime application. The FMECA used, however, a risk matrix which only focused on operational consequences. This means that the consequence analysis did not focus on safety-related consequences.

Jeon et al. (2020) did a re-established FMECA for a 100 kW molten-carbonate fuel cell hybrid liquefied hydrogen power system for ships, with a battery and diesel generator.

# 6 Data Collection

To conduct the RCM analysis, several methods have been used to gather information and data relevant to the task. Since this type of technology is new, obtaining data can be difficult. Industry partners have delivered vessel and system specifications, such as HAZID risk analysis, P&IDs and single-line diagrams (confidential). Besides, the author has participated in project meetings to understand the project better. Meetings with experts within fuel cell and hydrogen propulsion, such as researchers and ship owners has also been held to increase knowledge. In addition, a visit to the Lofotfishing fishery mass in Lofoten was made during March 2023. During the visit to Lofotfishing, the author got to speak with fishers about safety, maintenance and opinions on hydrogen as a fuel. In addition, some of the companies from Lofoten, which also work with hydrogen, gave good insights into safety barriers, maintenance and operation of fuel cell-driven fishing vessels using hydrogen. The author spoke with two fishermen, a shipyard which will build a hydrogen-fueled vessel, a company that delivers solutions for hydrogen-fueled speed boats, a hydrogen infrastructure company, a repair shipyard for fishing vessels, and other relevant stakeholders.

For failure modes and degradation of fuel cells, Sintef gave in a meeting insights from some of their fuel cell experts on how a fuel cell can degrade or fail and what kind of maintenance is required. Selfa Arctic provided more specific details about the hydrogen-electric fishing vessel in a meeting, which is analysed in this thesis. With all the technical specifications, it is easier to analyse the system. In addition, a design company and a shipowner working on similar projects have provided valuable input for hydrogen-fueled vessels concerning safety philosophy, maintenance requirements and failure information. The vessels are different from coastal fishing vessels. However, many safety philosophies are the same for these types of systems.

Several databases and sources have been used for reliability and failure data of the components in the system used for the FMECA. Some frequencies have been determined from other risk analyses or literature. Reliability databases such as PDS, OREDA, IEEE and IAEA have been used in this thesis. A thorough presentation of the sources for the data in the FMECA is presented at a later stage. Consequences have mostly been estimated through literature, discussions with industry partners and the author's judgement. For the cost estimations, relevant literature and information from suppliers have been used. Manhour estimations have mostly been from OREDA or assumptions by the student. A Postdoc from NTNU also gave some knowledge about failures and frequencies for parts of the safety system.

# 7 Fishing Vessel Characteristics

Before the analysis, it is important to understand fishing vessels and the environments they operate in. This thesis will focus on a small fishing vessel with a length less than 13 meters, which will operate in cold marine environments along the coast of Norway with partially rough weather conditions. These types of fishing vessels are commonly known in Norway as a ”sjark” or ”fiskesjark” and have a characteristic appearance as seen in Figure 2. These vessels typically have diesel engines and use fishing equipment such as Danish seine, long lines, and gill nets. These vessels are typically below 11.99 meters, with a breadth of 3-4.5 meters. From Zerokyst (2023), it is understood that most fishing vessels in this category use diesel engines for propulsion. These vessels are typically operated by 1-3 crew members, and the shipowner often works as a fisher on the vessel.

## 7.1 Operational Profile & Environment

The coastal fishing vessels have various operational patterns throughout the year, depending on the fishery. According to Hüllein et al. (2023), most fishers rely on a good catch during the Lofoten fisheries in the late winter/early spring months. If this is not achieved, they might fish for other species during summer further off from the coast or travel to Finnmark for further cod fishing or crab fishing during autumn if the vessel quota is not reached. This means that the vessels' operation will differ depending on the season and the catch.

During operation, it is expected that most of the power is required for sailing to and from the fishing field, while some auxiliary loads are required to power the fishing gear during fishing. If the vessel is hybrid-electric, battery power can power the fishing gear. This leads to noise-free fishing operations.

For zero-emission hybrid-electric vessels, alternative fuels such as hydrogen can power the vessel for sailing instead of diesel to reduce greenhouse gas emissions.

Figure 13 illustrates the operational environment of a hydrogen-fueled fishing vessel. It is expected that during normal operations, the vessel will be in one of four modes: at sea, delivering fish, filling hydrogen or at berth.

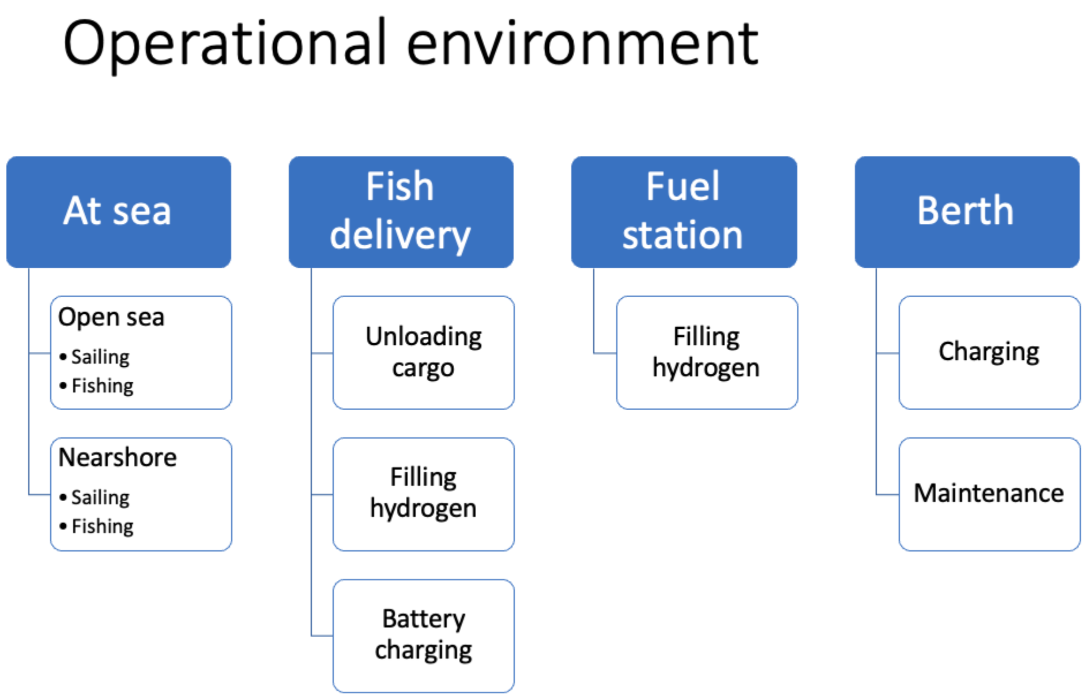


Figure 13: Operational environment for hydrogen-fueled fishing vessel

### 7.2 Operational Assumptions

Some assumptions regarding the vessel's operations are necessary since the vessel is not yet built. After discussing with two fishers with similar-sized coastal fishing vessels, they estimated that every fishing trip takes 10-12 hours. The first fisher did only go to the seasonal fishery in Lofoten and another seasonal halibut fishery for a total time of around 60 days, whilst the other fisher estimated around 230 days per year for fishing. In this thesis, 200 fishing days per year are estimated, with 12 hours of operation every day. From the operational profile distribution (confidential), which uses data from many fishing vessels, it is estimated that roughly 4 hours go to sailing on full load, while the rest is on a lower load for fishing. It is therefore assumed that the fishing vessel uses the fuel cell for propulsion for 4 hours per fishing day and the battery at 100% capacity for 8 hours each day. This leads to the following yearly operations of the following components:

| Equipment | Yearly operation [h] |
|---|---|
| PEM Fuel Cell | 800 |
| Battery | 1600 |

Table 1: Yearly operation

Since the two fishermen have different fishing operations yearly, their fishing income differs. However, they estimated both an income of around 30 000 NOK daily while fishing which has been used as a basis for this analysis. The salary for a fisher varies depending on whether the fisher is the ship owner as well as investments, company structure, etc. An average salary of 700 000 NOK per fisher is assumed annually, corresponding to about 337 NOK per hour. It is assumed that the battery is charged every fishing day and that the hydrogen tank is filled every fishing day, which means 200 cycles of charging the battery and 200 cycles of filling the hydrogen tank per year.

# 8 System & Vessel Description

The vessel used in this analysis is the HyMAX hydrogen-fuelled fishing vessel that will be built by Selfa Arctic Shipyard. It has a hydrogen-electric propulsion system. It will have a battery pack, a PEM fuel cell and an emergency diesel generator. The battery pack and the electrical motor are located in the bottom of the vessel in a separate room while the fuel cell is located in a separate room on the main deck. The hydrogen storage tank is located on the top of the vessel. The storage tank is a pressurized cylindrical tank. The length of the vessel is 12.99 meters.

To answer the first questions of the seven questions to Moubray (1991), one must have a fundamental understanding of the system one is looking at. This analysis will cover the hydrogen power generation system of the fishing vessel. From drawings from the suppliers, it is known that the vessel will be equipped with a compressed hydrogen tank, a fuel cell, a battery, an emergency diesel generator and safety systems. A simplified illustration of the flow of the propulsion and power generation system is shown in Figure 14. It shows how the power flows through the system for propulsion and auxiliary systems.

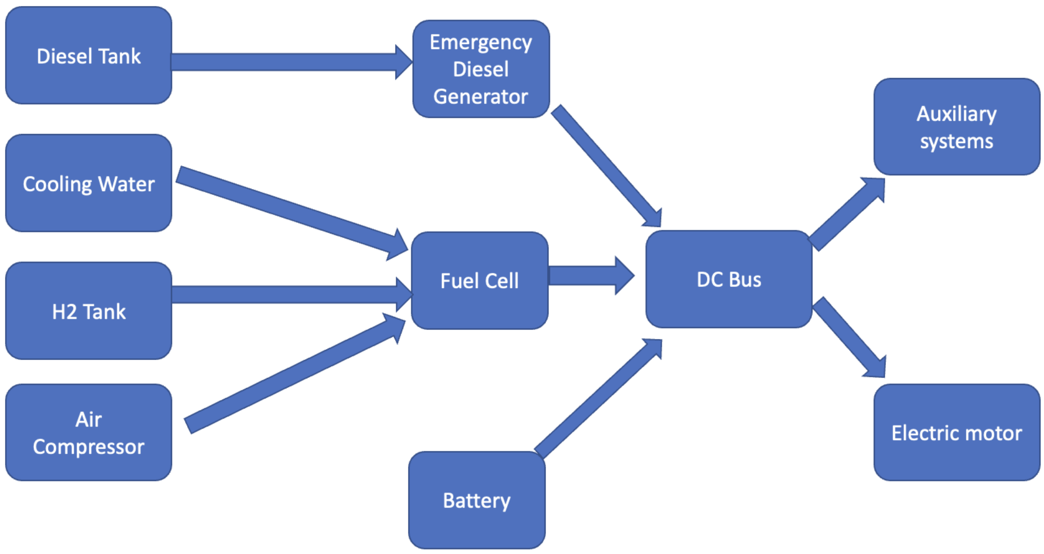


Figure 14: Power generation logic of the system, showing the main components.

## 8.1 Fuel Cell System

The fuel cell is responsible for the main power generation for propulsion for the fishing vessel. It is a PEM fuel cell which consists of a fuel cell stack, an air management and a water management system. The fuel cell stack is supplied with hydrogen and air, and through a membrane, hydrogen is oxidized to generate electricity using an anode and a cathode. The air compressor is there to increase the pressure of the air and feed more air to the fuel cell to increase the efficiency. Water is the byproduct of the reaction and has to be managed. In addition, water is used to cool down the fuel cell. The air management and water management system is analysed separately in this analysis. The electricity generated from the FC is sent to the DC bus to distribute the power for the vessel. The main function of the fuel cell is to generate power from hydrogen.

### 8.1.1 Water Management System

In addition to the fuel cell stack, support systems are needed for the fuel cell to function. The water management system is there to handle the water generated from the fuel cell reaction, and also to handle cooling of the FC stack. A water pump and piping are important parts of the water management system.

### 8.1.2 Air Management System

Oxygen and hydrogen is needed for the oxidization process in the fuel cell to generate electricity. It is essential to provide a steady flow of air to the fuel cell to ensure that the fuel cell can operate at the intended level. It is assumed that the air management system consists of an air compressor to supply the air to the fuel cell. The main function of the air management system is to compress air to the fuel cell and handle exhaust air.

## 8.2 Emergency Diesel Generator

If the fuel cell stack should fail, an emergency diesel generator is available to power the system for crew & vessel safety. The main function of the emergency generator is to generate electrical energy in an emergency situation.

## 8.3 Electric Systems

### 8.3.1 Battery System

The vessel is also equipped with a battery. The battery can be charged when the vessel is berthing when the fisher has sailed home for the night. The battery system can be used to power the fishing gear, the cabin and it can potentially serve as reserve power for propulsion. It may also be used for peak-shaving which means that the fuel cell can run at the optimal load at all times. The main function of the battery is to store electrical energy.

### 8.3.2 Converters & Inverters

The electric system also consists of converters and inverters which are devices that can convert electricity from one source to another source or changing the voltage level. For converters, you can have a DC-DC converter, which accepts direct current (DC) input voltage and produces a DC output voltage with a variable voltage level. Another converter type is an AC-DC converter, which converts an input voltage with alternating current (AC) into an output voltage with direct current (DC). On the other hand, an inverter is a piece of technology that transforms DC electricity into AC power. For this system, both inverters and converters are used. For the fishing vessel, converters are used to converter AC current from the fuel cell to the DC or from the generator. The inverters are used to invert the current from the DC bus to the electric motor or to the auxiliary system.

### 8.3.3 DC Bus/Switchboard

A DC bus, is a conductor or electrical node used to distribute power to various components or subsystems in a DC power system. In this system it is connecting the diesel generator, battery, fuel cell, onshore charging with auxiliary loads and the electric motor for propulsion. The main function of the DC switchboard is to distribute power to the components from multiple power sources.

## 8.4 Safety Systems

As seen from the system hierarchy in Figure 15, the safety systems are split in the ESD and the F&G detection system. The ESD system is related to the fuel process system for the fuel cell, which consists of input devices, CLU and safety valves. This is meant to prevent overpressure, ignitions and other hazardous situations in the fuel system. The ESD system should be able to automatically or manually shutdown the fuel cell and the entire fuel system. This is done by either triggering an alarm where the vessel operator can manually shut the system down, or an automatic system shutdown. This is done by monitoring process parameters through transmitters, having alarms, automatic shutdown systems through a control logic unit which can shut off certain valves. The F&G detection system is a system for detecting hydrogen, smoke and fire. Several detectors are placed at various locations in case of a leakage, smoke or fire. If this is detected, a signal is sent to the alarm and control logic unit.

### 8.4.1 F&G Detection

The fire and gas detection system is meant to detect potential ignitions, fires and/or hazardous gases. The primary function of F&G detectors is to detect either a concentration of hydrogen or heat/flames and then provide an electronic output signal to the CLU and alarm system. This is done by having separate detectors which search for gas or heat/fire. Failure data and failure modes for the detectors are obtained from OREDA, PDS and Miller (2019). It is assumed a 1-o-o-2 redundancy, which means that if only one of the detectors detect a certain $H_2$ concentration or a hazardous amount of fire/smoke, a signal is then sent to the CLU system and alarm system for a potential shutdown. This can lead to false positives which potentially can lead to unnecessary shutdowns. The failure rate calculations are done by using Equation 9.

### 8.4.2 Control Logic Unit

The control logic unit (CLU) is an important part of the safety system, as it is the ”brain” of the system. The primary function of the CLU is to receive a signal from a sensor or a transmitter, determine from the signal if a certain safety function shoud be initiated and then send an output signal to the relevant equipment. An example of this could be to shutdown the system if a concentration of hydrogen is detected. The logic solver consists of a central processor unit (CPU), random access memory (RAM), software and a watchdog/diagnostic unit according to OREDA (2015). There are different standards of CLU´s depending on the reliability level demanded. Standard industrial programmable logic controllers (PLC), SIL-certified programmable safety systems and hardwired safety systems according to the PDS handbook by Håbrekke et al. (2013). The standard industrial programmable logic controllers are the least reliable and it assumed that these are used in this system. Based on a system piping and instrumentation diagram (P&ID) (confidential), it is assumed a 2-o-o-5 redundancy logic for the CLU. The failure rate is estimated based on Equation 9 for 2-o-o-5 redundancy.

### 8.4.3 Alarm System

The primary function of the alarm is to provide an alarm signal to warn the crew if a hazardous situation has occurred. The alarm is assumed to consist of a siren and a flashing light. The failure rates were difficult to obtain, so it is assumed that the alarm system that the system is certified according to a SIL2 level which is shown in Figure 10. MSR Electronic is one supplier of alarm and gas detection systems which is certified according to a SIL2 level, which is the reason for this assumption. The alarm system is not assumed to be redundant.

### 8.4.4 Input Devices

Input devices are defined as sensors that convert process parameters such as pressure, temperature and flow to an electric signal that can be monitored (OREDA (2015)). The function of the input devices is to measure a certain property of the process fluid, and send this signal to a dashboard and control logic unit. The properties can be used to monitor if the pressure, level, temperature and other values are at a normal level. If there is a deviation from expected value (for instance high temperature), a safety function can be performed such as an emergency shutdown. This vessel will have several input devices such as pressure, temperature and level transmitters. From the P&ID drawings (confidential), no redundancy is assumed which will affect the failure rate.

## 8.5 Electric Motor

The electric motor is essential in the propulsion system, as the electric motors main function is to convert electrical energy to propulsion thrust for the vessel. It receives power from the DC bus through an inverter from either the fuel cell, battery or diesel generator (in emergency situations) and converts it to mechanical energy for the propeller. It is assumed to be an electric motor running on alternating current (AC). Stator, rotor shaft, stator windings and bearings are important components of the electric motor.

## 8.6 Hydrogen Storage

As mentioned earlier, the fishing vessel will store the hydrogen in compressed form at approximately 250 bar. This is done by having a cylindrical pressure tank at the top of the vessel. The tank is equipped with input devices such as pressure transmitters. It is also equipped with a pressure relief valve in case of an overpressure. This will automatically release hydrogen through a vent line to vent if a certain pressure threshold is met. The function of the hydrogen storage tank is simply to store the fuel. The fuel goes from the tank, through a fuel supply line directly to the fuel cell, which is placed directly below the tank.

### 8.6.1 Fuel Supply Line

The fuel supply lines primary function is to transport hydrogen to the fuel cell from the storage tank. It is equipped with several input devices and valves which can be closed of in case of a hazardous situation. Access to the vent line is also possible from the fuel supply line according to the P&ID (confidential).

## 8.7 System Hierarchy & Functional Hierarchy

The system hierarchy is presented in Figure 15. This is useful to get a basic understanding of how the system and the equipment within the system interacts. The asset hierarchy shows how the system is made up of equipment and components. This hierarchy can then be used to develop a functional hierarchy. This makes a clear overview of what components belong to which system and avoids that the same components is not included in two different systems.

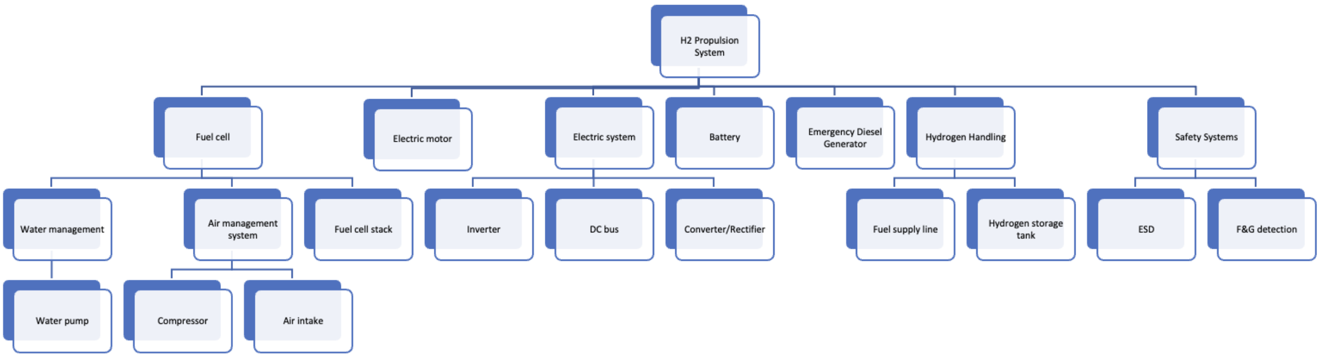


Figure 15: System hierarchy of hydrogen propulsion system.

Figure 16 shows the functional hierarchy of the system in this analysis. A functional hierarchy illustrates the functions of the different subsystems in the system.

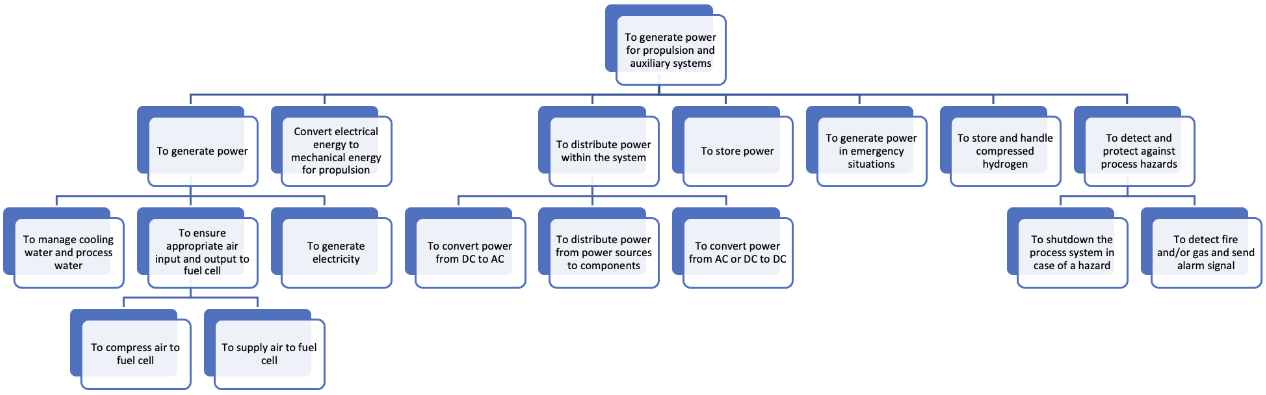


Figure 16: Functional hierarchy of hydrogen propulsion system.

## 8.8 Single Line Diagram

The single line diagram shows a simplified representation of the electrical power system of the vessel. It is used to show where the power is generated and obtained in the system, and what components uses it. It also shows where the electrical support systems such as inverter and converters are used. The single line diagram is illustrated in Figure 17.

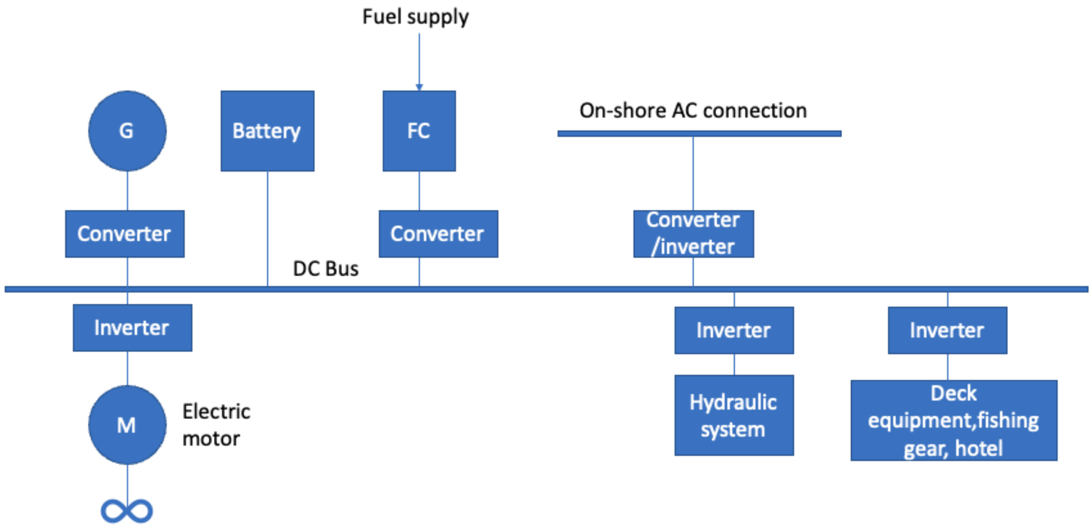


Figure 17: Simplified Single Line Diagram of the power system.

# 9 Analysis

When the system and vessel with all the functions are described, one can proceed to answer the rest of the seven questions of Moubray (1991). Following comes a definition of all the input parameters which are used in the analysis to perform the RCM using an FMECA and MTA.

## 9.1 Risk Matrix & Frequency, Consequence categories

In the following sections, will the pre-defined categories for frequency, consequences and the overall risk matrix be presented. They are used as a basis for the criticality analysis in the FMECA which is an essential part of the RCM process. The categories are used as a basis to determine the risk index of every failure mode, whilst the risk acceptance criteria are used to see if the risk index is acceptable.

### 9.1.1 Frequency Categories

Figure 18 presents the frequency index used in this analysis. The frequency index defines the likelihood for an event to happen. The frequency index FI for this thesis varies from 1-7, where one is defined as extremely remote and seven is frequent. The frequency categories are logarithmic and based on IMO guidelines for formal safety assessments (MSC-MEPC.2/Circ.12/Rev.2 - 9 April 2018). The detailed description is illustrated in the figure.

| FREQUENCY INDEX | | | |
|---|---|---|---|
| FI | FREQUENCY | DEFINITION | F (per ship year) |
| 7 | Frequent | Likely to occur once per month per ship | 10 |
| 6 | Little frequent | Likely to occur once per year per ship | 1 |
| 5 | Reasonably pro | Likely to occur once per year in a fleet of 10 ships, or once every 10 year per ship | 0,1 |
| 4 | Not probable | Likely to occur once per year in a fleet of 100 ships | 1,E-02 |
| 3 | Remote | Likely to occur once per year in a fleet of 1,000 ships, or once in the lifetime (20 years) in a fleet of 50 ships | 1,E-03 |
| 2 | Very remote | Likely to occur once per year in a fleet of 10,000 ships, or once in the lifetime (20 years) in a fleet of 500 ships | 1,E-04 |
| 1 | Extremely remo | Likely to occur once per year in a fleet of 100,000 ships, or once in the lifetime (20 years) in a world fleet of 5,000 ships | 1,E-05 |

Figure 18: Frequency index applied in the FMECA. From the vessel HAZID (confidential).

### 9.1.2 Consequence Categories

The consequence categories for this analysis are presented in Figure 19. The consequence index classifies the consequences of a potential event with regards to human safety and economic losses. It is ranked from 0-4 where zero is defined as having no consequences on human safety or no economic losses, while 4 is defined as a catastrophic consequence. The consequence categories are used in the HAZID for the fishing vessel and are also based on IMO revised formal safety assessment guidelines from 2013, as the frequency index. The detailed categories are presented in the figure below.

| Index | Category | Human safety | Economical |
|---|---|---|---|
| 0 | None | No injuries | No damage to equipment or other property |
| 1 | Minor | Single and/or minor injuries | Local equipment damage or small damage to other property |
| 2 | Significant | Multiple minor injuries and/or severe injury | Damage to ship or to other property |
| 3 | Severe | Single fatality and/or multiple severe injuries | Severe damage to ship or other properties |
| 4 | Catastrophic | Multiple fatalities and severe injuries | Loss of ship or other properties |

Figure 19: Consequence Index applied in the FMECA. From the vessel HAZID (confidential).

### 9.1.3 Risk Acceptance Criteria

The risk acceptance criteria are presented in Figure 20. As described earlier, the risk index RI is defined as the sum of the frequency index (FI) and the consequence index (CI), which is possible when using logarithmic scales (M. Rausand and Haugen (2020)). From that, a risk matrix is defined where one looks at what risks and consequences combined give an acceptable risk. The risk index is therefore in the range from 1-11. 11 is the most critical risk index while 1 is the least critical. Generally, the risk index for an event should follow the as low as reasonably practicable (ALARP) principle. The green area of the risk acceptance matrix is classified as acceptable risk, which is the area of a risk index from 1-3. Unacceptable risk is in the red area with a risk index from 8-11. For these failure modes, risk reducing measures must be done to reduce the risk to an acceptable level or eliminated completely. The hazards in the orange area is classified as the orange ALARP and have a risk index from 6-7. The hazards in the yellow area are the yellow ALARP failures and have a risk index from 4-5. The hazards in these two areas should follow the cost-benefit principle to assess whether risk reducing measures should be taken or not. Generally speaking, the hazards in the orange area, should be reduced to the yellow ALARP area. The risk acceptance criteria are also based on IMOs revised FSA guidelines from 2013.

| RISK INDEX WITH ALARP PRINCIPLE | | | | | |
|---|---|---|---|---|---|
| | | SEVERITY (SI) | | | |
| FI | FREQUENCY | 1 | 2 | 3 | 4 |
| | | Minor | Significant | Severe | Catasthropic |
| 7 | Frequent | 8 | 9 | 10 | 11 |
| 6 | Little frequent | 7 | 8 | 9 | 10 |
| 5 | Reasonably probable | 6 | 7 | 8 | 9 |
| 4 | Not probable | 5 | 6 | 7 | 8 |
| 3 | Remote | 4 | 5 | 6 | 7 |
| 2 | Very remote | 3 | 4 | 5 | 6 |
| 1 | Extremely remote | 2 | 3 | 4 | 5 |

Figure 20: Risk acceptance criteria for human safety applied in the FMECA. Based on the risk acceptance criteria from IMO revised FSA guidelines.

## 9.2 Failure Modes, Effect and Criticality Analysis

When the system is properly defined, the FMECA can start. In this thesis, the FMECA was structured using Microsoft Excel worksheets. The FMECA framework is presented in Figure 21.

**FMECA Worksheet**

*System: H2 Propulsion System on Fishing Vessel* *Owner: Aleksander Aira-Andersen* *Page: 1 of 1*

| Unit description | | | Failure description | | | Failure effect | | Risk ranking | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Tag | Description | Function | Failure mode | Failure cause | Failure detection | Local failure effect | Failure effect on system function | FI | CI | RI | Risk reducing measure | Responsible | Comment |
| | | | | | | | | | | | | | |
| | | | | | | | | | | | | | |
| | | | | | | | | | | | | | |

Figure 21: FMECA Worksheet applied in the analysis.

The failure modes were identified from the HAZID, discussion with industry experts, from existing literature on similar analyses performed on similar systems and other failure modes identified by the author. The FMECA was done on every system component identified in the system description to see how the separate systems could fail and the consequences of every failure mode. The consequence and frequency index were categorized after the frequency and consequence categories presented in Section 9.1.1 and Section 9.1.2. This has resulted in a risk index for every failure mode from 1-11, ranking every failure mode based on criticality.

### 9.2.1 Failure Modes & Failure Causes

Since the system in this analysis consists of many complex components, finding failure data and information regarding failure modes is challenging. In this chapter, a brief overview of where the data for failure modes and failure causes has been found is summarized. For the battery, fuel cell, converter and inverter, Igder et al. (2021) suggested some failure modes and failure causes that have been applied in the FMECA. Their failure modes are however performed for a molten carbonate fuel cell. OREDA (2015) and IEEE Std 3006.8-2018 (2018) also suggested failure modes for the battery system. Yue et al. (2019) also provided some input here. The batteries that Igder et al. (2021) based failure modes on are assumed to be photovoltaic and lithium-ion based, it is unknown what kind of battery the vessel in this analysis is using. The study also presented some failure modes related to insufficient airflow and some consequences of the failures of fuel cells.

Some of the fuel cell failure modes and causes are also discovered from a meeting with industry experts on fuel cells and fuel cell degradation from Sintef. Failure modes and effects related to membrane degradation, electrical shorts and fuel supply failures for the fuel cells are also obtained from Stephens et al. (2009).

The failure modes for the converter, inverter and DC bus are found in literature from Igder et al. (2021), Ogbonnaya et al. (2021), Trivyza et al. (2021), Liu et al. (2019) and IEEE Std 3006.8-2018 (2018).

Many failure modes related to safety systems and F&G detection are found from the OREDA database (OREDA (2015)). These process systems are widely used in the offshore oil & gas industry and therefore assumed to be similar to the equipment for this system. Other failure mode sources for the F&G detection system is the HAZID for the ZeroKyst project and Miller (2019). For the CLU, failure modes were discovered also from a meeting with Postdoc at NTNU. Failures of input devices, such as the fluid transmitters (flow, pressure and temperature) had many sources for failure modes in litterature, from Schüller (1997) and Miller (2019). The air compressor is a common instrument used in marine systems so many failure modes for compressors are assumed to be known from previous analysises, for instance from OREDA database. The same is for the emergency diesel generator which is common on many vessels. The electric motor is also a component which we have operational experience with. OREDA (2015) and IEEE Std 3006.8-2018 (2018) provided data for failure modes and causes for the electric motor.

Many of the failure modes for the hydrogen storage tank are discovered from the Zerokyst HAZID (confidential) for the hydrogen-fueled fishing vessel. Ogbonnaya et al. (2021) also presented some failure modes for hydrogen leakage from a storage tank. The HAZID from the Brødrene Aa concept report for the hydrogen high speed ferry also identified some failure modes. Stephens et al. (2009), Miller (2019) and Collong and Kouta (2015), Al-Douri et al. (2023) also provides some failure mode information related to the storage system of hydrogen.

In addition to all the sources for the failure modes and causes, some additional sources had to be used to estimate the probability index for each failure mode. Al-Douri et al. (2023) provided frequency data for releases and failure modes related to loss of hydrogen containment for a hydrogen-fueled FC forklift. Collong and Kouta (2015) provided input on probabilities for leakage of the PEM fuel cell. Miller (2019) had many probabilities regarding leakage from the storage system and fuel supply line. Åstrøm et al. (2007) provided leakage information of the probability of a pipe rupture in the fuel supply line. Kösters and Gao (2021) also provided data on the probability of leakage from the hydrogen storage system and the PEM fuel cell. Other sources has been from conversations with industry experts, fishermen, etc. A full presentation of all sources in the FMECA is presented in Appendix A.

## 9.3 Tag System

To have a clear analysis which is easy to understand, having a proper tag system of the failure modes is important. The analysis has divided all equipment in the FMECA with a letter from A-M. The failure modes for each equipment is then numbered starting on 1, and subsequently the failure causes are also numbered for every failure mode starting on 1. For instance will A.1.1 mean that one is looking at failure cause 1 for failure mode 1 for equipment A (Fuel Cell). A table illustrating the equipment tags is illustrated in Table 2.

| Tag | Unit |
|---|---|
| A | Fuel Cell |
| B | Air management system |
| C | Battery |
| D | Converter |
| E | Emergency diesel generator |
| F | Safety system |
| G | Electric motor |
| H | F&G detection |
| I | DC Bus |
| J | Hydrogen storage tank |
| K | Inverter |
| L | Fuel supply line |
| M | Water management system |

Table 2: $H_2$ power generation system sorted after tag defined for the FMECA.

## 9.4 Maintenance Task Analysis

From the FMECA, all failure modes are assessed after criticality. The failure modes are then used to determine which action should be taken and what kind of maintenance tasks are most fitting for the relevant failure mode. This is done by assessing the consequences of the failure mode. Using the RCM decision diagram presented in Section D, one can classify a maintenance task for every failure mode, whether it should be preventive, predictive or corrective maintenance. Maintenance intervalls and costs can then be estimated using the available data. The final step to conclude the maintenance program is to make maintenance packages which describe the tasks on a more detailed level. Crew requirements, equipment requirements and task description is provided. Some tasks can also be grouped and be done simultaneously for a more efficient maintenance program.

The analysis started with assessing whether the failure mode has safety, environmental or operational consequences. Thereafter, an assessment was done to research what kind of maintenance task is necessary or if a redesign/run-to-failure is more suitable. In addition, the failure pattern for every failure mode has to be determined to understand if some maintenance tasks are not suitable. When all of this is done, a suitable maintenance task can be proposed.

## 9.5 Maintenance Costs

Due to lacking data about costs of these systems, some costs has been estimated. Costs have been found from various suppliers for many of the most common equipment such as transmitters, alarm system and compressors/pumps. It was however more difficult to estimate costs related to hydrogen storage tank, battery and the PEM fuel cell, which was found from relevant literature. The costs for these complex systems are based on estimations from litterature. All sources for the spare parts are listed in Table 5 in Appendix B.1. Considerations for downtime and repair time of the various equipment are based mostly from OREDA (2015) and IEEE Std 3006.8-2018 (2018). Some assumptions from the author has also been done on repair time. When it comes to costs related to loss of income, this has been estimated after conversation with two fishermen on their average income per year. The average income per fishing day has been estimated to around 30 000 NOK per day. Repair costs related to labour have been divided into two categories, depending if the fisherman himself can do the repair or if the repair must be done at a shipyard. Selfa shipyard has a consultancy cost of 1732 NOK per hour, while fisherman salary has been estimated to be 700 000 NOK per year, which corresponds to about 337 NOK per hour. To make the costs comparable, all maintenance costs have been calculated as yearly costs. This means that maintenance tasks that have intervals different than a year is multiplied with a factor to convert it for a year. Scheduled replacement are based on how many replacements are expected during the vessels lifetime, divided by the expected vessel lifetime. One of the assumptions of the analysis is that the vessel lifetime is 15 years.

# 10 Results & Discussion

In the following subchapters, the results will be presented. The FMECA for every system will be presented before the complete maintenance task analysis. In the end, a more thorough description of the maintenance tasks and maintenance packages is shown.

## 10.1 FMECA

In the following subsections, the FMECA for the different systems is presented in the same order as the analysis. The figures showing the FMECA are simplified. All frequency indices marked in red are based on general failure rates, not for every failure mechanism. This is done due to a lack of data for the specific failure cause. If the frequency indices are marked in black, they are based on data from sources. Consequence indices are based on the risk matrix presented for this analysis.

### 10.1.1 Fuel Cell Stack

The fuel cell stack had five failure modes with 23 failure causes related to those failure modes. All failure modes and failure causes were within the ALARP area for the risk acceptance criteria. Twenty of the identified causes were identified in the orange sector of ALARP (risk index 6-7), and the remaining three were within the yellow sector (risk index 4-5). No failure modes were in the green or red sector. The failure modes are presented in Figure 22 and Figure 23.

**FMECA Worksheet**

*System: H2 Propulsion System on Fishing Vessel* *Owner: Aleksander Aira-Andersen* *Page: 1 of 1*

| Unit description | | | | Failure description | | | | Failure effect | | Risk ranking | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Tag | Description | Function | | Failure mode | | Failure cause | Failure detection | Local failure effect | Failure effect on system function | FI | CI | RI |
| *1* | *2* | *3* | | *4* | | *5* | *6* | *7* | *8* | *9* | *10* | *11* |
| A | Fuel cell stack | To generate electrical energy | 1 | Fail to function on demand | 1 | Start-stop of FC | Dashboard, voltage test | Fuel cell failure, no electricity generated | Power loss | 5 | 2 | 7 |
| | | | | | 2 | Idling | | | | 5 | 2 | 7 |
| | | | | | 3 | High/low voltage | | | | 4 | 2 | 6 |
| | | | | | 4 | Temperature cycling | | | | 5 | 2 | 7 |
| | | | | | 5 | Relative humidity cycling | | | | 5 | 2 | 7 |
| | | | | | 6 | Air overflow (compressor failure) | | | | 4 | 2 | 6 |
| | | | | | 7 | Stack runaway | | | | 4 | 2 | 6 |
| | | | | | 8 | Membrane degradation (thermal/mechanical/chemical) | | | | 5 | 2 | 7 |
| | | | 2 | Degraded performance | 1 | Start-stop of FC | Dashboard , voltage test | Degrated output from fuel cell, less than required, low electric voltage in stack module | Not generated enough power to sail at required speed, not enough power to power the fishing gear, fuel cell damage | 5 | 1 | 6 |
| | | | | | 2 | Idling | | | | 5 | 1 | 6 |
| | | | | | 3 | High/low voltage | | | | 4 | 1 | 5 |
| | | | | | 4 | Temperature cycling | Dashboard, temperature transmitter | | | 5 | 1 | 6 |
| | | | | | 5 | Relative humidity cycling | Dashboard | | | 5 | 1 | 6 |
| | | | | | 6 | Air overflow (compressor failure) | Compressor failure, dashboard | | | 4 | 1 | 5 |
| | | | | | 7 | Short circuit | Dashboard, voltage test | | | 3 | 1 | 4 |
| | | | | | 8 | Membrane degradation (thermal/mechanical/chemical) | Dashboard, voltage test, temperature transmitter | | | 5 | 1 | 6 |

Figure 22: FMECA for the fuel cell stack part 1

| Tag | Description | Function | | Failure mode | | Failure cause | Failure detection | Local failure effect | Failure effect on system function | FI | CI | RI |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 3 | Leakage | 1 | Pipe rupture | H2 detector, inspection | Loss of fuel | Loss of fuel, ignition potential | 2 | 4 | 6 |
| | | | | | 2 | Corrosion | | | | 2 | 4 | 6 |
| | | | | | 3 | Membrane rupture | | | | 2 | 4 | 6 |
| | | | 4 | Insufficient air flow | 1 | Air supply failure | Flow transmitter, dashboard, pressure transmitter, | Unstale electrochemical reaction at the cathode | Fire, damage to fuel cell, less output | 4 | 3 | 7 |
| | | | | | 2 | Air filter clogged | | | | 3 | 3 | 6 |
| | | | 5 | No fuel supply | 1 | Fuel supply failure | Flow transmitter, dashboard, pressure transmitter | No power generation, potential membrane failure and fire | No power generation, fire | 3 | 3 | 6 |
| | | | | | 2 | Hydrogen filter clogged | | | No power generation, fire | 4 | 3 | 7 |

Figure 23: FMECA for the fuel cell stack part 2

The highest risk index was seven and was related to these fuel cell failure modes: Failure to function on demand, insufficient airflow and no fuel supply. The failure pattern for the fuel cell is assumed to be failure pattern A from Figure 6. This is due to the fuel cell stack being complex equipment with electric and chemical components with low operational experience. High infant mortality is assumed. This pattern also assumes a normal wear-out after a specific operational time. A failure of the fuel cell has a consequence index of 2 which is a significant consequence. However, it is judged not to be a fatal failure mode. The degradation of the FC is set to a consequence of 1, with low consequences. A hydrogen leakage from the fuel cell can have catastrophic consequences due to the ignition and explosion potential. Insufficient air flow and no fuel supply can lead to a fire in the fuel cell and is set to a consequence index of 3, which is a severe consequence. Failure modes 1, 3 and 5 are assumed to be evident for the crew during regular operation, whilst failure modes 2 and 4 are assumed to be hidden failures. The first two failure modes have operational consequences, while the last three have safety/environmental consequences.

### 10.1.2 Air Management System

For the air management system, there was identified a total of four failure modes and 16 failure causes. The highest risk index was 8, which is in the unacceptable area of the risk acceptance criteria. Nine failure causes were identified in the unacceptable red area (risk index above 7), and seven failure causes in the orange ALARP area. It is assumed that a compressor failure can lead to a fire in the fuel cell, and therefore, failure mode 1 and 3 has a consequence index of 3. The remaining failure modes can have operational consequences such as reduced output or damage to equipment. The most critical failure mode is compressor failure to start on demand and compressor degradation with a risk index of 8. However, the first failure mode related to failure to start on demand is considered more critical because the consequence index is higher, with a consequence index of 3. The failure modes are presented in Figure 24.

| Tag | Description | Function | | Failure mode | | Failure cause | Failure detection | Local failure effect | Failure effect on system function | FI | CI | RI |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| B | Air Management System | To compress air to the fuel cell and handle exhaust air from fuel cell | 1 | Compressor failure to start on demand | 1 | Vibration | Flow indicator, pressure indicator, dashboard, inspection, vibration monitoring | No air flow to FC | No/less power generation from FC, unstable electrochemical reaction in FC, fire/explosion | 5 | 3 | 8 |
| | | | | | 2 | Mechanical failure | | | | 5 | 3 | 8 |
| | | | | | 3 | Corrosion | | | | 5 | 3 | 8 |
| | | | | | 4 | Signal faiure | | | | 5 | 3 | 8 |
| | | | | | 5 | Power failure | | | | 5 | 3 | 8 |
| | | | | | 6 | Burnout | | | | 5 | 3 | 8 |
| | | | 2 | Compressor degradation | 1 | Vibration | Flow indicator, pressure indicator, dashboard, inspection, vibration monitoring | Insufficient air flow to FC | No/less power generation from FC, unstable electrochemical reaction in FC | 4 | 2 | 6 |
| | | | | | 2 | Mechanical failure | | | | 4 | 2 | 6 |
| | | | | | 3 | Corrosion | | | | 6 | 2 | 8 |
| | | | | | 4 | Power failure | | | | 6 | 2 | 8 |
| | | | | | 5 | Burnout | | | | 6 | 2 | 8 |
| | | | 3 | Compressor leakage | 1 | Vibration | Flow indicator, pressure indicator, dashboard, inspection, vibration | Less compressed air to FC | No/less power generation from FC, unstable electrochemical reaction in FC, fire/explosion | 4 | 3 | 7 |
| | | | | | 2 | Mechanical failure | | | | 4 | 3 | 7 |
| | | | | | 3 | Corrosion | | | | 4 | 3 | 7 |
| | | | 4 | Compressor failure to stop on demand | 1 | Signal failure | Software monitoring, flow monitoring | Excessive air to FC | High pressure in fc, compressor damage, fuel cell damage, reduced power output | 4 | 2 | 6 |
| | | | | | 2 | Power failure | | | | 4 | 2 | 6 |

Figure 24: Failure modes for the air management system.

The failure pattern for the air compressor is assumed to be failure pattern B since this is mechanical equipment known to wear out. Failure modes 1 and 4 are assumed to be evident for the crew during normal operations, while 2 and 3 are assumed to be hidden. Failure mode 1 and 3 has safety consequences, while the rest of the failure modes have operational consequences.

### 10.1.3 Battery

For the battery, two failure modes were identified, with a total of nine failure causes. Three failure causes were identified in the yellow ALARP sector, while the remaining six were in the orange sector. The highest risk index is 6. Both failure modes have a risk index of six. However, the failure of the battery is assumed to be the most critical failure mode. The results are presented in Figure 25.

| Tag | Description | Function | | Failure mode | | Failure cause | Failure detection | Local failure effect | Failure effect on system function | FI | CI | RI |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| C | Battery | To store electrical energy | 1 | Battery failure to function on demand | 1 | Faulty power/voltage | | No power output from battery, battery damage | Not enough power to power the fishing gear, reduced sailing range, fire | 4 | 2 | 6 |
| | | | | | 2 | No power/voltage | | | | 4 | 2 | 6 |
| | | | | | 3 | Breakage | | | | 4 | 2 | 6 |
| | | | | | 4 | Corrosion | | | | 3 | 2 | 5 |
| | | | | | 5 | Electrical failure | | | | 4 | 2 | 6 |
| | | | 2 | Battery degradation | 1 | Hole in separator | | Less power output from battery, voltage reduction, heat generation, battery damage | Not enough power to power the fishing gear, reduced sailing range, fire | 3 | 2 | 5 |
| | | | | | 2 | Short circuit between anode and cathode | | | | 4 | 2 | 6 |
| | | | | | 3 | Corrosion | | | | 3 | 1 | 4 |
| | | | | | 4 | Wear | | | | 5 | 1 | 6 |

Figure 25: Failure modes for the battery system.

Since the equipment is electrical, failure pattern E is assumed. Both failure modes are assumed to be evident for the crew under normal circumstances due to the battery management system. Both failure modes can lead to safety consequences.

### 10.1.4 Converter

The converter has two failure modes with a total of 6 failure causes. Four failure mechanisms were within the yellow ALARP risk acceptance criteria; the remaining two were in the orange risk sector. The failure of the converter is the most critical failure mode as it can lead to no output to the propeller in case of a failure, shown in the consequence index of 3. The highest risk index identified was 6. The FMECA is presented in Figure 26.

| Tag | Description | Function | | Failure mode | | Failure cause | Failure detection | Local failure effect | Failure effect on system function | FI | CI | RI |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| D | Converter | Convert power from AC/DC or DC/DC | 1 | Converter degradation | 1 | Capacitor degradation | | Power reduction | Reduced power to DC bar, reduced power for propulsion and auxiliary systems | 3 | 1 | 4 |
| | | | | | 2 | Open Circuit | | Power reduction | | 3 | 1 | 4 |
| | | | | | 3 | Current omission | | Power reduction | | 4 | 1 | 5 |
| | | | | | 4 | Short circuit | | Power reduction, fire | | 3 | 2 | 5 |
| | | | 2 | Converter failure | 1 | Open circuit | | No current flow, power reduction | No DC supply to DC bar, no power output to propulsion and fishing gear expect battery supply | 3 | 3 | 6 |
| | | | | | 2 | Short circuit | | No current flow, power reduction, fire | | 3 | 3 | 6 |

Figure 26: Failure modes for the converter.

The converter failures are also assumed to follow the random failure pattern E since it is electric equipment. The failures of the converter should be evident for the crew under operation, whilst a degradation is assumed to be a hidden failure. Both failure modes have safety consequences due to fire potential.

### 10.1.5 Emergency Diesel Generator

A total of four failure modes were identified for the Emergency Diesel Generator system, with a total of 12 failure causes. The highest risk index was seven. 10 out of 12 failure causes were in the orange ALARP sector, and the last two failures were in the yellow sector. The most critical failure mode was a generator failure to start on demand. A failure of the emergency diesel generator is a hidden failure since the purpose is for emergencies. Failure to start on demand is judged to have severe consequences since it is critical in an emergency. The generator degradation is seen as significant since it can also lead to dangerous situations. Leakage and failure to stop on demand are not considered severe consequences. They have, however, high probabilities, giving the high-risk index. The result is presented in Figure 27.

| Tag | Description | Function | | Failure mode | | Failure cause | Failure detection | Local failure effect | Failure effect on system function | FI | CI | RI |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| E | Emergency Diesel Generator | To generate electrical energy in an emergency situation | 1 | Generator failure to start on demand | 1 | Vibration | Vibration monitoring, inspection, dashboard | No power output | No power in emergency situation | 4 | 3 | 7 |
| | | | | | 2 | Clogged air filter | | | | 3 | 3 | 6 |
| | | | | | 3 | Mechanical failure | | | | 4 | 3 | 7 |
| | | | | | 4 | Power failure | | | | 4 | 3 | 7 |
| | | | 2 | Generator degradation | 1 | Vibration | Vibration monitoring, inspection, dashboard | Less power output | Less power in emergency situation | 4 | 2 | 6 |
| | | | | | 2 | Clogged air filter | | | | 3 | 2 | 5 |
| | | | | | 3 | Mechanical failure | | | | 4 | 2 | 6 |
| | | | | | 4 | Power failure | | | | 4 | 2 | 6 |
| | | | 3 | Leakage | 1 | Gasket failure | Vibration monitoring, inspection, dashboard | Release of fuel | Loss of fuel, unintended release of diesel | 5 | 1 | 6 |
| | | | | | 2 | Vibration | | | | 5 | 1 | 6 |
| | | | | | 3 | Mechanical failure | | | | 5 | 1 | 6 |
| | | | 4 | Generator failure to stop on demand | 1 | Generator failure | Inspection, dashboard | Power generated when not intended | Unintended combustion of fuel, unintended emissions | 4 | 1 | 5 |

Figure 27: Failure modes for the emergency diesel generator.

Since this diesel generator is only intended for emergencies, all failures are hidden during normal operations. Only the first failure mode has safety consequences; the remaining three are assumed to have operational consequences. The failure pattern for the system is B.

### 10.1.6 Safety Systems

Five different failure modes were identified for the safety systems. Two failure modes related to the CLU, one for the transmitters and two for the alarm system. 11 failure causes were identified. A total failure of the CLU, input devices and alarm has been given the highest consequence index of 4 since these safety systems are essential barriers against hazardous situations. The highest risk index was 8. Four failures were in the red zone, five in the orange zone, and the yellow and green zone had one failure each. The critical failure mode categorized as unacceptable was a failure of the input devices in the process system. Figure 28.

| Tag | Description | Function | | Failure mode | | Failure cause | Failure detection | Local failure effect | Failure effect on system function | FI | CI | RI |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| F | Safety systems | To initiate emergency system shutdown on demand | 1 | CLU failure to function on demand | 1 | Input/output failure | Dashboard | No shutdown signal | No emergency shutdown | 3 | 4 | 7 |
| | | | | | 2 | Power failure | Dashboard | No shutdown signal | No emergency shutdown | 3 | 4 | 7 |
| | | | | | 3 | Software failure | Dashboard | No shutdown signal | No emergency shutdown | 3 | 4 | 7 |
| | | | 2 | CLU erratic output | 1 | Software failure | Dashboard | Output signal error | Error alarm | 2 | 1 | 3 |
| | | | 3 | L/T/PIT failure | 1 | Mechanical failure | Dashboard, inspection | No/wrong detection of fluid properties | No emergency shutdown, incorrect data on hydrogen storage, false alarm, false shutdown | 4 | 4 | 8 |
| | | | | | 2 | Corrosion | | | | 4 | 4 | 8 |
| | | | | | 3 | Calibration error | | | | 4 | 4 | 8 |
| | | | | | 4 | Signal failure | | | | 4 | 4 | 8 |
| | | | 4 | Alarm failure | 1 | Power supply failure | Dashboard, inspection | No alarm signal sent | No notification of hazardous situation | 3 | 4 | 7 |
| | | | | | 2 | Signal failure | Dashboard, inspection | No alarm signal sent | No notification of hazardous situation | 3 | 4 | 7 |
| | | | 5 | Spurious alarm signal | 1 | Calibration error | Dashboard | Alarm error, potential false positive | Error message from alarm to dashboard | 3 | 1 | 4 |

Figure 28: Failure modes for the safety systems.

The first two failure modes are related to the CLU, an electrical component assumed to have a random failure pattern E. The input devices are electromechanical, which are also assumed to have a random failure pattern. The last two failure modes are related to the alarm system, which is electrical, and also assumed random failure pattern E. A control logic unit total failure is assumed to be evident for the crew, whilst erratic output is not certainly evident for the crew under normal operations. Transmitter failures are also assumed to be evident, whilst alarm failures are not evident. Total failures of the CLU, input devices, or alarm system have consequences which can hurt other humans, whilst erratic output and spurious signals from the CLU and alarm consecutively have operational consequence

### 10.1.7 Electric Motor

The electric motor had three failure modes with 12 failure causes. Seven of the 12 failure causes were in the yellow ALARP area, and the remaining five were in the orange area. The highest risk index was seven and was related to a motor failure to start on demand. This is also the failure mode with the highest consequence index since it can lead to the vessel losing all propulsion. The FMECA is presented in Figure 29.

| Tag | Description | Function | | Failure mode | | Failure cause | Failure detection | Local failure effect | Failure effect on system function | FI | CI | RI |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| G | Electric motor | To convert electrical energy to mechanical energy for propulsion thrust | 1 | Motor failure to stop on demand | 1 | Motor failure | Dashboard | Motor will not stop distributing power, damage to motor | Unnecessary waste of fuel | 3 | 1 | 4 |
| | | | 2 | Motor failure to start on demand | 1 | Winding/insulation failure | Dashboard | No power to propeller, motor damage | No vessel propulsion | 4 | 3 | 7 |
| | | | | | 2 | Power supply failure | Dashboard | | | 3 | 3 | 6 |
| | | | | | 3 | Corrosion | Inspection | | | 4 | 3 | 7 |
| | | | | | 4 | Bearing failure | Inspection | | | 4 | 3 | 7 |
| | | | | | 5 | Vibration | Inspection, vibration monitoring | | | 3 | 3 | 6 |
| | | | 3 | Motor degradation | 1 | Winding/insulation failure | Dashboard | Less power generated, motor damage | Less output to propulsion | 4 | 1 | 5 |
| | | | | | 2 | Power supply failure | Dashboard | | | 3 | 1 | 4 |
| | | | | | 3 | Corrosion | Inspection | | | 4 | 1 | 5 |
| | | | | | 4 | Bearing failure | Inspection | | | 3 | 1 | 4 |
| | | | | | 5 | Overheating | Dashboard, temperature transmitter | | | 3 | 1 | 4 |
| | | | | | 6 | Vibration | Inspection, vibration monitoring | | | 3 | 1 | 4 |

Figure 29: Failure modes for the electric motor.

The electric AC motor is assumed to be a complex electromechanical device assigned to the bathtub curve failure pattern (A). Degradation of the motor is not assumed to be evident for the crew. However, a failure to stop or to start on demand should be evident for the crew. A failure to start on demand (failure mode 2) is assumed to have safety consequences, while failure mode 1 and 3 has operational consequences.

### 10.1.8 F&G detection

For the fire & gas detection system, three failure modes were identified with five failure causes. The highest risk index was six, a failure of the F&G detector. This failure mode also is judged to have catastrophic consequences due to no detection of fire or gas, which in the worst case, can lead to an explosion if flammable substances are nearby. Three failures were within the orange ALARP area, while the remaining two had an acceptable green risk index. Figure 30 shows the FMECA for the system.

| Tag | Description | Function | | Failure mode | | Failure cause | Failure detection | Local failure effect | Failure effect on system function | FI | CI | RI |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| H | F&G detection | To detect fire and/or gas and send alarm signal | 1 | Failure of fire or gas detector | 1 | Mechanical | Inspection, dashboard | No alarm signal sent | No shutdown initiated, no detection of fire or gas | 2 | 4 | 6 |
| | | | | | 2 | Non optimal sensor location | Inspection | No alarm signal sent | No shutdown initiated, no detection of fire or gas | 2 | 4 | 6 |
| | | | | | 3 | Inadequate calibration | Inspection, dashboard | No alarm signal sent | No shutdown initiated, no detection of fire or gas | 2 | 4 | 6 |
| | | | 2 | Erratic output | 1 | Inadequate calibration | Inspection, dashboard | Signal error to alarm | Alarm error, shutdown error | 2 | 1 | 3 |
| | | | 3 | False positive signal | 1 | Inadequate calibration | Dashboard | False alarm | False alarm, false shutdown | 2 | 1 | 3 |

Figure 30: Failure modes for the fire and gas detection system.

Since the F&G detection system is designed to detect rare occurrences of fire or gas, any of the failures of these systems are not evident for the crew typically. The first failure mode, which is a total failure, has safety consequences; a false positive signal has operational consequences, while erratic alarm output is assumed to have no consequences of significance.

### 10.1.9 DC Switchboard

The DC switchboard had two failure modes, and six failure causes. A switchboard failure is judged to have severe consequences because it will lead to a failure to distribute power around the vessel for propulsion and the auxiliary systems. The highest risk index is six. Four failures were within the orange area, and the last two were within the yellow risk acceptance criteria. The four failures with the highest risk index were for the DC switchboard total failure.

| Tag | Description | Function | | Failure mode | | Failure cause | Failure detection | Local failure effect | Failure effect on system function | FI | CI | RI |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| I | DC Switchboard | To distribute power to various components from multiple power sources | 1 | Degraded | 1 | Low electrical voltage | oltage measureme | Less power supply | Less power output to propulsion, hydraulic system or equipment | 3 | 1 | 4 |
| | | | 2 | Failure to distribute power | 1 | Wire cuts | Inspection, dashboard | No power supply | No power output to propulsion, hydraulic system or equipment | 1 | 3 | 4 |
| | | | | | 2 | Insulation (winding, bushing, other) | Inspection, dashboard | No power supply | No power output to propulsion, hydraulic system or equipment | 3 | 3 | 6 |
| | | | | | 3 | Overloading | Inspection, dashboard, voltage measurement | No power supply | No power output to propulsion, hydraulic system or equipment | 3 | 3 | 6 |
| | | | | | 4 | Short circuit | Inspection, dashboard | No power supply | No power output to propulsion, hydraulic system or equipment | 3 | 3 | 6 |
| | | | | | 5 | Ground fault | Inspection, dashboard, voltage measurement | No power supply | No power output to propulsion, hydraulic system or equipment | 3 | 3 | 6 |

Figure 31: Failure modes for the DC bus.

The DC bus is an essential electrical distributor and is assumed to have a random failure pattern. A DC bus degradation is assumed to be a hidden failure, whilst a total failure will be evident. The total failure is also assumed to have safety consequences due to power distribution loss.

### 10.1.10 Hydrogen Storage Tank

Three failure modes and ten failure causes were found for the hydrogen storage tank. Loss of containment and failure to empty on demand, the first two failure modes, were given the highest consequence indices since they can lead to an explosion. The highest risk index identified was seven, related to the failure mode "Failure to empty on demand" due to a PRV failure. All failures were within the ALARP zone, four in the orange zone and six in the yellow zone. Figure 32 presents the failure modes for the hydrogen storage tank.

| Tag | Description | Function | | Failure mode | | Failure cause | Failure detection | Local failure effect | Failure effect on system function | FI | CI | RI |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| J | Hydrogen Storage Tank | To store compressed hydrogen as fuel | 1 | Loss of containment | 1 | Corrosion | H2 detector, tank level indicator, inspection | No fuel to FC, leakage of fuel | Ignition, explosion, loss of fuel | 1 | 4 | 5 |
| | | | | | 2 | Rupture (mechanical) | H2 detector, tank level indicator, inspection | No fuel to FC, leakage of fuel | Ignition, explosion, loss of fuel | 1 | 4 | 5 |
| | | | | | 3 | Too high/low hose pressure may lead to unexpected release | H2 detector, tank level indicator, inspection, pressure indicator | No fuel to FC, leakage of fuel | Ignition, explosion, loss of fuel | 2 | 4 | 6 |
| | | | | | 4 | Rupture (fire/crash induced) | F&G detector, H2 detector, tank level indicator | No fuel to FC, leakage of fuel | Ignition, explosion, loss of fuel | 1 | 4 | 5 |
| | | | | | 5 | Seal/liner degradation | F&G detector, H2 detector, tank level indicator | No fuel to FC, leakage of fuel | Ignition, explosion, loss of fuel | 2 | 4 | 6 |
| | | | | | 6 | Embrittlement | H2 detector, tank level indicator, inspection | No fuel to FC, leakage of fuel | Ignition, explosion, loss of fuel | 2 | 4 | 6 |
| | | | 2 | Failure to empty on demand | 1 | Fuel supply valve fail open | FC level indicator, dashboard | No fuel to FC | No power generation, potential FC membrane failure, potential fire, overpressure(?) | 3 | 2 | 5 |
| | | | | | 2 | Pressure relief valve fail open | Pressure indicator, temperature indicator | Tank explosion, fire, release of hydrogen | Explosion | 3 | 4 | 7 |
| | | | 3 | Unintended pressure relief | 1 | Pressure relief valve leakage | H2 detector, tank level indicator, dashboard, pressure transmitter | Release of hydrogen through vent line | Unnecessary operations stop, not enough fuel to return to port, h2 leakage | 3 | 2 | 5 |
| | | | | | 2 | ESD system error | H2 detector, tank level indicator, dashboard, pressure transmitter | Release of hydrogen through vent line | Unnecessary operations stop, not enough fuel to return to port, h2 leakage | 3 | 2 | 5 |

Figure 32: Failure modes for the hydrogen storage tank.

Since the hydrogen storage tank is a component which will stay in place and rarely be touched, a failure of the storage tank is not assumed to be evident. However, a failure to empty the tank will be assumed to be evident for the crew. Hydrogen storage tanks are often exposed to stress cycles due to loading and unloading, which is a fatigue issue. Therefore, failure pattern C, a fatigue-related failure pattern, has been assumed for the two first failure modes. The last failure mode is related to the ESD system and the PRV, which is mechanical and therefore assumed to have failure pattern B. All three failure modes are assumed to have safety consequences.

#### 10.1.11 Inverter

The inverter has two failure modes, and six failure causes. The highest risk index, seven, was found for a total failure of the inverter. It has a consequence index of three since it can lead to total loss of propulsion and potentially a fire. The remaining failures were within the yellow zone except for degradation due to a short circuit. Figure 33 shows the FMECA for the inverter.

| Tag | Description | Function | | Failure mode | | Failure cause | Failure detection | Local failure effect | Failure effect on system function | FI | CI | RI |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| K | Inverter | DC-AC inversion | 1 | Failure to invert on demand | 1 | Short circuit | Dashboard | No AC output | No output to propulsion, hydraulic system or equipment, fire | 4 | 3 | 7 |
| | | | | | 2 | Open Circuit | | | | 4 | 3 | 7 |
| | | | 2 | Inverter degradation | 1 | Open Circuit | Dashboard | Less AC output | Reduced power to DC bar, reduced power for propulsion and auxiliary systems, fire | 4 | 1 | 5 |
| | | | | | 2 | Short circuit | | | | 4 | 2 | 6 |
| | | | | | 3 | Capacitor degradation | | | | 3 | 1 | 4 |
| | | | | | 4 | Overheating | | | | 3 | 1 | 4 |

Figure 33: Failure modes for the inverter.

As the converter, the inverter is an electrical component and therefore assumed to have a random failure pattern. Degradation of the inverter is assumed to be hidden. Both failure modes have safety consequences for humans due to the fire potential and the vital function of inverting power for the electric motor.

### 10.1.12 Fuel Supply Line

Four failure modes and thirteen failure mechanisms were identified for the fuel supply line. Eleven failures were in the orange risk sector and two in the yellow. The highest risk index is seven, related to a fuel supply rupture and if the fuel supply valve should fail close. These are also the two failure modes with the highest consequence indices of 4 since they can lead to the release of hydrogen and an explosion. Failure mode number 2 has a consequence categorization of 3 since it can lead to a potential fire, and failure mode number 4 also has a consequence of 3. Failure mode four is not categorized as the catastrophic consequence since the leak rate is assumed to be much lower. The FMECA for the fuel supply line is presented in Figure 34.

| Tag | Description | Function | | Failure mode | | Failure cause | Failure detection | Local failure effect | Failure effect on system function | FI | CI | RI |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| L | Fuel supply line | To transport hydrogen from the storage tank to the FC stack | 1 | Rupture of fuel supply | 1 | Overpressure | Pressure indicator, inspection | Unintended fuel release | Leakage of hydrogen, ignition, explosion | 3 | 4 | 7 |
| | | | | | 2 | Thermal/ UV degradation | | | | 3 | 4 | 7 |
| | | | | | 3 | Corrosion | | | | 3 | 4 | 7 |
| | | | | | 4 | Gasket failure | | | | 3 | 4 | 7 |
| | | | | | 5 | Mechanical degradation | | | | 3 | 4 | 7 |
| | | | 2 | Fuel supply valve fail open | 1 | Breakage | Level indicator, flow indicator, pressure indicator | No fuel supplied to FC | No power generation, potential FC membrane failure, potential fire, overpressure(?) | 3 | 3 | 6 |
| | | | | | 2 | Control failure | | | | 3 | 3 | 6 |
| | | | | | 3 | Corrosion | | | | 3 | 3 | 6 |
| | | | 3 | Fuel supply valve fail close | 1 | Breakage | Level indicator, flow indicator, pressure indicator | Fuel supply when not demanded | Leakage of hydrogen , damage to FC | 3 | 4 | 7 |
| | | | | | 2 | Control failure | | | | 3 | 4 | 7 |
| | | | | | 3 | Corrosion | | | | 3 | 4 | 7 |
| | | | 4 | Piping leak | 1 | Mechanical degradation | H2 detector, inspection, flow transmitter, level transmitter | Less fuel supply | Leakage of hydrogen | 2 | 3 | 5 |
| | | | | | 2 | Corrosion | | Less fuel supply | Leakage of hydrogen | 1 | 3 | 4 |

Figure 34: Failure modes for the fuel supply line.

The fuel transportation system is assumed to be mechanical and subject to wear out. Therefore failure pattern B is assumed for all failure modes. Two failure modes are hidden: a rupture and a piping leak. All failure modes related to this system are assumed to have safety consequences due to containing hydrogen.

### 10.1.13 Water Management System

Two failure modes were identified for the water management system. The failure and degradation of the water pump were the two failure modes. A water pump failure is not judged to be dangerous for the crew. However, operational consequences are possible. Eleven failure causes were identified, and the highest risk index was seven, related to a pump failure due to a clogged water filter. Six failures are in the orange sectors, mostly related to a total failure of the pump, four failures in the yellow sector and one in the green risk sector. Figure 35 shows the failure modes for the water management system.

| Tag | Description | Function | | Failure mode | | Failure cause | Failure detection | Local failure effect | Failure effect on system function | FI | CI | RI |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| M | Water management | Cooling of the FC stack and handling exhaust water from FC | 1 | Degraded water pump | 1 | Vibration | Inspection, vibration monitoring | Less or excessive water flow | Overheated FC, damage to FC, less power output | 4 | 1 | 5 |
| | | | | | 2 | Water filter clogged | | | | 5 | 1 | 6 |
| | | | | | 3 | Corrosion | | | | 4 | 1 | 5 |
| | | | | | 4 | Power failure | | | | 2 | 1 | 3 |
| | | | | | 5 | Burnout | | | | 4 | 1 | 5 |
| | | | 2 | Failure of water pump | 1 | Vibration | Inspection, vibration monitoring | No water flow | Overheated FC, damage to FC, fire | 4 | 2 | 6 |
| | | | | | 2 | Clogged water filter | | | | 5 | 2 | 7 |
| | | | | | 3 | Degradation | | | | 4 | 2 | 6 |
| | | | | | 4 | Corrosion | | | | 4 | 2 | 6 |
| | | | | | 5 | Power failure | | | | 2 | 2 | 4 |
| | | | | | 6 | Burnout | | | | 4 | 2 | 6 |

Figure 35: Failure modes for the water management system.

The water management system consists of a pump assumed to follow the same failure pattern as the air compressor, which is subject to wear-out. This is due to the rotational nature of the pump. A degradation of the pump is assumed to be a hidden failure. A total failure of the pump is assumed to have safety consequences, while degradation has operational consequences.

### 10.1.14 Summary of the FMECA

Figure 36 shows all failures per risk category. A total of 41 failure modes with 140 corresponding failure causes were identified for the systems. Most failures are within the ALARP category, with 86 within the orange ALARP area and 37 within the low yellow ALARP area. Only four failure modes have an acceptable risk index according to the risk acceptance criteria, and 13 failures are categorized as unacceptable, where risk-reducing measures should be taken. The most critical systems are the air management system and the input devices for the safety systems, the only two systems with unacceptable risks.

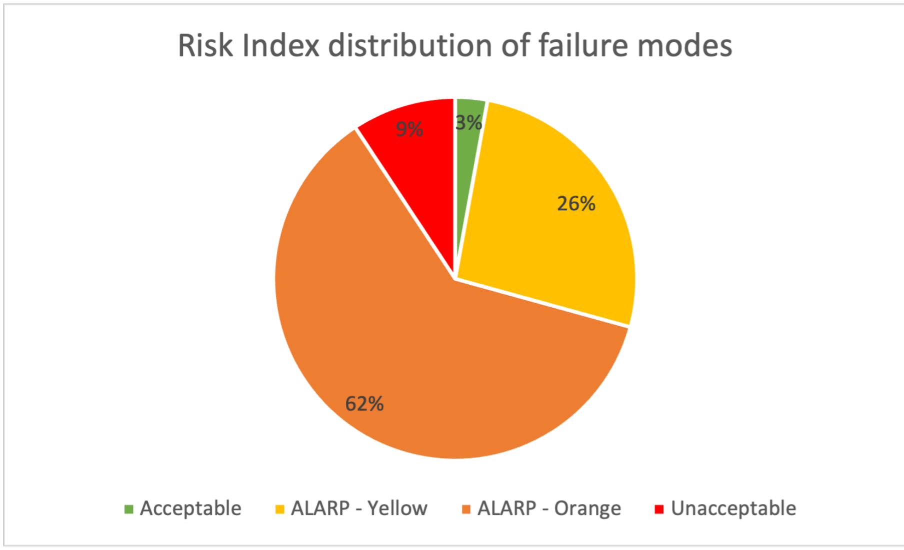


Figure 36: Number of failures per risk category.

The air management system is critical because it is assumed that a failure of the air compressor can lead to high pressure within the fuel cell, leading to severe consequences. According to OREDA, failures can be frequent. A combination of these makes the air management system a critical system.

The input devices probably came within this category due to the assumption of no redundancy. If the transmitters were redundant following an M-o-o-N logic, it is expected that the frequency index would reduce, sending the risk index out of the unacceptable category. The consequence index is high since these components are essential for safety. Undetected deviations in pressure or temperature can lead to hazardous situations, and this lead to a high consequence index.

| Index | Average index | Median index |
|---|---|---|
| Frequence | 3.5 | 4 |
| Consequence | 2.4 | 2 |
| Risk | 6.0 | 6 |

Table 3: Average and median value for the criticality assessment in the FMECA.

Table 3 shows the average and median values for the criticality assessment of the FMECA. The frequency index is, on average, 3.5, while the average consequence index and risk index are, respectively, 2.4 and 6.0. This means that, on average, every failure mechanism has severe consequences and can occur remotely according to the frequency definitions.

## 10.2 Maintenance Task Analysis

By utilizing the RCM decision tree and evaluating costs and failure patterns, it was possible to establish a maintenance plan for the described system. A maintenance task was suggested for every failure mode for the system, which ended up in a maintenance plan. Some of the failure modes on an acceptable risk level were not assessed. Also, some maintenance tasks cover more than one failure mode. All maintenance tasks are presented in the maintenance packages in Section 10.3. A distribution of all the proposed maintenance tasks for the system is presented in Figure 37. The complete maintenance task analysis using the decision tree is illustrated in Appendix D. The result ended up in a total of 33 maintenance tasks, where nine were preventive, and 24 were predictive maintenance tasks.

Since hydrogen fuel cell technology for maritime vessels is fairly new, there are many failure modes with safety and environmental consequences. Many critical auxiliary systems ensure the reliable and safe operation of the vessel. The vast majority of the proposed tasks are scheduled on-condition tasks. Corrective maintenance tasks are often difficult on a fishing vessel as it requires many spare parts, which can be challenging on a fishing vessel with limited space. This led to all proposed maintenance tasks being preventive or predictive.

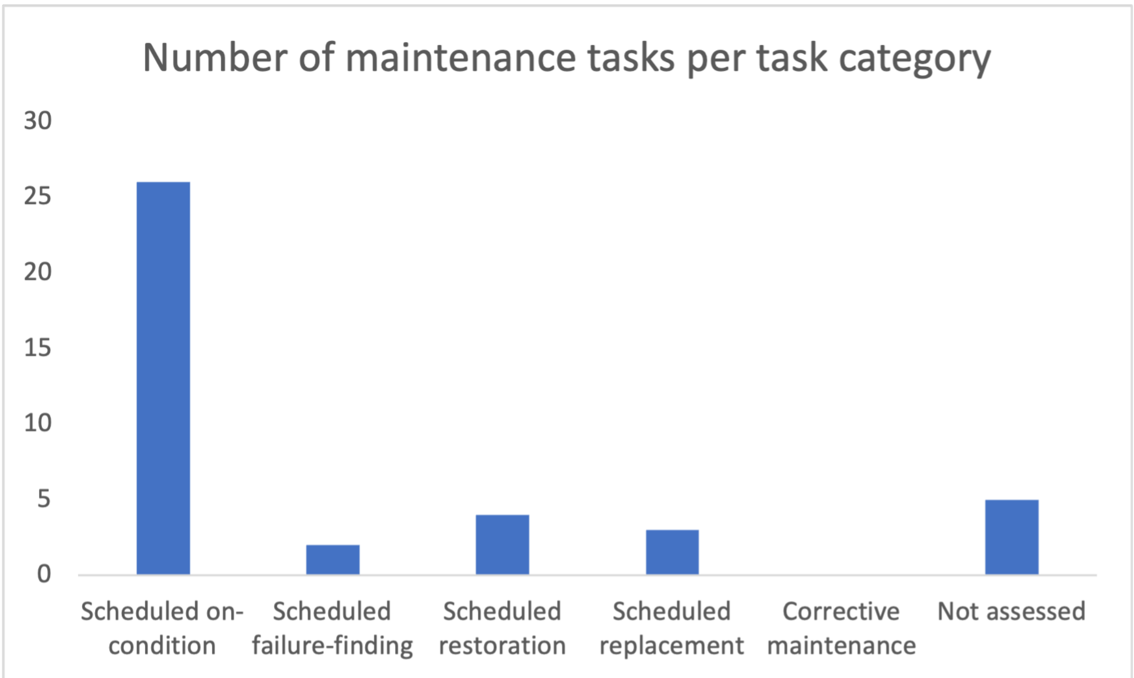


Figure 37: Results of maintenance task distribution.

Maintenance intervals were based on the failure rate data, failure pattern and the consequences of the failure mode in addition to the own judgement by the author. The maintenance tasks had various intervals, from continuous monitoring to 5-year time-based maintenance intervals. It was important to ensure that the maintenance intervals were lower than the MTBF so that the failure could be discovered in time; this was done for failures failure patterns of A and B. For random failure patterns, the interval should be much lower than the MTBF since it is difficult to estimate when a failure occurs. Also, the proposed maintenance task had to be in mind when choosing the interval. It is essential to have a suitable P-f interval to discover and maintain the failure at a suitable time. Other maintenance tasks had intervals based on condition or hours of operation. The maintenance tasks related to scheduled replacement are related to replacing the most complex and critical components, which are the battery, fuel cell, hydrogen storage tank and electric motor, after a certain period. The tasks related to scheduled failure finding are due to hidden failures of essential safety systems such as the emergency diesel generator and the fire detection system. It is vital to ensure high availability of these systems in case of a multiple failure. The failure-finding interval was therefore set to lower or equal to 1% of the MTBF. According to Moubray (1991), this ensures an availability of at least 99.5%, which is important for such critical safety systems.

## 10.3 Maintenance Packages

The last step of the RCM analysis is to propose a total maintenance program for the systems that have been analyzed. This includes a detailed description of the tasks and maintenance job grouping. Tasks can be coordinated according to their intervals, maintenance type, required personnel and shutdown requirements. Since this vessel has not yet been built, deciding on maintenance packages without operational experience is challenging. However, a maintenance plan is proposed in this chapter based on the maintenance task intervals. The maintenance packages which show the complete maintenance plan are presented in correspondingly Figure 38, Figure 39 and Figure 40. They are grouped into packages based on the intervals. Further grouping can also be done within the maintenance packages of similar tasks. For instance, tasks K1, D1, and I2 should be done simultaneously since the same personel and the tasks are similar. This is done to make the maintenance planning and maintenance tasks more manageable. The maintenance intervals are from continuous monitoring to 5 years. Also, some intervals are based on the time in operation and charging and filling cycles of the battery and storage tank, respectively. The maintenance packages also show the yearly cost of the maintenance task. The calculations are shown in Appendix C.

| Package | Interval | Task | Description | Personnel | Equipment | Yearly cost of task |
|---|---|---|---|---|---|---|
| 1 | Continuous | C:2 Condition monitoring of battery | Continous monitoring of battery status, output and level by battery management system | Crew | Battery Management System | NOK 6 644 |
| 2 | Weekly | E:1. Functional testing of emergency diesel engine | Weekly functional testing of emergency diesel generator. Check if the generator starts in battery mode. | Crew | No special equipment needed | NOK 16 850 |
| | | G:2. Inspection of electric motor | Weekly inspection of oil levels. | Crew | No special equipment needed | NOK 16 850 |
| 3 | 6 months | B:1 Condition monitoring of air compressor | Visual inspection of compressor for corrosion, degradation, check oil levels. | Crew | Corrometer | NOK 14 821 |
| | | E2: Scheduled restoration of emergency diesel engine | Clean or replace air filter if needed | Crew | No special equipment needed | NOK 1 537 |
| | | F:3. Condition monitoring of input devices | Test the input devices, recalibrate if values deviate. Inspect for damage, wear and corrosion | Crew/craftsmen | Multimeter, HART communicator, pressure pump | NOK 14 241 |
| | | F:4 Condition monitoring of alarm system | Test the alarm system. Inspect for damage, wear and corrosion | Crew | Calibration tools | NOK 3 370 |
| | | H1: Failure finding task of F&G detection system | Test the F&G detectors, recalibrate if necessary. Inspect for damage, wear and corrosion | Crew | Calibration tools | NOK 14 241 |

Figure 38: Maintenance packages 1-3.

The first maintenance package is the continuous condition monitoring of the battery system using the battery management system from the supplier. The cost of the battery management system is assumed to be 5% of the capital cost of the battery system, where the costs are spread over the assumed lifetime of the vessel, which is 15 years.

The second maintenance package is the maintenance tasks which must be done weekly. This includes failure-finding testing of the emergency diesel generator and inspection of the electric motor. The interval for the failure-finding tasks is based on being 1% of the MTBF to ensure high availability. These two tasks are only related to inspection and can be done by the crew on the fishing vessel. No special tools are assumed to be necessary. The costs are based on the assumptions of the weekly inspection with a required number of manhours multiplied by the salary.

The third maintenance package is done bi-annually. All tasks except one are assumed to be done by the crew. Many of these tasks are based on inspection and testing of the equipment. Only task E2, which is a scheduled restoration of the air filter for the emergency generator, is not based on inspection. For monitoring the input devices, special calibration and measuring tools are needed. Special calibration tools are also necessary for testing the fire  gas, and alarm systems. The cost estimations are based on the equipment costs for the condition monitoring and the manhour cost to do the maintenance task.

| Package | Interval | Task | Description | Personnel | Equipment | Yearly cost of task |
|---|---|---|---|---|---|---|
| 4 | Yearly | A:2: Condition monitoring of fuel cell stack | Voltage test of a specific current to detect degradation. Thorough inspection for corrosion, fatigue, wear | Craftmen | Calibration tools | NOK 52 463 |
| | | A:4: Scheduled restoration of air filter | Clean or replace air filter if needed | Crew | No special equipment needed | NOK 1 537 |
| | | A:5: Scheduled restoration of H2 filter | Clean or replace hydrogen filter if needed | Crew | No special equipment needed | NOK 8 737 |
| | | E:3 Condition monitoring of emergency diesel generator | Visual inspection for damage, wear and corrosion | Crew | No special equipment needed | NOK 10 392 |
| | | G3: Electrical/insulation condition monitoring of electric motor | Meggertest, current and voltage test | Craftmen | Insulation tester resistance meter | NOK 6 557 |
| | | G:3 Physical condition monitoring of electric motor | Visual inspection of bearings and windings for corrosion, wear and damage | Crew | No special equipment needed | |
| | | J:2 Condition monitoring of hydrogen storage tank | Ultrasonic pressure test, visual inspection of tank and liner for damage, embrittlement, wear and corrosion | Crew and craftsman | High-frequency ceramic microphone | NOK 9 267 |
| | | J:3 Condition monitoring of hydrogen storage tank | Leak test of PRV and fuel supply valves. Ultrasonic leak detection. | Crew | High-frequency ceramic microphone | NOK 3 416 |
| | | L2: Condition monitoring of fuel supply line | Leak test of PRV and fuel supply valves. Ultrasonic leak detection. | Crew | High-frequency ceramic microphone | NOK 3 416 |
| | | M1: Scheduled restoration of water pump | Clean or replace water filter if needed | Crew | No special equipment needed | NOK 2 737 |
| 5 | 2 years | F:1. Condition monitoring of CLU | Test the PLC system, backup file, update software if necessary, visual inspection for loose connection and corrosion | Skilled technician | No special equipment needed | NOK 8 660 |

Figure 39: Maintenance package 4 and 5.

The fourth maintenance package is the maintenance tasks which are done every year. Some essential maintenance tasks are the condition monitoring of the fuel cell stack to detect degradation by voltage and current testing. This is the most expensive maintenance task in this package due to the need for tools and the assumption of a high number of manhours by expensive craftsmen. A few tasks are related to cleaning/repairing filters and inspections for damage, corrosion and wear. Ultrasonic leak tests of the PRV and fuel supply valves on the tank and fuel supply line should also be conducted to inspect the hydrogen tank. Also, a megger test of the electric condition of the motor is done. Some tasks can be done by the crew, and some tasks by external skilled technicians. Meggermeter is required for the megger test, and a high-frequency microphone for ultrasonic leak detection.

The fifth maintenance package is done every second year. This is a test of the CLU/PLC system, taking backup, updating software and checking the electric system visually. A skilled technician must do this.

| Package | Interval | Task | Description | Personnel | Equipment | Yearly cost of task |
|---|---|---|---|---|---|---|
| 6 | 3 years | B:3 Condition monitoring of air compressor | Vibration measurements and frequency analysis. Fast Fourier Transformation of Data. The FFT gives a measured spectrum which is then compared to a normal spectrum. | Crew to test and craftsmen to analyse | Vibration analyser | NOK 5 903 |
| | | B4: Condition monitoring of air compressor | Check loose connection on power supply of air compressor | Crew | No special equipment needed | NOK 1 123 |
| | | D1: Condition monitoring of converter | Inspect electrical connections, corrosion check | Craftsman | No special equipment needed | NOK 2 887 |
| | | I2: Condition monitoring of DC switchboard | Inspect electrical connections, corrosion check | Craftsman | No special equipment needed | NOK 2 887 |
| | | K1: Condition monitoring of inverter | Inspect electrical connections, corrosion check | Craftsman | No special equipment needed | NOK 2 887 |
| | | L:1 Condition monitoring of fuel supply line | Acoustic emission testing to test for damage, corrosion and wear. | Craftsman | Transducers, sensor, strain gauges | NOK 12 454 |
| | | M2: Condition monitoring of water pump | Visual inspection of pump for corrosion, degradation, check oil levels. Check bearings, impeller, etc | Crew | No special equipment needed | NOK 674 |
| 7 | 5 years | L4: Condition monitoring of fuel supply line | Ultrasonic leak detection | Craftsmen | High-frequency ceramic microphone | NOK 7 648 |
| 8 | Individual maintenance tasks | A1: Scheduled replacement of fuel cell stack | Replace fuel cell stack after 30 000 hours of operation | Craftsmen | Must be done on a shipyard | NOK 228 131 |
| | | C1: Scheduled replacement of battery | Replace battery after 2500 charging cycles or 10000 hours of operation, whichever comes first | Craftsmen | Must be done on a shipyard | NOK 136 335 |
| | | G1: Scheduled replacement of motor | Replace electric motor after 28 000 hours of operation | Craftsmen | Must be done on a shipyard | NOK 27 726 |
| | | J1: Scheduled replacement of hydrogen storage tank | Replace hydrogen storage tank after 5000 filling cycles | Craftsmen | Must be done on a shipyard | NOK 16 400 |

Figure 40: Maintenance packages 6-8.

The sixth maintenance package is conducted every three years. The tasks in this package are related to the air compressor, electrical system of the DC switchboard, converters and inverters, water pump and the fuel supply line. Noticeable maintenance tasks in this package are the air compressor's vibration measurements and frequency analysis. The crew can conduct the test; however, a skilled craftsman must analyse the vibration. Another important maintenance task is the acoustic emission test of the fuel supply line to check for leaks, wear and corrosion. Transducers, sensors and strain gauges are necessary to do the test.

The seventh maintenance package is the last time-based maintenance task and is done every five years. It is an ultrasonic leak detection on the fuel supply line to detect any possible hydrogen leakages from the pipes. A high-frequency microphone is also necessary to do the test.

The last maintenance package consists of tasks done on an individual basis, which are the tasks that do not fit into any of the intervals above. They are related to a scheduled replacement of the fuel cell stack, battery, motor and storage tank. The replacement interval is illustrated in Figure 40. These components are expensive and must also be done at a shipyard by craftsmen, as the components are complex and large. This means these maintenance tasks are the most significant of yearly maintenance costs. They are estimated by adding the spare parts costs with the assumed manhours and salary plus costs related to downtime and transportation needed to replace the systems.

Most specific maintenance tasks, such as the megger test, ultrasonic leak detection and acoustic emission, are based on Moubray (1991). Voltage and current testing of the fuel cell were proposed after a discussion with industry experts in Sintef. Other sources are conversations with fishermen and the student's judgement. Based on this, a suitable maintenance plan for the system is proposed, which should lead to a safe and reliable operation of the hydrogen-fueled coastal fishing vessel.

## 10.4 Evaluation of the FMECA

The FMECA provided an in-depth study of failure modes of the hydrogen power generation system for the fishing vessel. It has created a perception of the system failures and the likelihood and consequence of every failure mode. Effects and consequences have been studied on a failure mechanism level to understand the whole risk picture of every failure mode. This results in a detailed and good view of how every system can fail on its own and what are the most critical failure modes.

This is, however, a tedious and time-consuming process as it is a detailed approach. The systems in this analysis are critical. Making the same approach on other less critical systems should be assessed whether the time and costs of the analysis are worthwhile. The results from this FMECA have discovered failure modes of a complex system which has not been used on a similar vessel before. FMECA is, therefore, a good approach to discovering failures of systems where we have limited knowledge. Before the analysis, the author did not believe that the air management system would be such a critical system in terms of failure. Therefore doing such analyses is important when knowledge and experience are lacking. This has been used as a basis to establish maintenance tasks that aim to handle each failure mode's failure causes. In addition, the analysis has created a framework that can be used further for other systems onboard the vessel or similar vessels.

Generally, the risk index values obtained in the FMECA were higher than expected. This might be due to consequence and frequency categories in addition to the risk acceptance criteria. As observed in Table 3, the average risk index was six, corresponding to an orange level in the risk acceptance criteria. The general rule is that risks in the orange area should be reduced to the yellow area. However, a cost-benefit analysis should be conducted. This shows that the general risk of the failure modes is high. These are essential systems, so a failure of them is critical. However, the risk indices could differ with other risk acceptance criteria. The actual redundancy configurations and more realistic failure data would also impact the results of the FMECA. Due to limited experience, the consequences of some failure modes were unclear. For instance, some sources had contradicting consequences of a failure mode of a fuel cell stack. It made it difficult to determine a consequence category for some failure modes. However, since this is a new technology, it was decided to go for a more conservative approach which may have led to higher consequence index classifications and corresponding high-risk indices.

The frequency index for the hidden failures could also be calculated in a different manner. Since a hidden failure is not critical in itself, an unwanted incident or another failure has to happen before the hidden failure is critical. This means that the frequency index could have multiplied the probability of the unwanted incident with the failure rate to get the actual failure rate. However, due to lacking data, this was not done. This would reduce the frequency indices of the hidden failures significantly.

## 10.5 Evaluation of the Maintenance Plan

Using the results from the FMECA and by using the RCM decision tree, one could propose maintenance tasks to target the failure modes. This is a suitable method to avoid failures from occurring. Following the RCM decision logic, all proposed maintenance tasks were preventive or predictive. Some failure modes were not assessed further in the maintenance task. These failure modes were already in the acceptable risk category before maintenance was conducted. Since the risk was acceptable, it was decided not to analyse them further. They could have been analysed on a cost-benefit level to see if costs could have been reduced. However, since the analysis is time-consuming, they were left out. Some failure modes were also covered by other maintenance tasks, and they were also categorised as "not-assessed". For instance, the failure causes of motor degradation and motor failure are often the same. If a maintenance task covers the most critical failure mode, the other failure mode will often be covered.

Overall, the maintenance program obtained by doing the RCM analysis should be a suitable method to avoid the risk of failure modes, increasing the safety and availability of a critical system onboard the fishing vessel. One of the main goals of RCM is to focus on tasks that increase system reliability, and the author believes the proposed tasks that target the failure modes are important for the objective. In addition, the intervals between the maintenance tasks are also important. It was crucial not to pick too long intervals as this leads to many failures before the failure is detected or maintenance occurs. However, one does not want too short maintenance intervals since this can lead to unnecessary maintenance costs. It can also lead to failures due to inadequate maintenance, and some equipment has higher infant mortality, so this can, in some cases, increase the failure rate. For equipment with clear wear-out periods and equipment with failure patterns A and B, maintenance intervals were picked shorter than the MTBF to avoid most failures. The interval was significantly shorter for random failure patterns than the MTBF since the failures can happen more randomly, and a specific wear-out point is difficult to find. The intervals were based on availability predictions from Moubray (1991) for hidden failures. The intervals for scheduled replacement were based on manufacturer data and literature. In addition, maintenance tasks were in mind when choosing the intervals, as some tasks can discover failures earlier than other tasks.

The cost calculations were based on many assumptions about the cost, repair time and equipment. Using it for cost-benefit analysis was challenging since the analysis did not include the probability of detecting a failure using condition monitoring. Due to a lack of data, this was not included in the maintenance analysis. This would give more accurate estimates of the costs of on-condition tasks. In addition, there was little data to be found on the necessary manhours to do maintenance, leading to many assumptions by the author. However, the cost calculations show the clear trend that preventive and predictive maintenance is much more cost-effective than corrective maintenance. This is one of the reasons why the RCM method often has a trend to prefer preventive maintenance. Another parameter influencing the costs is the vessel lifetime, estimated to be 15 years. A longer or shorter operational lifetime is expected to affect the yearly cost significantly since some of them are divided på the lifetime. Income estimates are also uncertain, and they would affect the loss of income as well. With more operational experience and supplier data, the costs can be re-evaluated to get a better cost-benefit analysis of the maintenance program to improve it further.

The RCM analysis did not contain any specific estimates of how much the system's availability, reliability and cost-efficiency are improved. This is difficult to estimate since there is no existing maintenance plan, and the vessel is not built. However, the RCM analysis gives clear indications of the risks of the system and what can be done to improve the availability before the vessel begins to operate.

## 10.6 Limitations & Error Sources

When conducting the analysis, this study has several limitations and sources of error. Since the vessel is still under design, many uncertainties are related to the system design.

Many assumptions about the power generation system have been made where there has not been enough information. For example, the safety systems' redundancy level is unknown, which impacts the probability index significantly in the FMECA. In addition, no reliability data for the systems are known. This means that data from OREDA, a reliability database from the offshore oil & gas industry, has been used in many cases. The equipment used in the offshore oil & gas industry and the equipment onboard a small coastal fishing vessel can be very different in terms of operational context and size. This is a source of error for the frequency index for the systems using the OREDA database. Also, data from IEEE has been used, which is not fitted to maritime appliances. Reliability, hazard/failure and frequency data related to the hydrogen storage, PEM fuel cell and fuel supply line have been found in literature. Many articles reviewed are from other industries, such as aircraft, forklift and power generation. Since the literature in many cases has not been from the maritime industry or similar vessel types, it is uncertain how good the data used is. Many failure modes obtained from the literature have used different frequencies, consequence indices and risk acceptance criteria. Some analyses have had vague indices, and translating these into the categories used in this thesis has been difficult, giving uncertainty to categorising some failure modes. Another parameter that has affected the analysis results is the categories and risk acceptance matrix used. Other categories and criteria could give widely different results. For instance, could a different choice of indices take a failure mode from unacceptable to ALARP or acceptable risk level. From the FMECA, it is observed that most of the failure modes were within the ALARP category. Having more specific consequence indices with more alternatives would have made it easier to get a more accurate risk picture. The consequence index is vague, with only four categories, and does not include environmental damage, economic damage, loss of reputation, etc. More indices and specific definitions would make it easier to categorise the failure modes, giving a more accurate categorisation that could affect the results.

Another limitation of the analysis is that the student did the RCM analysis alone. Moubray (1991) suggests that the analysis should be done in groups with experts in different fields about RCM and the system to cover all information about failures, risk and maintenance. Regarding the costs of the systems, the information used in this thesis is highly uncertain and based on costs found from various suppliers online and estimates from the literature. Downtime sources have been from OREDA or assumptions from the author. The failure patterns for the different equipment are not certain, which gives uncertainty to some maintenance tasks. The difference in failure patterns highly affects which maintenance tasks are worthwhile doing. Limited knowledge and experience with the complex technology make it difficult to propose fitting maintenance tasks for the maintenance task analysis. Especially grouping maintenance tasks and proposing a specific task on systems with limited experience is difficult to judge. This is why the maintenance program should continuously be improved, so when more experience has been gained, one can see if alterations to be program are needed. Lastly, the maintenance program has many scheduled on-condition tasks. The assumption in this analysis is that this will detect every failure. However, one can not expect that the condition monitoring and inspections are 100% correct every time. The effects of unnoticed failures are not included in the analysis, which would impact the results and strategy. This also impacts the estimation of the cost of scheduled on-condition tasks.

# 11 Conclusion

The overall objective of this thesis was to perform an RCM analysis of the power generation system on a hydrogen-fueled coastal fishing vessel. This was done by doing a Failure Modes, Effect and Criticality Analysis and Maintenance Task Analysis of the specific system, giving the basis for proposing a maintenance plan. The procedure for the RCM method followed the methodology from Moubray (1991). The analysis has covered every equipment part of the system, covering all failures and failure modes, following the RCM decision diagram to propose a maintenance task program for the system. The analysis used the ship designer's frequency and consequence categories in addition to their risk matrix.

From the FMECA, 9% of the failure modes were categorized as unacceptable according to the risk acceptance criteria. 62% were in the orange ALARP category, which are failure modes that should be assessed to see if it is worthwhile to reduce the risk. 26% of the failures were in the yellow ALARP category, while the remaining 3% had an acceptable risk level. Forty-one failure modes were discovered, and 140 failure mechanisms for those failure modes. The analysis showed that the most critical failure modes were the failure of the air management system and the failure of the input devices for fuel monitoring, which were in the unacceptable risk acceptance region. This is due to a combination of significant consequences and a high probability of failure of the given failure modes. The worst consequences include the potential of fire and explosion on the vessel. Based on the results from the FMECA and the RCM decision diagram from Moubray (1991), a Maintenance Task Analysis was conducted. The MTA gave 33 maintenance tasks as a barrier against the failure modes. No corrective maintenance tasks were proposed. Twenty-four of the maintenance tasks were predictive, and the remaining nine were categorized as preventive maintenance. The maintenance tasks have various maintenance intervals, from continuous maintenance to maintenance every five years. The tasks are sorted into maintenance packages based on maintenance interval, describing the maintenance tasks, crew and equipment requirements. Yearly maintenance costs are also estimated, where scheduled replacement of the fuel cell stack is the most expensive maintenance task. Since the full design is not yet clear and the limited operational experience with these systems, the maintenance program should be revised periodically. By revising the program, improvements can be made concerning safety, costs and availability.

The results of this analysis can be used to understand how the power generation system can fail and what maintenance tasks can be used to counter the failures safely and effectively. Since this is a new technology, it is highly beneficial to get an understanding of the systems to ensure improvement of safety, reliability and availability. It can be concluded that the RCM method helps evaluate new technology regarding safety and maintenance. The results of this analysis can also be used for design changes since the vessel is not yet built.

This thesis has been challenging due to little information, knowledge and experience. From the author's knowledge, this will be the first-ever hydrogen-fueled coastal fishing vessel. Therefore, the study includes some uncertainty related to the data used. However, the student believes that the results give a realistic picture of the risk picture of the system and that the proposed maintenance program is suitable towards the failure modes.

# 12 Recommendations and further work

This thesis analyzed the hydrogen propulsion system for a coastal fishing vessel using the RCM method. The following recommendations can be made to the shipowner and operator:

- First of all, the analysis and the system description should be verified with professionals and the crew once the final design is chosen. As this analysis is based on a preliminary design, changes can be made, which can impact the results. This can also make the crew feel more ownership of the maintenance program.
- All failure modes that happen should be recorded and included in the vessel's maintenance plan. After some time in operation, the FMECA and maintenance tasks should also be updated to observe if new tasks should be added or if some tasks are erroneous. Recording of useful failure data such as time to failure, downtime and failure cause should also be done for future analysis.
- The risk matrix, frequency and consequence parameters should also be evaluated to study how the risk picture changes with different parameters and criteria.

For further work, the author would first recommend looking more into finding the probability of detecting a failure when doing on-condition tasks. This would lead to a more accurate cost estimation of the on-condition tasks. It would also show if changes were necessary for the maintenance plan. Second of all, simulating the failures and the maintenance plan would be interesting. For instance, a Monte Carlo simulation which consists of many different simulations, could be used to see what one could expect from the system. This could be used to simulate the number of failures and see how the maintenance plan affects the costs. It could also be used to compare different maintenance plans to find the most suitable plan.

Lastly, the RCM analysis should also be considered on other systems onboard the vessel to get a complete picture and a complete maintenance plan of all systems.

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# Appendix

## A FMECA sources

| System tag | Failure source | Probability source |
|---|---|---|
| A | Sintef FC experts, Yue et al. (2019), Stephens et al. (2009), Collong and Kouta (2015), Miller (2019), Åstrøm et al. (2007), Igder et al. (2021), OREDA (2015), Al-Douri et al. (2023) | Kösters and Gao (2021), Sintef FC experts, Collong and Kouta (2015), Miller (2019), Schüller (1997), OREDA (2015), Al-Douri et al. (2023), Igder et al. (2021), Jeon et al. (2020) |
| B | OREDA (2015), Igder et al. (2021) | OREDA (2015), Igder et al. (2021) |
| C | OREDA (2015), Igder et al. (2021) | OREDA (2015), IEEE Std 3006.8-2018 (2018) |
| D | Igder et al. (2021), Ogbonnaya et al. (2021) | Ogbonnaya et al. (2021), IEEE Std 3006.8-2018 (2018) |
| E | OREDA (2015) | OREDA (2015) |
| F | OREDA (2015), Postdoc at NTNU, Schüller (1997), Miller (2019) | OREDA (2015), Miller (2019), Schüller (1997), Postdoc at NTNU, Håbrekke et al. (2013) |
| G | OREDA (2015), IEEE Std 3006.8-2018 (2018), Liu et al. (2019) | OREDA (2015), IEEE Std 3006.8-2018 (2018) |
| H | OREDA (2015), ZeroKyst HAZID (confidential), Miller (2019) | OREDA (2015), Miller (2019), Håbrekke et al. (2013) |
| I | Trivyza et al. (2021), Ogbonnaya et al. (2021), Årdalsbakke (2015) | Ogbonnaya et al. (2021), IEEE Std 3006.8-2018 (2018) |
| J | OREDA (2015), Collong and Kouta (2015), ZeroKyst HAZID (confidential), Stephens et al. (2009), HAZID Brødrene Aa, Doffin (lag ref), Miller (2019) | OREDA (2015), Ogbonnaya et al. (2021), Collong and Kouta (2015), Miller (2019), Al-Douri et al. (2023) |
| K | Ogbonnaya et al. (2021), Liu et al. (2019), Igder et al. (2021) | Ogbonnaya et al. (2021), Igder et al. (2021) |
| L | Åstrøm et al. (2007), Stephens et al. (2009), HAZID Brødrene Aa, Doffin (lag ref), ZeroKyst HAZID (confidential), Miller (2019), Al-Douri et al. (2023), OREDA (2015) | Åstrøm et al. (2007), Stephens et al. (2009), OREDA (2015), Miller (2019), Al-Douri et al. (2023), Igder et al. (2021) |
| M | Jeon et al. (2020) | Jeon et al. (2020) |

Table 4: Sources for the failure modes, failure causes and the probabilities for each system in the FMECA.

# B Cost sources

## B.1 Spare Part Costs

| Equipment | Source |
|---|---|
| Pressure Relief Valve | Stra-Val (2023), Houchins and James (2023) |
| Air compressor | RS Components AS (2023a) |
| Water pump | RS Components AS (2023u) |
| PEM Fuel Cell | Institute (2016),Cigolotti et al. (2021), Sødal (2009) |
| Non-return valve | RS Components AS (2023m) |
| DC Bus | RS Components AS (2023k), RS Components AS (2023q) |
| Converter | Elfa Distrelec (2023a), Elfa Distrelec (2023b) |
| Control Logic Unit | RS Components AS (2023o) |
| Inverter | Elektroimportøren (2023), RS Components AS (2023p) |
| Electric Motor | Evøy (2023) |
| Battery | DNV (2023) |
| Diesel Generator | Cimex (2023) |
| Hydrogen Storage Tank | TZIMAS et al. (2003), Elberry et al. (2021) |
| Temperature Transmitter | RS Components AS (2023r), RS Components AS (2023n), Houchins and James (2023) |
| Alarm Siren | RS Components AS (2023j) |
| Alarm Strobe | RS Components AS (2023c) |
| Fire detector kit | RS Components AS (2023d) |
| H2 detector | RS Components AS (2023i) |
| Pressure Transmitter | RS Components AS (2023f), RS Components AS (2023g), Houchins and James (2023) |
| Flow transmitter | RS Components AS (2023e), RS Components AS (2023h) |
| Level Transmitter | RS Components AS (2023b) |
| Vibration transmitter | RS Components AS (2023s) |
| Air filter | RS Components AS (2023t) |
| Hydrogen filter | RS Components AS (2023l) |

Table 5: Cost sources for spare parts

# C Cost Calculations

| | | CM | | | | | | PM | | | PdM | | | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| System | Failure Mode | Spare part cost | Manhours to repair | Repair cost | Loss of income | Cost of run to fail | Task | Manhours to restore/install | Cost of scheduled restoration | Cost of Scheduled Replacement per year | Condition monitoring equipment cost | Condition monitoring hours | Cost of condition monitoring | Yearly maintenance costs |
| A | 1 | NOK 3 124 811 | 200 | NOK 346 400 | NOK 486 584 | NOK 263 853 | Scheduled replacement | 200 | NOK - | NOK 231 414 | | | NOK - | |
| | 2 | NOK 3 124 811 | 200 | NOK 346 400 | NOK 486 584 | NOK 263 853 | Scheduled on-condition | 200 | NOK - | NOK - | NOK 7 545 | 30 | NOK 52 463 | |
| | 3 | NOK 3 124 811 | 200 | NOK 346 400 | NOK 486 584 | NOK 263 853 | Scheduled on-condition | 200 | NOK - | NOK - | | 0 | NOK - | |
| | 4 | NOK 1 200 | 4 | NOK 1 348 | NOK 9 732 | NOK 819 | Scheduled restoration | 1 | NOK 1 537 | NOK - | | | NOK - | |
| | 5 | NOK 8 400 | 4 | NOK 1 348 | NOK 9 732 | NOK 1 299 | Scheduled restoration | 1 | NOK 8 737 | NOK - | | | NOK - | NOK 294 151 |
| B | 1 | NOK 10 000,00 | 32 | NOK 55 424 | NOK 77 853 | NOK 9 552 | Scheduled on-condition | 27 | NOK 46 764 | NOK 56 764 | NOK 4 509 | 6 | NOK 14 901 | NOK - |
| | 2 | NOK 10 000,00 | 30 | NOK 51 960 | NOK 72 988 | NOK 8 997 | Scheduled on-condition | 25 | NOK 43 300 | NOK 53 300 | | | NOK - | |
| | 3 | NOK 10 000,00 | 30 | NOK 51 960 | NOK 72 988 | NOK 8 997 | Scheduled on-condition | 25 | NOK 43 300 | NOK 53 300 | NOK 9 470 | 20 | NOK 5 907 | |
| | 4 | NOK 10 000,00 | 22 | NOK 38 104 | NOK 53 524 | NOK 6 775 | Scheduled on-condition | 17 | NOK 29 444 | NOK 39 444 | NOK - | 10 | NOK 1 123 | NOK 21 932 |
| C | 1 | NOK 2 029 248 | 42 | NOK 72 744 | NOK 102 183 | NOK 146 945 | Scheduled replacement | 30 | NOK - | NOK 138 747 | | 0 | NOK - | |
| | 2 | NOK 2 029 248 | 25 | NOK 43 300 | NOK 60 823 | NOK 142 225 | Scheduled on-condition | 13 | NOK - | NOK - | NOK 6 764 | 0 | NOK 6 764 | NOK 145 511 |
| D | 1 | NOK 50 755 | 4 | NOK 6 928 | NOK 9 732 | NOK 4 494 | Scheduled on-condition | | NOK - | NOK 50 755 | | 5 | NOK 2 887 | |
| | 2 | NOK 50 755 | 4 | NOK 6 928 | NOK 9 732 | NOK 4 494 | Scheduled on-condition | | NOK - | NOK 50 755 | | | NOK - | NOK 2 887 |
| E | 1 | NOK 147 406 | 39 | NOK 67 548 | NOK 94 884 | NOK 20 656 | Scheduled on-condition | 31 | NOK 54 038 | NOK 201 444 | | 50 | NOK 16 850 | |
| | 2 | NOK 147 406 | 41 | NOK 71 012 | NOK 99 750 | NOK 21 211 | Scheduled restoration | 1 | NOK 1 537 | NOK 149 138 | | | NOK - | |
| | 3 | NOK 147 406 | 126 | NOK 218 232 | NOK 306 548 | NOK 44 812 | Scheduled on-condition | 101 | NOK 174 586 | NOK 321 992 | | 6 | NOK 10 392 | |
| | 4 | NOK 147 406 | 86 | NOK 148 952 | NOK 209 231 | NOK 33 706 | Scheduled on-condition | 69 | NOK 119 162 | NOK 266 568 | | | NOK - | NOK 28 779 |
| F | 1 | NOK 1 000 | 24 | NOK 41 568 | NOK 58 390 | NOK 6 731 | Scheduled on-condition | 22 | NOK - | NOK 38 411 | | 5 | NOK 8 660 | |
| | 2 | NOK 1 000 | 6 | NOK 10 392 | NOK 14 598 | NOK 1 733 | Corrective maintenance | 6 | NOK - | NOK 11 392 | | | NOK - | |
| | 3 | NOK 13 510 | 27 | NOK 45 898 | NOK 64 472 | NOK 8 259 | Scheduled on-condition | 27 | NOK 45 898 | NOK 59 408 | NOK 11 408 | 20 | NOK 14 241 | |
| | 4 | NOK 2 400 | 20 | NOK 34 640 | NOK 48 658 | NOK 5 713 | Scheduled on-condition | 20 | NOK 34 640 | NOK 37 040 | | 5 | NOK 3 370 | |
| | 5 | NOK 2 400 | 20 | NOK 34 640 | NOK 48 658 | NOK 5 713 | Corrective maintenance | 20 | NOK 34 640 | NOK 37 040 | | | NOK - | NOK 29 003 |
| G | 1 | NOK 420 679 | 29 | NOK 50 228 | NOK 70 555 | NOK 36 097 | Scheduled replacement | | NOK - | NOK 28 045 | | | NOK - | |
| | 2 | NOK 420 679 | 31 | NOK 53 692 | NOK 75 420 | NOK 36 653 | Scheduled on-condition | | NOK - | NOK 420 679 | | 50 | NOK 16 850 | |
| | 3 | NOK 420 679 | 19 | NOK 32 908 | NOK 46 225 | NOK 33 321 | Scheduled on-condition | | NOK - | NOK 420 679 | NOK 5 246 | 6 | NOK 6 557 | NOK 51 452 |
| H | 1 | NOK 9 600 | 7 | NOK 11 258 | NOK 15 814 | NOK 2 445 | Scheduled on-condition | | NOK - | NOK 9 600 | NOK 11 408 | 20 | NOK 14 241 | |
| | 2 | NOK 9 600 | 16 | NOK 27 712 | NOK 38 927 | NOK 5 083 | Corrective maintenance | | NOK - | NOK 9 600 | | | NOK 4 | |
| | 3 | NOK 9 600 | 16 | NOK 27 712 | NOK 38 927 | NOK 5 083 | Corrective maintenance | | NOK - | NOK 9 600 | | | NOK 4 | NOK 14 241 |
| I | 1 | NOK 4 250 | 40 | NOK 69 280 | NOK 97 317 | NOK 11 390 | Corrective maintenance | | NOK - | NOK 4 250 | | | NOK 8 | |
| | 2 | NOK 4 250 | 40 | NOK 69 280 | NOK 97 317 | NOK 11 390 | Scheduled on-condition | | NOK - | NOK 4 250 | | 5 | NOK 2 887 | NOK 2 887 |
| J | 1 | NOK 250 462 | | NOK - | NOK - | NOK 16 697 | Scheduled replacement | | NOK - | NOK 16 697 | | | NOK 12 | |
| | 2 | NOK 7 000 | 9 | NOK 15 068 | NOK 21 166 | NOK 2 882 | Scheduled on-condition | | NOK - | NOK 7 000 | NOK 9 109 | 5 | NOK 9 267 | |
| | 3 | NOK 8 800 | 9 | NOK 15 588 | NOK 21 896 | NOK 3 086 | Scheduled on-condition | | NOK - | NOK 8 800 | NOK 10 800 | 8 | NOK 3 416 | NOK 29 381 |
| K | 1 | NOK 42 000 | 8 | NOK 13 146 | NOK 18 466 | NOK 4 907 | Scheduled on-condition | | NOK - | NOK 42 000 | | 5 | NOK 2 887 | |
| | 2 | NOK 42 000 | 8 | NOK 13 146 | NOK 18 466 | NOK 4 907 | Scheduled on-condition | | NOK - | NOK 42 000 | | | | NOK 2 887 |
| L | 1 | | | NOK - | NOK - | NOK - | Scheduled on-condition | | NOK - | NOK - | NOK 13 643 | 20 | NOK 12 456 | |
| | 2 | NOK 1 800 | 8 | NOK 13 856 | NOK 19 463 | NOK 2 341 | Scheduled on-condition | | NOK - | NOK 1 800 | NOK 10 800 | 8 | NOK 3 416 | |
| | 3 | NOK 1 800 | 8 | NOK 13 856 | NOK 19 463 | NOK 2 341 | Scheduled on-condition | | NOK - | NOK 1 800 | | | NOK - | |
| | 4 | | | NOK - | NOK - | NOK - | Scheduled on-condition | | NOK - | NOK - | NOK 10 800 | 20 | NOK 7 648 | NOK 23 520 |
| M | 1 | NOK 2 400 | 49 | NOK 84 868 | NOK 119 213 | NOK 13 765 | Scheduled restoration | 1 | NOK 2 737 | NOK 4 132 | | | | |
| | 2 | NOK 2 400 | 52 | NOK 90 064 | NOK 126 512 | NOK 14 598 | Scheduled on-condition | | NOK - | NOK 2 400 | | 6 | NOK 674 | NOK 3 411 |

Figure 41: Cost calculation for all failure modes

# D RCM Decision Analysis

**RCM Decision Worksheet** Description: This worksheet follows the RCM decision tree presented in my Masters thesis, and is referencing to the FMECA worksheet for the failure modes

*System: H2 Propulsion System on Fishing Vessel* *Owner: Aleksander Aira-Andersen* *Page: 1 of 1*

| Failure referen | | Consequence evaluation | | | | Technical feasibility of tasks | | | Default action | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| System reference | Failure mode reference | Evident? | Safety? | Environmental? | Operational? | Is on-condition task feasible? | Is scheduled restoration feasible? | Is scheduled replacement feasible? | Failure detection feasible? | Could the task affect safety or the environment? | Failure pattern | Proposed task | Interval |
| A | 1 | Y | N | N | Y | N | N | Y | - | - | A | Scheduled replacement | 30 000h |
| | 2 | N | N | N | Y | N | N | Y | - | - | A | Scheduled on-condition | Yearly |
| | 3 | Y | Y | - | - | Y | N | Y | - | - | A | Scheduled on-condition | Yearly |
| | 4 | N | Y | - | - | N | Y | - | - | - | B | Scheduled restoration | Yearly |
| | 5 | Y | Y | - | - | N | Y | - | - | - | B | Scheduled restoration | Yearly |
| B | 1 | Y | Y | - | - | Y | - | - | - | - | B | Scheduled on-condition | 6 months |
| | 2 | N | N | N | Y | Y | - | - | - | - | B | Scheduled on-condition | 6 months |
| | 3 | N | Y | - | - | Y | - | - | - | - | B | Scheduled on-condition | 3 years |
| | 4 | Y | N | N | Y | Y | - | - | - | - | B | Scheduled on-condition | 3 years |

Figure 42: MTA decision for system A and B.

| System reference | Failure mode reference | Evident? | Safety? | Environmental? | Operational? | Is on-condition task feasible? | Is scheduled restoration feasible? | Is scheduled replacement feasible? | Failure detection feasible? | Could the task affect safety or the environment? | Failure pattern | Proposed task | Interval |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| C | 1 | Y | Y | - | - | N | N | Y | - | - | E | Scheduled replacement | 2500 cycles or 10 000h |
| | 2 | Y | N | N | Y | Y | - | - | - | - | E | Scheduled on-condition | Continuosly |
| D | 1 | N | Y | - | - | Y | - | - | - | - | E | Scheduled on-condition | 3 years |
| | 2 | Y | Y | - | - | Y | - | - | - | - | E | Scheduled on-condition | 3 years |
| E | 1 | N | Y | - | - | N | N | N | Y | - | B | Scheduled failure-finding | Monthly |
| | 2 | N | N | N | Y | N | Y | - | - | - | B | Scheduled restoration | 6 months |
| | 3 | N | N | Y | - | Y | - | - | - | - | B | Scheduled on-condition | Yearly |
| | 4 | N | N | N | Y | Y | - | - | - | - | B | Scheduled on-condition | Yearly |

Figure 43: MTA decision for system C, D and E.

| System reference | Failure mode reference | Evident? | Safety? | Environmental? | Operational? | Is on-condition task feasible? | Is scheduled restoration feasible? | Is scheduled replacement feasible? | Failure detection feasible? | Could the task affect safety or the environment? | Failure pattern | Proposed task | Interval |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| F | 1 | Y | Y | - | - | Y | - | - | - | - | E | Scheduled on-condition | 2 years |
| | 2 | N | N | N | N | N | N | N | N | N | E | - | 2 years |
| | 3 | Y | Y | - | - | Y | - | - | - | - | E | Scheduled on-condition | 6 months |
| | 4 | N | Y | - | - | Y | - | - | - | - | E | Scheduled on-condition | 6 months |
| | 5 | N | N | N | N | N | N | N | N | N | E | - | - |
| G | 1 | Y | N | N | Y | N | N | Y | - | - | A | Scheduled replacement | 28 000h |
| | 2 | Y | Y | - | - | Y | - | - | - | - | A | Scheduled on-condition | Weekly |
| | 3 | N | N | N | Y | Y | - | - | - | - | A | Scheduled on-condition | Yearly |

Figure 44: MTA decision for system F and G.

| System reference | Failure mode reference | Evident? | Safety? | Environmental? | Operational? | Is on-condition task feasible? | Is scheduled restoration feasible? | Is scheduled replacement feasible? | Failure detection feasible? | Could the task affect safety or the environment? | Failure pattern | Proposed task | Interval |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| H | 1 | N | Y | - | - | N | N | N | Y | N | E | Scheduled failure-finding | Every 6 months |
| | 2 | N | N | N | N | N | N | N | N | N | E | - | - |
| | 3 | N | N | N | Y | N | N | N | N | N | E | - | - |
| I | 1 | N | N | N | Y | N | N | N | N | N | E | - | - |
| | 2 | Y | Y | - | - | Y | - | - | - | - | E | Scheduled on-condition | 3 years |
| J | 1 | N | Y | - | - | Y | - | - | - | - | C | Scheduled replacement | 5000 filling cycles |
| | 2 | Y | Y | - | - | Y | - | - | - | - | C | Scheduled on-condition | Yearly |
| | 3 | N | Y | - | - | Y | - | - | - | - | B | Scheduled on-condition | Yearly |

Figure 45: MTA decision for system H, I and J.

| System reference | Failure mode reference | Evident? | Safety? | Environmental? | Operational? | Is on-condition task feasible? | Is scheduled restoration feasible? | Is scheduled replacement feasible? | Failure detection feasible? | Could the task affect safety or the environment? | Failure pattern | Proposed task | Interval |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| H | 1 | N | Y | - | - | N | N | N | Y | N | E | Scheduled failure-finding | Every 6 months |
| | 2 | N | N | N | N | N | N | N | N | N | E | - | - |
| | 3 | N | N | N | Y | N | N | N | N | N | E | - | - |
| I | 1 | N | N | N | Y | N | N | N | N | N | E | - | - |
| | 2 | Y | Y | - | - | Y | - | - | - | - | E | Scheduled on-condition | 3 years |
| J | 1 | N | Y | - | - | Y | - | - | - | - | C | Scheduled replacement | 5000 filling cycles |
| | 2 | Y | Y | - | - | Y | - | - | - | - | C | Scheduled on-condition | Yearly |
| | 3 | N | Y | - | - | Y | - | - | - | - | B | Scheduled on-condition | Yearly |

Figure 46: MTA decision for system K, L and M.

# E RCM Decision Diagram

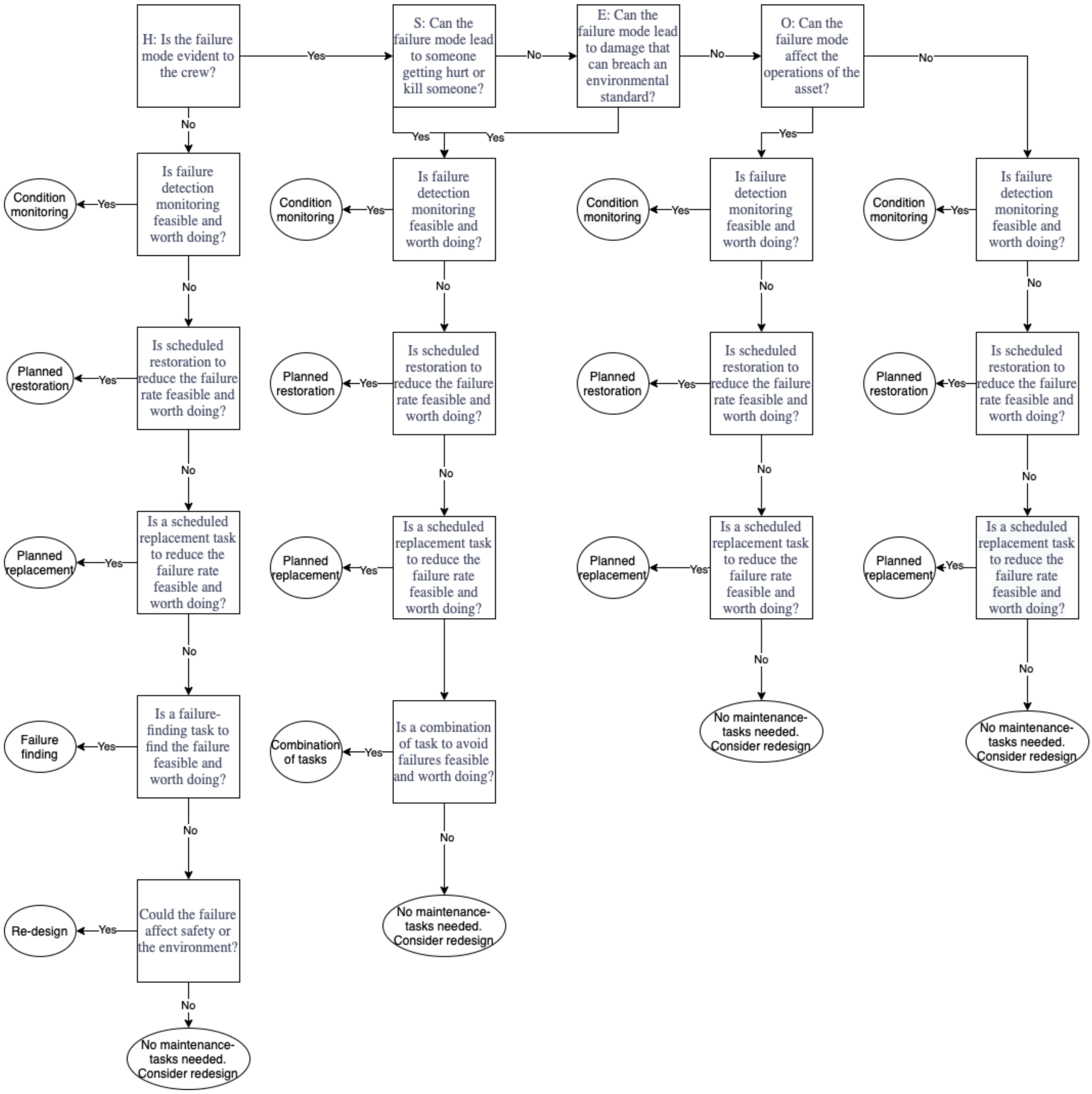


Figure 47: RCM Decision Diagram, adopted from Moubray (1991).

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