



# **Evaluation study for an Ammonia-fed and Solid-Oxide Fuel Cell powered Trailing Suction Hopper Dredger for Van Oord Offshore Contractors**

Thesis of 60 ECTS credits submitted to the School of Science and Engineering  
at Reykjavík University in partial fulfillment of  
the requirements for the degree of  
**Master of Science (M.Sc.) in Sustainable Energy  
Science**

May 2019

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Thomas Cornelis  
May 2019



# **Evaluation study for an Ammonia-fed and Solid-Oxide Fuel Cell powered Trailing Suction Hopper Dredger for Van Oord Offshore Contractors**

Thomas Cornelis

May 2019

## **Abstract**

In the quest to meet the Paris agreement goals, the maritime industry is facing some serious challenges. To reduce the GHG emissions in the industry, many Zero-Emission technologies and clean fuels have been studied. United Nations' International Maritime Organization has set the goal to reduce the industry's emissions by 50% in 2050. To meet this goal every newbuild ship should be emission free as of 2030. In partnership with Van Oord Offshore Contractors an evaluation study has been conducted to examine the possibility of a Zero-Emission Trailing Suction Hopper Dredger. For this evaluation study the possibility towards an Ammonia-fed and Solid-Oxide-Fuel-Cell powered hybrid Trailing Suction Hopper Dredger (TSHD) has been researched. This has been done through the analysis of the Power Demand behavior of an existing TSHD, a multi-criteria analysis concerning a hybrid power system, a retrofit design of a TSHD and a cost estimation study of the implementation of the researched technologies. It was found that the implementation of an Ammonia-fed and Solid-Oxide-Fuel-Cell will significantly decrease the autonomy of the TSHD by 80%. The decrease of autonomy comes together with an increase of cost of the new technology of almost 200%. The hourly fuel rate cost are expected to increase with roughly 300%. The CO<sub>2</sub> reduction of the TSHD amounts 3,420 metric tonne on an hourly base. Implementing the Ammonia and SOFC's in the TSHD will guarantee meeting emission reduction goals of the International Maritime Organization.



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Firstname Lastname

júní 2017

## Útdráttur

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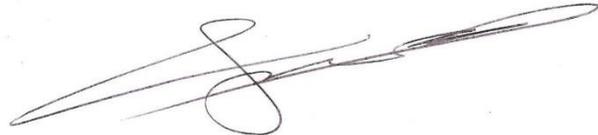
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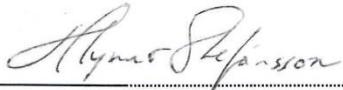
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.....  
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Thomas Cornelis  
Master of Science



*I dedicate this work to Bob and Lysette Cornelis, my parents. Who have always supported me, for better or worse.*

*It matters not how strait the gate,  
How charged with punishments the scroll,  
I am the master of my fate,  
I am the captain of my soul.*

*William Ernest Henley*

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# Preface

This MSc Thesis is original work by the author, Thomas Cornelis.



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# List of Abbreviations

|                 |   |
|-----------------|---|
| TSHD            | Trailing Suction Hopper Dredger                                     |
| EPC             | Engineering, Procurement & Construction                             |
| ZEV             | Zero-Emission Vessel  |
| GHG             | Green House Gas   |
| MSC             | Marine Safety Committee   |
| MEPC            | Marine Environment Protection Committee                             |
| LC              | Legal Committee   |
| TCC             | Technical Co-operation Committee                                    |
| FC              | Facilitation committee  |
| STCW            | Standards of Training, Certification for Watchkeepers at sea        |
| MARPOL          | International Convention for the Prevention of Pollution from Ships |
| SOLAS           | Safety of Lives at Sea  |
| EEDI            | Energy Efficiency Design Index                                      |
| SEEMP           | Ship Energy Efficiency Management Plan                              |
| EEOI            | Energy Efficiency Operational Indicator                             |
| ITCP            | Integrated Technical Cooperation Programme                          |
| MTCC            | Maritime Training and Competence Centre                             |
| GloMEEP         | Global Maritime Energy Efficiency Partnerships                      |
| IACS            | International Association for Classification Society                |
| MJ              | Mega Joules   |
| Kg              | Kilograms   |
| POX             | Partial Oxidation   |
| ATR             | AutoThermal Reforming   |
| SMR             | Steam Reforming   |
| CO              | Carbon monoxide   |
| CO <sub>2</sub> | Carbon dioxide  |
| LH <sub>2</sub> | Liquid Hydrogen   |
| RT              | Room temperature  |
| AFC             | Alkaline Fuel Cell  |
| PEMFC           | Proton Exchange Membrane Fuel Cell                                  |
| DMFC            | Direct Methanol Fuel Cell   |
| MCFC            | Molten Carbonate Fuel Cell  |
| SOFC            | Solid Oxide Fuel Cell   |
| T               | Temperature   |
| CAPEX           | Capital Expenditures  |
| OPEX            | Operational Expenditures  |
| ICE             | Internal Combustion Engines   |
| DWT             | Dead Weight Tonnage   |
| HFO             | Heavy Fuel Oil  |
| NFPA            | National Fire Protection Association                                |
| DP              | Dredge Pumps  |
| PS/SB           | Portside / Starboard  |
| VODAS           | Van Oord Data Automation System                                     |
| ESS             | Energy Storage System   |
| COT/BOT         | Computed Output / Berkende Output                                   |

|        |   |
|--------|---|
| STW    | Speed Through Water                                   |
| NDC    | New Dredging Cycle                                    |
| ADC    | Average Dredging Cycle                                |
| PDC    | Parameter Dredging Cycle                              |
| CADC   | Corrected Average Dredging Cycle                      |
| DC     | Dredging Cycle  |
| BMS    | Battery Measurement System                            |
| CID    | Current Interruption Device                           |
| FESS   | Flywheel Energy Storage System                        |
| UC     | Ultra Capacitors                                      |
| VRFB   | Vanadium Redox Flow Battery                           |
| TCC    | Total Capital Cost                                    |
| MCA    | Multi Criteria Analysis                               |
| ROI    | Return On Investment                                  |
| YSZ    | Yttria Stabilized Zirconium                           |
| LSM    | Lanthanum Strontium Manganite                         |
| TCS    | Tank Connection Space                                 |
| HE 1-4 | Heat Exchanger 1-4                                    |
| APAC   | Asia-Pacific  |
| EMEA   | Europe, Middle-East and Africa                        |
| OECD   | Organisation of Economic Co-operation and Development |





# Chapter 1

## Introduction

The motivation for this research finds its origin in the need for the shift from fossil fuels towards renewable energy sources for the fleet of Van Oord. Van Oord is an Offshore contracting company operating from Rotterdam, The Netherlands. Like many other industries, also the maritime industry will need to cut off emissions in the quest to a clean and sustainable future. To accomplish this, the International Maritime Organization have set new rules and goals. Van Oord, with one of the largest fleets in the marine contracting industry will need to look into the future to determine the best way to comply with these new targets. The Trailing Suction Hopper Dredgers (TSHD) that Van Oord owns might need to have retrofits or new build ships will have to be environmentally and future proof. In this thesis preliminary research and evaluation study will be done to see what the possibilities are concerning Zero-Emission TSHD's for Van Oord. This is done by determining the operational profile of a reference ship, based on historical data. With this knowledge the optimal Zero-Emission solution will be determined, the necessary installed power will be calculated and a financial research will be conducted.

For this research the following research questions will be attempted to be answered.

Main research question:

*“Evaluate the possibilities for an Ammonia-fed and SOFC powered Trailing Suction Hopper Dredger for Van Oord offshore contractors”*

*“How does the Power demand of an existing Trailing Suction Hopper Dredger look like?”*

*“What is the most suitable set of the researched technologies?”*

*“How do the financial numbers of the suitable technologies look like?”*

## 1.1 Van Oord – The Company

Van Oord is a Dutch family-owned International EPC contractor that was founded in 1868 by Govert van Oord. Van Oord is specialized in Dredging, Oil & Gas infrastructure and Offshore Wind. This year, Van Oord celebrates its 150<sup>th</sup> anniversary and attained the Royal status. The leading expertise of Van Oord in the Marine contracting industry is part of the foundation of the economic wealth and existence of the Netherlands. The country's biggest civil works have been made by Royal Van Oord. This includes the 'Nieuwe Waterweg' Canal, the Delta works and the Port of Rotterdam Maasvlakte 2 expansion. Projects like these protect the Dutch against the infinite battle against the water and helped the Dutch economy grow to the levels it is at today. Internationally seen Van Oord left some serious engineering footprints as well. Van Oord has been part of major projects, such as the Suez Canal, port expansion in Surabaya Indonesia, Palm islands in Dubai and more recently the Gemini Offshore wind park, one of the biggest offshore windfarms on earth. (Van Oord , 2018)

The changing landscape in the world, towards sustainable business management, is also of great importance in Van Oord's philosophy. Over the past time Van Oord developed a new corporate strategy to invigorate its vision. *"Creating a better world for future generations by delivering Marine Ingenuity"*. To achieve these goals Van Oord holds on to their core values, these are described as the 4 'We's'. *"We Create, We Care, We Work Together, We Succeed."* This slogan has been of great importance for the success of the company. According to Van Oord's philosophy succession is only possible when one actually cares about quality, safety, environment, integrity and most important, people. Both within the Van Oord team as well as all the stakeholders are part of success. Without this cohesion success is not in the picture. (Van Oord , 2018)

To live up to this vision Van Oord developed a sustainable framework. The framework is basically split up into 2 parts. The 'license to grow' and the 'license to operate.' Van Oord sees growth in accelerating climate activities, enhancing the energy transition and empowering nature & communities. This means protecting populations and landscapes against rising sea levels and extreme water events. Secondly, to mediate in the transition from fossil fuels towards clean green energy and reducing GHG's. And lastly to help local economies, communities and nature with marine solutions. In this case contribution to socio-economic development and enrichment of biodiversity is the objective. (Van Oord , 2018)

## 1.2 The Paris Agreement

As described in the last paragraph, the first and second value to attain a license to grow are focused on climate and energy transition. The overlapping value to achieve this can be found in the energy efficiency of the fleet. These transitions are a common trend for many company's and people over the last few years. It finds their origin after the sealing of the Paris Agreement on the 12<sup>th</sup> of December 2015. (United Nations , 2018). At the COP21 in Paris the parties of the UNFCCC reached an agreement to fight climate change. The goal of the agreement is to keep the increase of global temperature below 2°C degrees Celsius, preferably to even keep it below 1.5°C. Besides this, the agreement needs to make countries more climate change resilient. To achieve these goals right allocation of governmental financial resources is needed, next to that new technologies will have to

come into play. This can only be done when developed countries co-operate with the most vulnerable countries.

Remarkably there are 2 important industries missing in the Paris Agreement, although they emit significant amounts of GHG's. The aviation and the maritime industry are not included in the Paris agreement. It is expected that the emissions in these sectors will double or triple by 2050. At the moment both the aviation as well as the maritime industry account each for 2%-3% of the anthropogenic GHG's on earth. This is similar to the total emission of Germany, for each sector. (Light, J. , 2018). The UN agencies that oversee the aviation and maritime industries, International Civil Aviation Organisation (ICAO) and International Maritime Organisation (IMO) respectively, have taken action to combat these emissions. In April 2018 the IMO adopted the first ever deal on GHG emission reduction. The goal is to reduce their emissions by at least 50% in 2050, based on index year 2008. (Light, J. , 2018). This sounds like a good prospect, but critics, like environmental groups and also renowned people from the industry itself are critical about this target. One was hoping for more ambitious plans. The European Union was aiming for a 70% reduction or even total carbon reduction by 2050.

### **1.3 International Maritime Organization**

The International Maritime Organization, IMO, is a specialized agency of the United Nations. It was founded in March 1948 in Geneva. The first Convention of the IMO was held in January 1959. The agency is founded to improve the safety and security of international shipping, prevent pollution from ships and legal matters. (International Maritime Organization - Structure , 2018)

Throughout the years the IMO gathered more member states and currently there are 174 members. The 174 member states together form the 'Assembly' of the organization and is the governing body. Every 2 years the IMO comes together for Assembly sessions. During these conventions the IMO sets budget, technical resolutions and recommendations for the next 2 years and sometimes for longer periods. In between the Assembly sessions, the Council is in charge of preparing budgets and makes the work programme in name of the Assembly. The Council exists of 40 member states that have been elected by all the members. The council is supported by 5 committees; Maritime Safety, Marine Environment Protection, Legal Committee, Technical co-operation and the Facilitation committee. (International Maritime Organization - Structure , 2018). The member states are all allowed to be in the committees, there is no election for the committee.

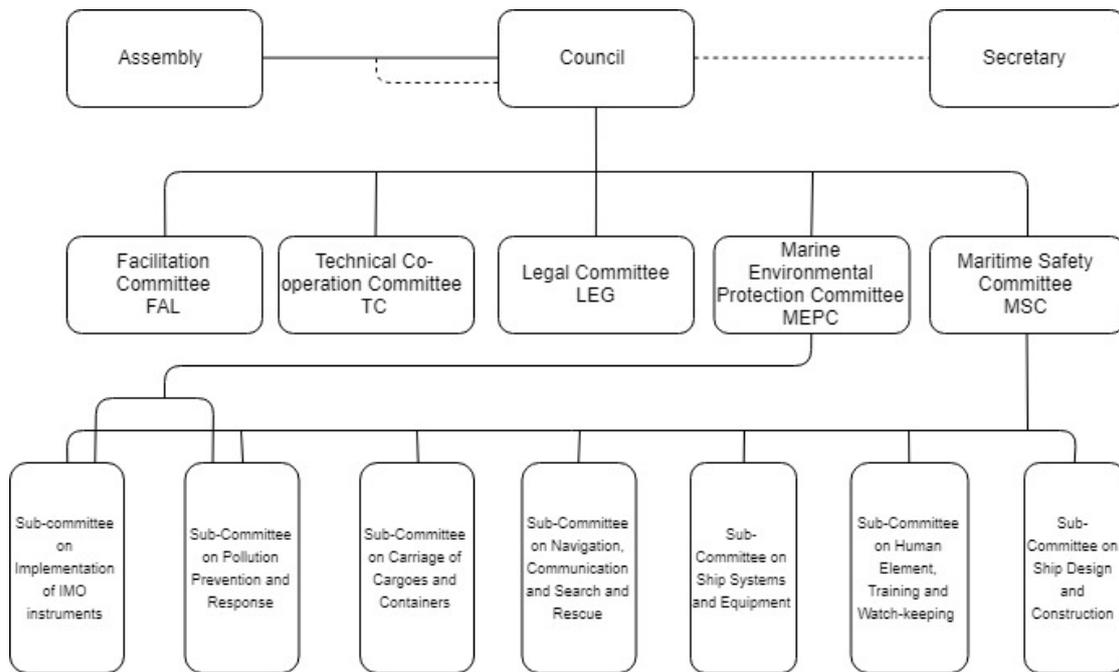


Figure 1: Flow diagram of IMO structure, (International Maritime Organization - Structure , 2018)

### 1.3.1 Committees

The Maritime Safety (MSC) and Marine Environment Protection Committee (MEPC) are the largest committee bodies of the Organization. As the names already reveal the committees deal with safety and environment. For the MSC this entails matters such as navigation aids, construction and equipment, safety on board, prevention of collisions and many more topics. The MEPC focusses on the prevention and control of pollution from ship and is particularly interested in the adoption and Annexes of the conventions and implementation and compliance of regulations. (International Maritime Organization - Structure , 2018)

To support the committees there are a few sub-committees. They all have their own responsibility within the division and report to the committee. Examples of some sub-committees are;

- S-C on Human Element, Training and Watchkeeping (HTW)
- S-C on Navigation, Communication and Search & Rescue (NCSR)
- S-C on Pollution Prevention and Response (PPR)
- S-C on Ship Design and Construction (SDC)
- S-C on Ship Systems and Equipment (SSE)
- S-C on Implementation of IMO Instruments (III)
- S-C on Carriage of Cargoes and Containers (CCC)

Same holds as for the Main Committees, Sub-Committees are also accessible for each member state. They do have to be elected though. Together the Sub-Committees support the Main Committees to make decisions on further development of the regulations at sea and in the Maritime World. Often professional help from outside the IMO and Committees is consulted. This can be done by Classification Societies. More in-depth explanation on the Classification in a later chapter.

### 1.3.2 IMO Conventions

Since the establishment of the IMO there have been many conventions, policy and rule implementations. From all these conventions the 3 most important conventions are the SOLAS convention (1974), MARPOL (1973,1997) and the STCW (1995). (International Maritime Organization - SOLAS, 2018)

The SOLAS, Safety Of Lives At Seas, convention was implemented to improve the safety of merchant ships. This implementation was done after the disaster of the Titanic in 1914. After the first convention more conventions were held to amend and improve the prior ones. In 1929, 1948, 1960 and 1974 the second, third, fourth and final conventions were held. With the introduction of the SOLAS Convention minimum standards were introduced in the maritime world. This entails minimum requirements for construction, equipment and the operation of ships. All the member states together set out the rules and each member state is responsible that a ship, that sails under their flag, also complies with the rules of the SOLAS convention. The content of the convention is accommodated in an Annex, containing 14 chapters. The most important ones being; 'Fire-protection, Life-saving appliances, Radiocommunications, Safety of Navigation, Safety measures for different types of ships (high-speed, bulk carrier etc.) and Safety measures for dangerous goods. (International Maritime Organization - SOLAS, 2018)

The MARPOL convention was founded to protect the environment. MARPOL stands for 'International Convention for the Prevention of Pollution from Ships'. It is the most important convention that covers marine pollution from both operational and accidental causes in the maritime industry. The convention itself was established in November 1973 but was not adopted straight away. In 1978 a protocol was founded. (International Maritime Organization - MARPOL, 2018). This happened after a few consecutive tanker accidents in the years before. In 1983 the Protocol and Convention bundled together and entered into force. Ever since then amendments were added to the Convention to further protect the environment from Maritime Pollution. Regulations are covered in the annexes that have been amended over the years. They cover topics like: Prevention of Pollution by Oil (1983), Control of Pollution by Noxious Liquid Substances in Bulk (1983), Pollution from Garbage from Ships (1988), Pollution by Harmful Substances Carried by Sea in Packaged Form (1992), Pollution by Sewage from Ships (2003) and Air Pollution from Ships (2005). (International Maritime Organization - MARPOL, 2018).

STCW stands for the International Convention on Standards of Training, Certification and Watchkeeping for Seafarers. The STCW is mainly focusing on the safety of life and property at sea. This is done by making sure everyone at sea complies with the international standards of safety and that the standard of training and watchkeeping worldwide is universal. The STCW convention was adopted in 1978 and came into act in the spring of 1984. Throughout the years many amendments have been made to the convention. The amendments that made the most change to the convention are the so called 'Manila Amendments'. These amendments were made in 2010 and introduced in 2012 and are supposed to make bigger impacts. Chapters of the amendments focused on prevention of fraud with certificates, new requirements of the prevention of drug and alcohol abuse, working hours, new requirements of training standards, the use of new technologies (electronic charts, dynamic positioning

and information systems) and marine environmental awareness. Next to that the requirements for training courses has been set to a higher level. To be a training institute for the STCW and IMO, member states need to comply with new and higher requirements to guarantee safety for seafarers. (International Maritime Organization - STCW, 2018).

### 1.3.3 MEPC

As mentioned before, the MEPC is in charge of Marine Environment Protection. The committee sets the new targets for IMO towards a sustainable future for the marine environment. Every 6 months the MEPC gets together in a session to determine these goals. At the end of a session a report is presented. The last session of the MEPC was held in October 2018. This was the MEPC73, 73 referring to the 73<sup>rd</sup> session of the Committee. The report of the 73<sup>rd</sup> session is, by the time writing this thesis, not published yet. In the previous 72<sup>nd</sup> session the most important topic was the reduction of GHG emissions by the shipping industry. (International Maritime Organization - Strategy , 2018).

#### The Initial Strategy, MEPC72

In this session the initial IMO strategy on the reduction of GHG emissions from ships was adopted. The vision of IMO states: *“IMO remains committed to reducing GHG emissions from international shipping and, as a matter of urgency, aims to phase them out as soon as possible in this century.”* (IMO, 2018) The Initial Strategy is a strategy that has been introduced the last few years by IMO. IMO wants to tackle climate problems by reducing GHG emissions in International Shipping. The most important chapters in this strategy pathway have been written in the MEPC62 (July 2011), MEPC65 (May 2013) and MEPC70 (October 2016) net to the last session in 2018. (International Maritime Organization - Strategy , 2018).

The MEPC62 adopted the following resolution: *“Inclusion of regulations on energy efficiency for ships in MARPOL Annex VI.”* With this adoption the industry was introduced to the Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Plan (SEEMP). The EEDI expresses the energy efficiency level per capacity mile for different ships both size and segment dependent. The EEDI wants to stimulate the innovation of clean technologies or solutions on ships. It is purely a performance indicator and not a prescriptive rule. This means that developers are free to design or improve different technologies, as long as it fits within the class rules and it improves the energy efficiency. (International Maritime Organization - Strategy , 2018).

The SEEMP is an operational measure to make sure that improvements of energy efficiency is done in a cost-responsible way. The plan will help companies to manage their fleet efficiently. The SEEMP works together with the EEOI. This is a monitoring tool to check how the fleet performs and where improvements can be made. An important example of the use of the EEOI is the monitoring of fuel. The EEOI can track the fuel use and measure the efficiency of certain operations done with a ship. It is possible that ships could more efficiently plan their course, in-port manoeuvres, propeller cleaning or use waste heat recovery systems to make use there's no fuel used for electricity generation. (International Maritime Organization - Energy Efficiency , 2018).

The MEPC 65 (May 2013) adopted the following resolution: *“Promotion of technical co-operation and transfer of technology relating to the improvement of energy efficiency of ships.”* The scope of this resolution is knowledge sharing. The IMO will provide all member states technical assistance and will accommodate the transfer of energy efficient technologies for developing countries. The IMO has a few programmes that support this; ITCP, GloMEEP and MTCC. The ITCP is the integrated technical cooperation programme, as the name ITCP implies, this policy helps developing countries to reach a uniform level of capacities on humanitarian and institutional level. In this way the IMO can make sure that developing countries comply with the regulations of the Organization. GloMEEP and MTCC are rather similar to the ITCP. (International Maritime Organization - Strategy , 2018).

The MEPC 70 (October 2016) adopted the following resolution: *“Amendment to MARPOL VI, introduction to data collection systems for fuel oil consumption of ships, containing mandatory requirements for ships to record and report their fuel oil consumption.”* After implementation of this amendment ships above a 5,000 tonne gross weight are mandatory to report their fuel oil consumption. Ships with this tonnage or above are responsible for 85% of the CO<sub>2</sub> emission in the maritime industry. The collected data will be reported to the Flag State of the ship. In this way the IMO can check the performance on energy efficiency of each flag state. (International Maritime Organization - Strategy , 2018).

The level of ambition is clear, the IMO states that it wants to decline the carbon intensity of international shipping by implementing new phases of the energy efficiency design index (EEDI). A more detailed design index is needed to improve accuracy of carbon intensity reduction. IMO wants the index more accurately over a wider range of ship types. Next to that the general carbon intensity should be brought back with at least 40% by 2030 and 70% by 2050. Furthermore an International peak and decline should occur in GHG emissions. In 2050 a 50% GHG emission reduction should be achieved with respect to 2008.

### **1.3.4 The Classification Societies**

To ensure technical safety onboard, classification societies have been founded. Classification Societies are non-governmental and non-profit organizations that are responsible for the technical standards for the construction and operation of ships and offshore structures. The Classification Societies provides certificates for vessels that meet the technical standards of the Society. When a ship is in service, surveys will be held to make sure that the ship still complies with the terms of the certificates. Ship owners cannot register or insure their ship without these certificates. Next to that, some ports demand certain specific certificates. (IACS - about, 2018).

The 12 biggest Classification Societies are members of the IACS, International Association of Classification Societies. The IACS was founded back in 1930, when it was first called the International Load Line Convention. The outcome of this convention recommended a collaboration of the existing Classification Societies. The idea was that the collaboration would guarantee the most uniformity between the standards of the Societies. Nowadays these Societies together set the standards for the more than 90% of the world’s cargo-carrying ships tonnage. With these standards for the

design, construction and life-cycle maintenance of ships, offshore units and other marine-related facilities the Societies want to promote the safety of life, property and environment. In this, the IACS fills in a role as a platform for the Classification Societies. Within this platform the Societies can discuss, research and adopt technical criteria to come to a consensus of what certain certificates should entail. Next to that the IACS provides the IMO and her Committees technical support so there is a unified interpretation of how ships and offshore units are ought to build. (IACS - about, 2018).

Below a list of the present members of the IACS.

| <i>Name</i>                                    | <i>Abbreviation</i> | <i>Anno</i> | <i>Headquarters</i> |
|--|---------------------|-------------|---------------------|
| <i>American Bureau of Shipping</i>             | ABS                 | 1862        | Houston             |
| <i>Bureau Veritas</i>                          | BV                  | 1828        | Paris               |
| <i>China Classification Society</i>            | CCS                 | 1956        | Beijing             |
| <i>Croatian Register of Shipping</i>           | CRS                 | 1858        | Split               |
| <i>Det Norske Veritas – Germanischer Lloyd</i> | DNV GL              | 1864        | Oslo                |
| <i>Indian Register of Shipping</i>             | IRS                 | 1975        | Mumbai              |
| <i>Korean Register of Shipping</i>             | KR                  | 1960        | Busan               |
| <i>Lloyd’s Register</i>                        | LR                  | 1760        | London              |
| <i>Nippon Kaiji Kyokai</i>                     | NKK                 | 1899        | Tokyo               |
| <i>Polish Register of Shipping</i>             | PRS                 | 1936        | Gdansk              |
| <i>Registro Italiano Navalo</i>                | RINA                | 1861        | Genoa               |
| <i>Russian Maritime Register of Shipping</i>   | RS                  | 1913        | St Petersburg       |

Table 1: List of Members of the IACS, (IACS - about, 2018)

## **1.4 Alternative Fuels for the Maritime Industry**

As the first steps towards a cleaner maritime industry are being made in the MEPC 72 and MEPC 73, Lloyd's Register (LR) published an article on alternative fuels. 'Zero-Emission Vessels 2030, how do we get there?' takes a closer look at zero-emission fuel technology solutions for the maritime industry. In this article multiple emission free technologies, both at consumption as well as upstream level, and multiple ship types have been researched. This has been done under different regulatory and economic scenario's. (Lloyd's Register & UMAS, 2017)

LR worked together with the University Maritime Advisory Services (UMAS) in this research. First off all they set the conditions under which the ship owners see the future of shipping. The most important topics to be taken into considerations were: Viability under normal CO<sub>2</sub> price (\$50/tonne CO<sub>2</sub>), low increase in the Capital Expenditures (CAPEX) and no upstream shift of CO<sub>2</sub>. (Lloyd's Register & UMAS, 2017).

Under these conditions LR and UMAS identified the most suitable 7 alternative fuels and technologies that largely comply with the demands of the ship owners. As there are many different vessels in the maritime industry, it is not possible to bring all these technologies down under one denominator. Therefore 5 different types of vessels have been used for the research. And at last, the success of a certain technology is heavily depended on the future economic scenario's. LR and UMAS sketched 3 different 'Green' scenarios. These are 3 different foreseeable futures, in the eyes of LR and UMAS. The scenarios consider the main 'green' produced fuel. This means the cleanest, not the most abundant or preferable. (Lloyd's Register & UMAS, 2017).

### **1.4.1 Technologies**

For the Zero-Emission technology options, LR and UMAS chose the beforementioned 7 technologies. These technologies were chosen because they are serious options to replace conventionally powered engines in the present market. Implementing one of these technologies will not drastically affect the voyage times, routes or cargo-carrying capacity of the ships. Most importantly, the fuel technologies are emission free during operation and have some emission during production. Upstream there can be GHG emissions in the process. The only solution that does emit GHG is Bio-fuel. It is assumed that it is balanced over the life-cycle. The 7 selected fuel technologies, and their machinery combinations are shown in Figures 2 and 3.

| Electric  | Hybrid Hydrogen  | Hydrogen Fuel Cell  | Hydrogen + ICE  | Ammonia Fuel Cell  | Ammonia + ICE  | Biofuel   |
|---|--|---|---|--|--|---|
| <ul style="list-style-type: none"> <li>• batteries</li> <li>• Electric motor</li> </ul> | <ul style="list-style-type: none"> <li>• Hydrogen storage</li> <li>• Batteries</li> <li>• Fuel Cell</li> <li>• Electric Motor</li> </ul> | <ul style="list-style-type: none"> <li>• Hydrogen storage</li> <li>• Fuel Cell</li> <li>• Electric Motor</li> </ul> | <ul style="list-style-type: none"> <li>• Hydrogen Storage</li> <li>• Emergency HFO tank</li> <li>• Dual fuel ICE</li> </ul> | <ul style="list-style-type: none"> <li>• Ammonia storage</li> <li>• Reformer</li> <li>• Fuel Cell</li> <li>• Electric Motor</li> </ul> | <ul style="list-style-type: none"> <li>• Ammonia Storage</li> <li>• Emergency HFO tank</li> <li>• Dual fuel ICE</li> </ul> | <ul style="list-style-type: none"> <li>• Biofuel tank</li> <li>• ICE</li> </ul> |

Figure 2: Zero-Emission Technologies (ZEV) and machinery combinations, (Lloyd's Register & UMAS, 2017)

| Bulk carrier   | Containership   | Tanker  | Cruise  | RoPax   |
|--|---|---|---|---|
| <ul style="list-style-type: none"> <li>• 53,000 dwt</li> </ul> | <ul style="list-style-type: none"> <li>• 9,000 TEU</li> </ul> | <ul style="list-style-type: none"> <li>• 110,000 dwt</li> </ul> | <ul style="list-style-type: none"> <li>• 3,000 dwt</li> </ul> | <ul style="list-style-type: none"> <li>• 2,250 dwt</li> </ul> |

Figure 3 Deadweight tonnage of different test ship examples, (Lloyd's Register & UMAS, 2017)

How the technologies and fuels are going to develop over time have a level of uncertainty, both in the CAPEX/OPEX as well as the performance of the technology and fuel. LR and UMAS sketched different scenario types for these uncertainties. Each scenario shows the 'greenest' fuel. As mentioned before, this does not mean it's the most preferred fuel, but the greenest fuel in the market. It should slightly be seen as an 'economic pathway' after carbon and oil economies. (Lloyd's Register & UMAS, 2017).

| Green Electricity  | Green Ammonia  | Green Hydrogen  |
|--|--|---|
| <ul style="list-style-type: none"> <li>•Electricity produced from renewable energy sources. Prices are high, emissions are low. Rapid development in batteries.</li> <li>•Cheap Hydrogen production, but high in emissions (fossil fuels)</li> <li>•Hybrid Ammonia production, from 'green' electricity and cheap hydrogen.</li> <li>•Biofuels available with no emission in production</li> </ul> | <ul style="list-style-type: none"> <li>•Electricity produced from cheap fossil fuels, mass production of batteries.</li> <li>•Ammonia produced with near-zero emissions, big scale availability in maritime industry.</li> <li>•Hybrid hydrogen production, mix of renewables and fossil fuels.</li> <li>•Biofuels available with no emission in production</li> </ul> | <ul style="list-style-type: none"> <li>•Hydrogen only produced from renewable sources, no emissions but high prices.</li> <li>•Fuel Cell technology developed and efficient. Improved hydrogen storage makes CAPEX drop.</li> <li>•Hybrid electricity, both from renewables as well as fossil fuels. battery technology developed and averagely priced.</li> <li>•Ammonia produced from mix of expensive 'green' hydrogen and cheap electricity. Mid-emissions and high costs.</li> </ul> |

**Figure 4 Economic pathways and their greenest fuels. Each scenario describes the greenest fuel and the technology standards in those scenario's.**

LR and UMAS have completed several sensitivity analysis for different kinds of parameters to check what the viability of each fuel technology under each scenario would be. It used a regular HFO mothership for each type of vessel and compared it to the new technology. For the viability analysis relative profitability, cost implications, range, carbon-price and implications of upstream emission have been taken into account. (Lloyd's Register & UMAS, 2017).

## 1.4.2 Relative Profitability

For the relative profitability of the ZEV-technologies for all ship types and scenario's, biofuel was in all cases the most profitable option. This is due to the fact that for the use of biofuels there are hardly any extra significant capital cost needed.

The second best option would be the ammonia + ICE, followed by ammonia and hydrogen fuel cell technology. This is the case for each scenario possibility. In general ammonia-based technologies are very competitive to biofuels, with the hydrogen technologies as a good runner-up

The relative profitability, as shown in the graph below, shows the relative profitability of a bulk carrier under 3 different scenario's and with 7 different technologies. The example of the bulk carrier is chosen as it is closest in DWT to a TSHD and are probably the most comparable of the sample ships. (Lloyd's Register & UMAS, 2017).

## Bulk carrier

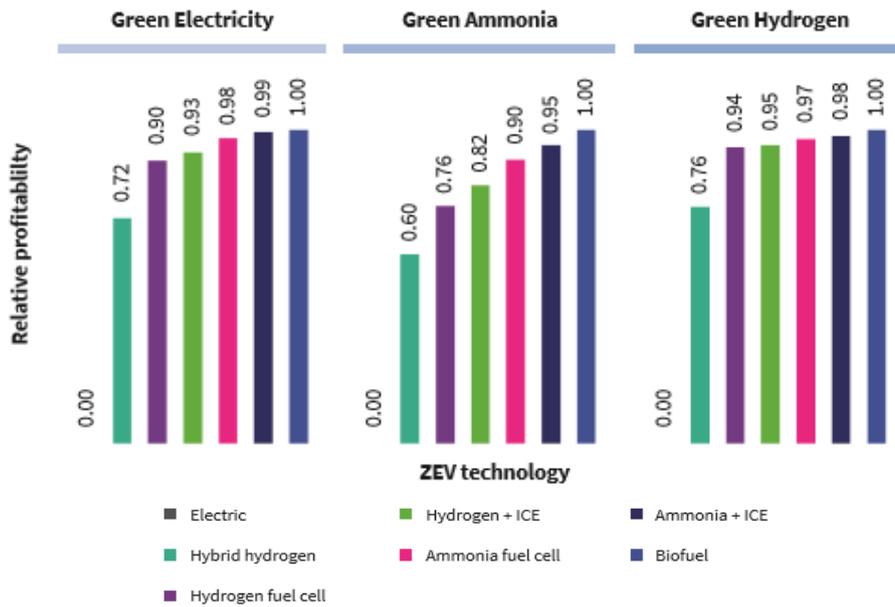


Figure 5 Bulk Carrier relative profitability under different scenario's, (Lloyd's Register & UMAS, 2017)

### 1.4.3 Cost of new technologies

An important part of the relative profitability is the development of the cost contributions of the fuel technologies for each ship. For the research to the cost implications LR and UMAS have considered different kinds of contributions. For this, Extra capital main machinery cost, extra capital storage cost, extra voyage cost and revenue lost have been taken into account. The installation of new technologies and the storage technologies can drive up cost. Besides that voyage cost can increase due to a higher price of the new fuel that has been installed, efficiency differences and technological developments. Furthermore, the volumetric density of the new fuel and technology can affect the cargo capacity, resulting in a loss in revenue. Below the breakdown of the cost contributions of the new technologies.

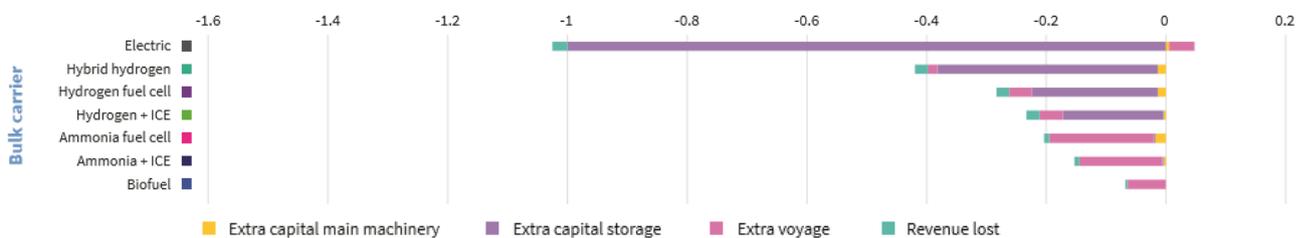


Figure 6 Relative cost of new technologies, (Lloyd's Register & UMAS, 2017)

The projected cost contributions are assumed under a green-ammonia scenario. Clearly the Electric technology will have the highest cost implications. Though, it is the only technology that has a positive effect on the voyage cost. This is due to the lack of need in HFO. The revenue loss is caused by the installation of batteries. This will take up a significant amount of space.

Biofuels are again the best performing. In this case only extra voyage cost will apply and a slight increase in revenue lost. The extra voyage cost are due to a higher fuel price than the conventional HFO. LR and UMAS state that there is a certain level in uncertainty about the Biofuel price, as it's heavily depending availability and sustainability of the product.

The difference in cost between Hydrogen and Ammonia is in voyage cost and extra capital cost. LR and UMAS state that Ammonia is most likely more expensive to produce whereas storing of pure Hydrogen is most likely more expensive and more complicated than Ammonia. Because of this the 2 product probably counterbalance each other. (Lloyd's Register & UMAS, 2017).

#### **1.4.4 Capital costs**

In the beginning of this chapter the boundary conditions were set for the best alternative ZEV technology. One of these conditions is that the newbuild capital cost of a ship should not increase with more than 10%. The figure below shows all the relative ZEV technology capital cost for newbuild ships with each type of technology under each of the scenario's. The Y-axis shows a logarithmic scale. It tells us again that the Electric technology is the least favorable. A capital cost increase between 1.100% - 10.000% under the 3 different scenarios can occur. Biofuel will see no difference in newbuild capital cost as there will hardly be any differences in the production of ships. Only minor tweaks might have to be done. The best alternative that falls within the 10% boundary, or close to it, will be the Ammonia ZEV solutions. This is the main reason for the focus on Ammonia ZEV solutions. This mainly holds for RoPax and Cruise ships and unfortunately not for the Bulk Carriers. Bulk carriers will most likely see an increase of capital cost around 30%-80%. (Lloyd's Register & UMAS, 2017).

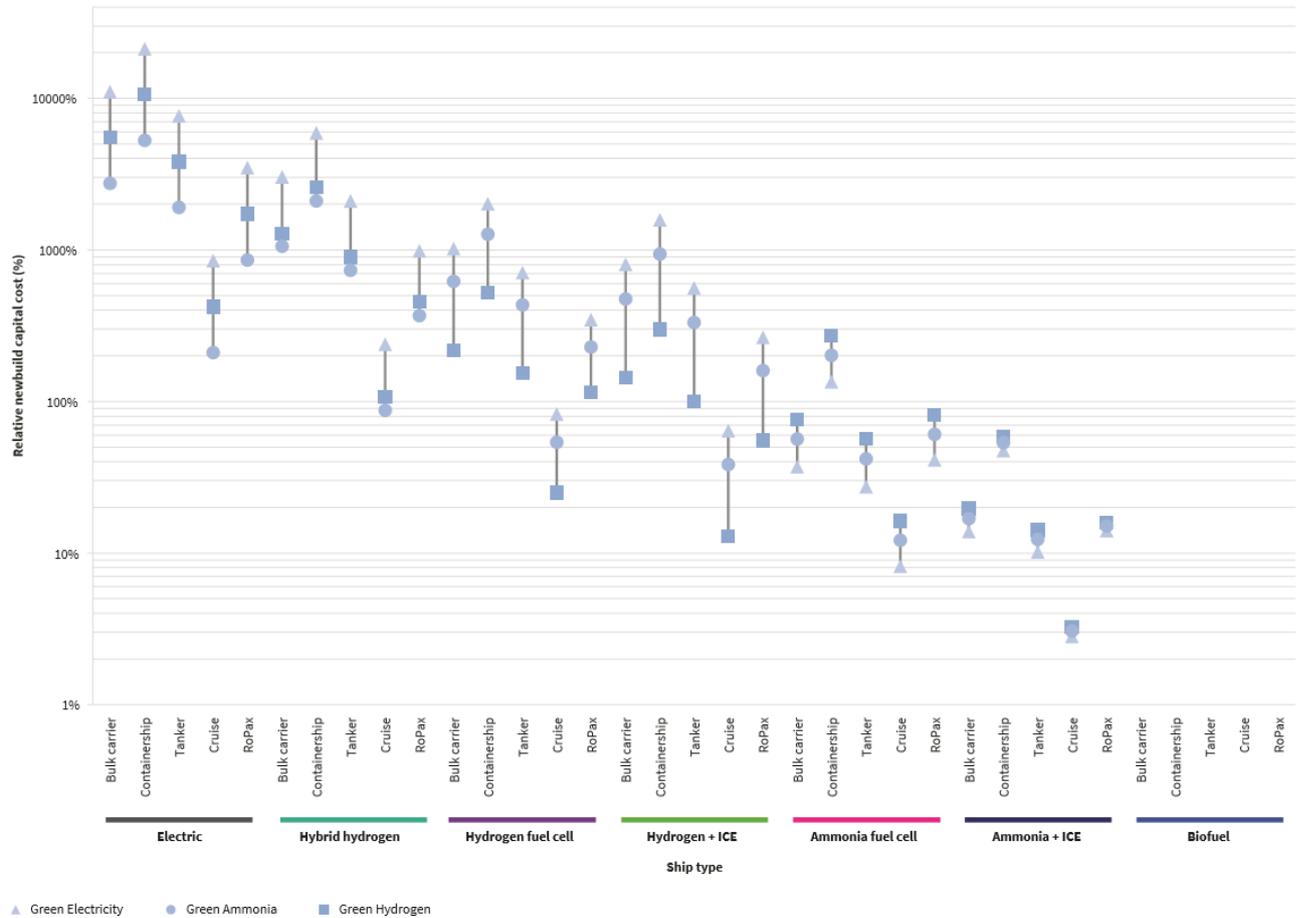


Figure 7 Relative ZEV technology capital costs for all ship types and scenario's, (Lloyd's Register & UMAS, 2017).

### 1.4.5 Conclusion on ZEV-technologies

Based on the research of LR and UMAS it is safe to say that both Hydrogen and Ammonia technology, with both FC's, can be suitable solutions. Apart from Biofuels, it scored fairly good in the research. Where Biofuels have more uncertainties about the future and sustainability of the product, the ammonia and hydrogen technology is less uncertain. The success of the products mostly depends on the 'economic pathway' society will follow. The decision to choose for an ammonia or hydrogen based solution for the TSHD finds its base in this research. As LR is one of the bench markers in the Maritime industry and is, like other classification organization as well, committed to state-of-the-art technology research and implementation, it is a trustworthy source and foundation for this thesis. The next couple of chapters will elaborate more about Hydrogen and Ammonia as a fuel

## 1.5 Hydrogen

Hydrogen (H), is the number one element in the periodic table. It is a substance that has no color, odor or taste and is flammable. The hydrogen atom itself consists of a single proton (H) that has one positively charged electron. With an atomic weight of 1.008, hydrogen is the lightest atom in the periodic table of elements and is the most abundant substance in the universe. Hydrogen forms covalent bonds with most nonmetallic elements, most of the hydrogen can thus be found in molecular forms, like water and organic structures. The first occurrence of artificial hydrogen found place in the 16<sup>th</sup> century. Henry Cavendish recognized the hydrogen atom. created water When hydrogen was burned, it. Hence the name Hydrogen. 'Hydro' meaning water and 'gen' from generation, water-former. (Brittanica - Hydrogen properties , 2018)

Hydrogen is one of the elements that has the most energy density value per mass. The energy density is approximately 142 MJ/kg. So for every kilogram of hydrogen there is an energy value of about 142 MJ. As mentioned before, hydrogen is highly flammable, if it occurs at regular temperature and pressure. This means it just needs a little bit of energy to burn. The products that are produced due to the burning of hydrogen are only heat and water. Which makes hydrogen look like an interesting fuel for the future. The only drawback of burning hydrogen in an internal combustion engine is the low efficiency of the fuel. The fuel cell technology, generating electricity, is much more efficient. Later in this study the fuel cell technology will be thoroughly explained. As mentioned before hydrogen does not occur naturally, it occurs in bonds. Therefore pure hydrogen has to be produced before it can be used. This process can be energy intensive and costly. These are interesting topics of improvements. Later in this study more about those topics. (Elert, 2018)

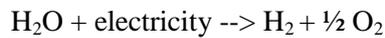
### 1.5.1 The Hydrogen Market

Hydrogen as a gas is at the moment already widely used in different kinds of industries. Last year, 2017, the hydrogen business was valued at \$115.25 billion and it is expected to grow approximately \$155 billion by the end of 2022. This is an increase of almost 35% in 5 years. Hydrogen is mostly used in the petrochemical and chemical industry. The petrochemical industry uses hydrogen for hydrocracking and desulphurization. In the chemical industry it is mainly used to produce fertilizers. Other industries entail the metal, methanol, electronics and food processing. The hydrogen market can be split up in two parts. The Captive and Merchant market. In the Captive market hydrogen doesn't leave the facility and the hydrogen is produced for internal use at factories, like the petrochemical industry. The merchant market is the opposite. Hydrogen is produced and transported to the customer or it is used to produce the consumer goods that are sold to customers. (Elert, 2018)

### 1.5.2 Production

To create free hydrogen atoms water electrolysis is needed. In the process of water electrolysis, water (H<sub>2</sub>O) is split into 2 atoms, Hydrogen and Oxygen. For this process a few things are needed. A body of water or substance (the electrolyte), 2 electrodes and an electricity source. The 2 electrodes are called the positively charged anode and the negatively charged cathode. The electrodes are generally made of

metal such as stainless steel, copper, platinum or iridium. By running an electrical current through the electrolyte, the water molecules will separate into Hydrogen and Oxygen. The Anode will attract the Oxygen atoms and the Cathode will attract the Hydrogen atoms. Hydrogen is formed. The chemical reaction is as follows. (Riis, Hagen, Vie, Ulleberg , & , 2006)



This is most common way of separating the H<sub>2</sub> atom from a molecule. There are many other different forms such as; Photo-electrolysis, Polymer Electrolyte Membrane, High-temperature electrolysis, Alkaline electrolysis etc. But for now let's stick to standard water electrolysis. As mentioned before, to split the molecules an electrical current is needed. The source of the electricity is rather important for the sustainability of the whole study. (Riis, Hagen, Vie, Ulleberg , & , 2006).

Hydrogen can be produced from many different kinds of sources. These can be fossil fuels and renewable sources. Fossil fuels include natural gas, coal and oil and the renewables include Solar, Wind, Tidal/Wave, Hydro, Geothermal etc. All of these technologies have different kinds of processes; electrolysis, biological, photovoltaic and (thermo)chemical. All these technologies and processes have many different kinds of characteristics, stages of development and learning-curves. (Riis, Hagen, Vie, Ulleberg , & , 2006).

The most common way of production at the moment is from fossil fuels. When hydrogen is formed from natural gas it can be done through 3 different processes. Steam reforming (SMR), Partial oxidation (POX) and Autothermal reforming (ATR). In the process of SMR methane and water vapor is combined with (waste) heat from a gas plant. The methane, water vapor and heat react and change into carbon monoxide and 3 hydrogen elements. (IEA, 2006)

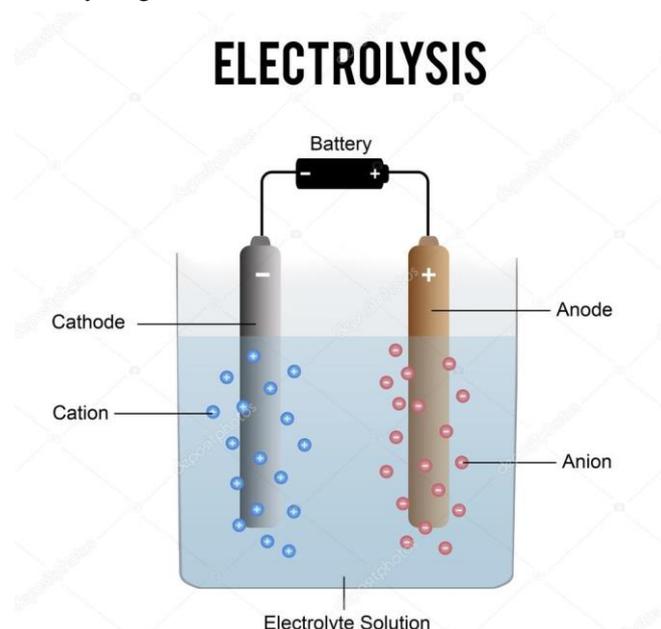
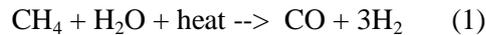


Figure 8 Hydrogen production through electrolysis, (Riis, Hagen, Vie, Ulleberg , & , 2006)



The left over carbon monoxide can be combined with water. Resulting in more hydrogen, excessive heat and carbon dioxide.



In the process of POX hydrogen is produced partly combusting the methane with oxygen .



The ATR process is a combination of both beforementioned processes. It's the latest stage and happens in very high temperature zones, around 1000°C, and with high pressure. It is basically again using the leftover CO to turn into useable H<sub>2</sub>. The 2 processes have some pro's and con's. SMR is generally higher in efficiency, lower in emissions and larger units cost less. On the other side, it is a more complex system. (Riis, Hagen, Vie, Ulleberg , & , 2006)

Hydrogen produced from coal is seen as a byproduct of making electricity from coal. The left over coal from the plant is used in combination with water vapor and waste heat to create carbon monoxide (CO) and Hydrogen (H<sub>2</sub>). This product is then again, as in (2), put back into the system to produce more H<sub>2</sub>. (Riis, Hagen, Vie, Ulleberg , & , 2006)

The processes described above are examples of 'grey hydrogen'. It is a process that produces 'clean' hydrogen, but at a cost. There's still CO<sub>2</sub> emitted into the atmosphere. The only advantages is that without the production of hydrogen, the CO<sub>2</sub> would have still been emitted.

'Blue hydrogen' is the next, cleaner, step of hydrogen production. Blue hydrogen can be produced from a variety of energy sources. The sources that power the production of hydrogen are both from renewables as well as from fossil fuels. In this process methane and CO<sub>2</sub> from CCS are combined with water vapor to produce hydrogen.

The last form of hydrogen is the 'Green Hydrogen' as the name already may reveal, hydrogen is in this case produced with, clean, renewable energy. The electricity from renewable sources like wind, solar, geothermal or other forms is used to power the electrolysis process. Electrolysis of water is the cleanest form of hydrogen production, if renewables are used. The source of the electricity for this process determines the 'cleanliness' of hydrogen production. With electrolysis water (H<sub>2</sub>O) is split into Hydrogen (H<sub>2</sub>) and Oxygen (O). (Riis, Hagen, Vie, Ulleberg , & , 2006)

### 1.5.3 Hydrogen Storage

The storage of hydrogen is not in particular an easy process. There are different possibilities to store hydrogen. Hydrogen can be stored in different states, liquid, vapor or solid. The biggest challenge is the material hydrogen is stored in. The 4 most common forms will be explained. These forms entail high pressure gas cylinders, liquid hydrogen, physisorption and metal hydrides.

Important in storage of hydrogen is that one wants to have the lowest volume of hydrogen with the most energy stored. This should be done with the least materials possible, to keep the cost of storage as low as possible. To store hydrogen as efficient as possible it needs the best volumetric density. To reach this point either the gas needs to be compressed, temperature decreased or hydrogen needs to

react with the right material. (Züttel, 2003).

Furthermore it is important that once the hydrogen is captured and stored, it is also possible to easily release the hydrogen from the system. So the storage material has to interact with hydrogen but also should not chemically react with hydrogen. It needs to be an inert material.

As mentioned before hydrogen reacts in different ways when temperatures and pressures are higher and lower. Hydrogen will change phase when these factors change. Looking at the pressure diagram in Figure 9 one can see how Hydrogen will change phase at different temperature and pressure levels. (Züttel, 2003).

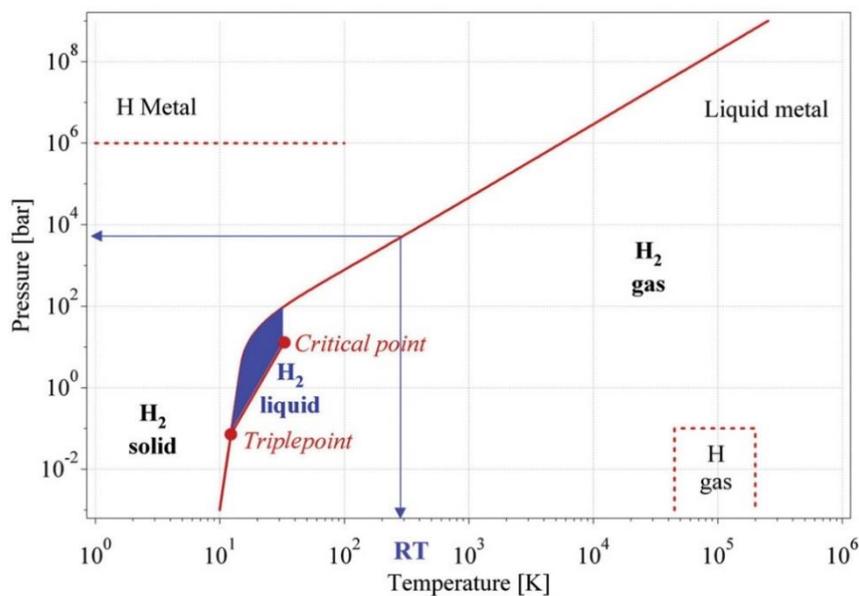


Figure 9 Pressure diagram Hydrogen , (Züttel, 2003).

### 1.5.3.1 High Pressure Gas cylinders

High pressure gas cylinders are the most common way of storing hydrogen gas. It depends on the tensile strength of the material that is being used for the cylinder how much Hydrogen gas can be stored in the cylinder. For the ideal way of storing hydrogen in high pressure gas cylinders the cylinder needs a very high tensile strength, low density and the material should not react with the hydrogen. High pressure gas cylinders that are being used at the moment have operate under a pressure of 700 bar at room temperature. The volumetric density is less than 40 kg H<sub>2</sub> m<sup>3</sup> and has a gravimetric density of 13% ρ<sub>m</sub>. These numbers describe also the drawbacks. The gas cylinders operate under very high pressure with a relatively low volumetric density. (Züttel, 2003)

### 1.5.3.2 Liquid Hydrogen Storage

Storing hydrogen in a liquid form needs a cryogenic process. Hydrogen is stored in tanks at -252°C under 1 atm. Critical point of liquid hydrogen is at -240°C and 13 bar. To liquefy the gas it needs to be compressed, after that it will be cooled in a heat exchanger. After these two steps the hydrogen goes

through a throttle valve. In the valve isenthalpic Joule-Thomson expansion takes place producing liquid. This is the process of actually putting pressure on the gas, turning it into liquid. The process of Liquid Hydrogen Storage is a very energy demanding process. Therefore it can only be used for applications that do not worry about high hydrogen cost, for example in space. The theoretical gravimetric density of LH<sub>2</sub> is 100%, but only 20 wt.% H<sub>2</sub> is practically possible. Volumetrically seen hydrogen has values that are in between 30 and 80 kg/m<sup>3</sup>. In this case, at -252°C the density is 70.8 kg/m<sup>3</sup>. These numbers show better energy densities than in a gaseous form. The only drawback is that 30-40% of the energy is lost in the process. (Züttel, 2003)

### 1.5.3.3 Physisorption

Physisorption of hydrogen happens through the physical bonding of the hydrogen gas molecules to the surface of a substance. This can be either a solid or a liquid. It occurs at very low temperatures under the Van Der Waals force. The Van Der Waals force defines the attraction and interactions of intermolecular forces between molecules and atoms. (Unknown , 2018)

All the interacted molecular bonds together form a film or monolayer on that solid or liquid. To calculate the quantity of adsorbed hydrogen in the monolayer, it is essential to know the density of the liquid adsorbate and the molecule volume. The more hydrogen that can be adsorbed on a surface, the higher the energy density and thus the better the performance is. The amount that is adsorbed depends on the specific surface area of the solid or liquid. Andreas Züttel's article "*Materials for Hydrogen storage*" points out nanostructured carbon as the most suitable adsorbent for hydrogen. Züttel states: "*The amount of adsorbed hydrogen from the gas phase at 77 K and electrochemically at RT is  $1.5 \times 10^3 \text{ mass}\% \text{m}^{-2} \text{g}^{-1}$ . Together with the maximum specific surface area of carbon ( $1315 \text{ m}^2 \text{g}^{-1}$ ) the maximum absorption capacity of the nanostructured material is 2 mass%*". Furthermore, the article mentions the advantages and drawbacks of physisorption. The low operating pressure, the relatively low costs and the easy construction of the storage system are the main advantages. Nevertheless, this system has a low gravimetric and low volumetric density. Next to that the operating temperatures low as well. (Züttel, 2003)

### 1.5.3.4 Metal Hydrides

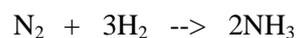
Metal hydrides are metals that have a bond with hydrogen. When metal hydrides are formed, the hydrogen molecule is split and its atoms will fill in the gaps in metals and alloys that are suited for this. The density of hydrogen in the stored metals is comparable to the liquid hydrogen storage method. Adding the mass of the metal into the equation gives a gravimetric density that is more comparable with the high pressure gas cylinders. (Züttel, 2003)

## 1.6 Ammonia

Ammonia is a gas that has no color and has a rather pungent smell. The molecule consists of 1 Nitrogen and 3 Hydrogen atoms. This makes Ammonia a Hydrogen carrier. It is a simple and stable combination and is used in lots of nitrogen based products. The majority of Ammonia is used as a fertilizer, it is also used for explosives and in the textile industry, to manufacture nylon, cotton or wool. Furthermore Ammonia is used in the petroleum refining, as it cancels out acidity in by-products. Most interesting for this research, as Ammonia can easily be broken down to use the hydrogen atoms, it can be easily used as a product in sectors where a lot of hydrogen is needed. (Brittanica , 2018).

### 1.6.1 Ammonia production

Ammonia is produced by directly reacting hydrogen with nitrogen. This process is called the Haber-Bosch process and is as follows



In the Haber-Bosch process Ammonia is formed by combining Hydrogen and Nitrogen and bringing them under high pressure and moderate temperatures together in a reactor. The pressure in this process is around 100 – 1000 atmosphere and the temperatures reach around 400°C – 550°C. In this reactor there's often iron as a catalyst to help the process of Ammonia forming. In other cases this could be either magnesium or aluminium oxide. As mentioned before, Ammonia is colourless and has a sharp penetrating smell. The boiling point of Ammonia is -33.35°C and freezing point is -77.7°C. To vaporize Ammonia 23.3Kj per mole are needed. The molecular weight of Ammonia is 17.031 g/mol. Ammonia in a gaseous state has a density of 0.86kg/m<sup>3</sup>, this is under a pressure of 1.013 bar at boiling point. In a liquid state the density of Ammonia is 681.9 kg/m<sup>3</sup> at -33.3°C (boiling point under pressure). (Brittanica , 2018).

Ammonia can be a hazardous product. The Global Hazardous System (GHS) pictograms display ammonia as a corrosive, toxic and an environmental hazard. The NFPA indication of Ammonia indicates a score of 3 for health, 1 for flammability and 0 for instability/reactivity and no special hazards. This means that for human health short exposure could cause serious temporary or moderate residual injury. For flammability Ammonia is in the category for materials that require considerable preheating, under all ambient temperature conditions, before ignition and combustion can occur. Flashpoint of these materials are at or above 93.3°C. (National Fire Protection Association , 2018).

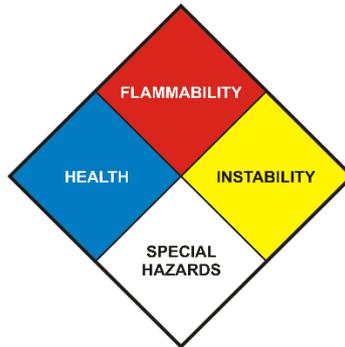


Figure 10 Global Hazardous System pictogram, (National Fire Protection Association , 2018)

## 1.6.2 Ammonia costs

As mentioned in the previous chapter, ammonia is made from both hydrogen and nitrogen. Therefore the cost price of ammonia is directly affected by the production cost of hydrogen. Producing hydrogen, via for example electrolysis, will include electricity costs and the partly CAPEX cost from the plant. In 2008, J.P. Bartels wrote in his paper on the ammonia economy about the cost of ammonia. It is described that the price all depends on demand/supply, electricity cost, transportation and storage. This 2008 paper, calculated that the production cost for hydrogen is around 3.00 \$/kg H<sub>2</sub> and for ammonia it would be around 3.80 \$/kg H<sub>2</sub>. This is due to the additional costs to produce ammonia. For pipeline transportation costs, the paper uses a fee of 1.87 \$/kg H<sub>2</sub> and 0.19 \$/kg H<sub>2</sub> for Hydrogen and Ammonia respectively. So far there's only a slight difference in price for Hydrogen and Ammonia. The big difference occurs when the aspect of storage comes into play. For the storage of hydrogen a price has been calculated for a 15-day storage and a 182-day storage. This is for hydrogen 15-day 1.97 \$/kg H<sub>2</sub> and for 182-days 14.95 \$/kg H<sub>2</sub>. (Bartels, 2008).

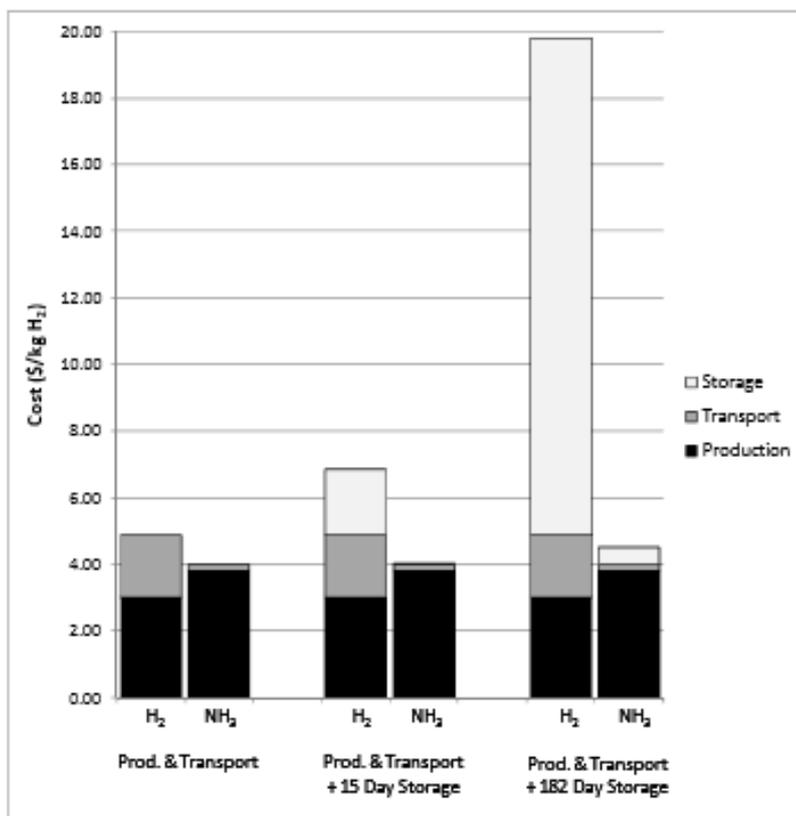


Figure 11 total cost of hydrogen and ammonia production, storage and transport (Bartels, 2008)

It has to be taken into account that these estimates are based on figures published in 2008. As Bartels already mentions in his research, is that due to development of technologies and demand/supply changes the price can be effect. Throughout the last 10-years there have been fluctuations on the price of hydrogen and ammonia. The prices have been fluctuating between the 300 \$/mt – 650 \$/mt for both ammonia and hydrogen. It is not clear what the current price for ammonia is from the resources that have been used for this literature review. The USGS reports a price of \$240 per tonne average for 2017. (Bartels, 2008). The varying prices of Ammonia are mainly caused by different price structures that are being maintained. For example the source of energy is very determinative. For this research it is important that the production of Ammonia, through electrolysis and the Haber-Bosch process, is as clean as possible. In the US government article, *'Ammonia fuel, opportunities, Markets and Issues'*, it is stated that a tonne of Carbon-free Ammonia has the potential of \$400 per tonne, produced with technologies that are currently in development. For this research this \$400/tonne will be used as a reference Ammonia price. (Wittrig, 2018).

### 1.6.3 Properties comparison Hydrogen vs Ammonia

When comparing the difference of Hydrogen and Ammonia, see Table 2 Properties of Hydrogen and Ammonia, one can see that there is a significant difference between the properties for the storing of both. Looking at the Energy Densities, one can conclude that hydrogen has a significant higher capability of storing energy per kg. This is even 3 times as high as the conventional hydrocarbons being used in the Maritime industry. The volumetric density of Ammonia itself is on the other hand higher than for hydrogen. In this case of volumetric density, Ammonia has more energy per m<sup>3</sup>. The biggest significance and advantage of Ammonia compared to Hydrogen lies in the storing conditions. When storing pure hydrogen, either a very high pressure or very low temperature needs to be maintained. This being 700 bar or -253°C respectively. These conditions make the Ammonia storing preferable over pure Hydrogen as energy will be lost in the process of storing. The lower storage temperatures and storage pressure make Ammonia easier to handle and less dangerous than pure Hydrogen.

|                      | Energy Density LHV [MJ/kg] | Volumetric density LHV [GJ/m3] | Renewable Synthetic Production Cost [MJ/MJ] | Storage Pressure [bar] | Storage temperature |
|----------------------|----------------------------|--------------------------------|---|------------------------|---------------------|
| Marine Gas Oil (ref) | 42.8                       | 36.6                           | Not appl.                                   | 1                      | 20                  |
| Ammonia (l)          | 18.6                       | 12.7                           | 1.8   | 1-10                   | -34 - 20            |
| Hydrogen (g)         | 120                        | 7.5                            | 1.8   | 700                    | 20                  |
| Hydrogen (l)         | 120                        | 8.5                            | 1.7   | 1                      | -253                |

Table 2 Properties of Hydrogen and Ammonia (Niels de Vries, 2018)

### 1.7 Fuel Cells

Now that Ammonia as a hydrogen carrier and fuel is determined a fuel cell that works with this fuel needs to be selected. At the moment there are several types of fuel cells in the maritime sector that are being tested for its viability and technical possibility. In general all the fuel cells work with either pure hydrogen or a fuel that is rich in hydrogen, this in combination with oxygen. This is to trigger a electrochemical reaction. So each Fuel Cell has its own characteristics and its own electrochemical reaction depending on the used fuel. In this chapter there will be a brief explanation of different kinds of fuel cells and which one is most suitable. Fuel cells can be classified in different kinds of ways. They can be either classified by the type of electrolyte that is used or by the temperatures they operate

at. (De-Troya, Álvarez, Fernández-Garrido, & Carral , 2016).

## 1.7.1 Fuel Cell types

Classification done by electrolyte is as follows:

- AFC                      Alkaline Fuel Cell
- PEMFCA                Proton Exchange Membrane
- DMFC                   Direct Methanol Fuel Cell
- PAFC                    Phosphoric Acid Fuel Cell
- MCFC                   Molten Carbonate Fuel Cell
- SOFC                    Solid Oxide Fuel cell

Or it could be done by temperature

- Low T                      FC's that work at approximately 80°C: AFC, PEMFC, DMFC
- Intermediate T            FC's that work at approximately 200°C: PAFC
- High T                      FC's that work at approximately 650°C - 1000°C: MCFC, SOFC

### 1.7.1.1 Alkaline Fuel Cell (AFC)

The Alkaline fuel cell operates in a low temperature zone, this is around 60°C - 100°C. The electrolyte that is used for this fuel cell is a Potassium Hydroxide (KOH) which is a watery dissolute. The electrolyte has a concentration of around 30%-35% KOH in weight. The biggest drawbacks of the AFC is that the electrolyte will react to CO<sub>2</sub> that could be in the Hydrogen or Oxygen that is taken into the system. It is common that the Oxygen taken in also contains CO<sub>2</sub>, as the air we take in is never pure. Same holds for Hydrogen. In the process of forming Hydrogen gas for electricity generation it could be that there is CO<sub>2</sub> left. The cell or electrolyte cannot handle concentrations of more than 50 PPM. The sensitivity to CO<sub>2</sub> makes it unsuitable for implementation in cars, but instead it is used in space programs. (De-Troya, Álvarez, Fernández-Garrido, & Carral , 2016). The fuel for the AFC is H<sub>2</sub> and O<sub>2</sub> and the ions that are transported through the KOH electrolyte are hydroxyl ions (OH<sup>-</sup>). Benefits of the AFC are the relatively low cost of the cell and catalysts, safety-wise the low temperature is a benefit. The AFC does not have any emissions other than water and cold starts with the cell are possible. Efficiency of the AFC is average compared to the other fuel cells with a efficiency percentage of 50-60%. (Tronstad, Haugom, Langfeldt , Astrand, & , 2017)

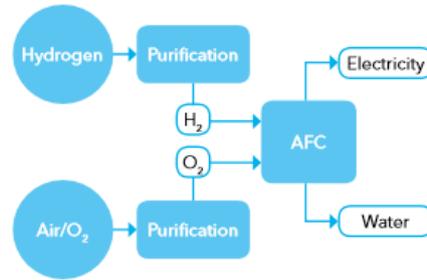
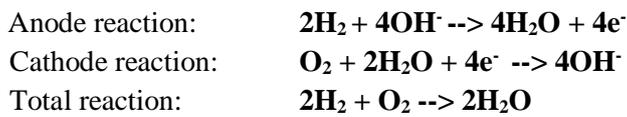


Figure 12 flowchart AFC, (Tronstad, Haugom, Langfeldt , Astrand, & , 2017)



### 1.7.1.2 Proton Exchange Membrane Fuel Cell (PEM)

The Proton Exchange Membrane Fuel Cell (PEMFC) is a cell that has an electrolyte that is constructed of polymers. These polymers are a combination of acidic structures with sulphonic groups and is a semi-permeable membrane.  $\text{H}^+$ -ions can be transported through a membrane, the electrons will be transported through an alternative route to create electrical current. The PEMFC operates on fairly low temperature ranges,  $60^\circ\text{C}$ - $100^\circ\text{C}$ . (Tronstad, Haugom, Langfeldt , Astrand, & , 2017) .

This temperature is a slight drawback of the cell. Because it operates at these temperatures, it is harder to perform the electrochemical reactions. Therefore, a electrocatalyst is needed. This is built in the cell in the form of platinum or ruthenium. The use of these metals will drive up the production cost of the cell. The positive side of the low operation temperatures is that the PEMFC starts up rapidly. Furthermore the PEMFC in general is very suitable for transportation and commercial operations. It has zero-emissions, high-power density and is quickly started up. The power density of the PEMFC is fairly high,  $100$ - $1000\text{W/kg}$ . This makes the cell useable for transportation. The efficiency is around  $50$ - $60\%$ , like the AFC also average. (Tronstad, Haugom, Langfeldt , Astrand, & , 2017).

The drawback of this cell is that it is very sensitive to fuel impurities. CO can damage the platinum electrocatalyst. The hydrogen that's being used needs to be purified before being used in the PEMFC. If another fuel than hydrogen is used, for example hydrocarbons, the fuel needs to be steam reformed before use. In this way it still emits  $\text{CO}_2$  in the process. (De-Troya, Álvarez, Fernández-Garrido, & Carral , 2016) (Tronstad, Haugom, Langfeldt , Astrand, & , 2017).

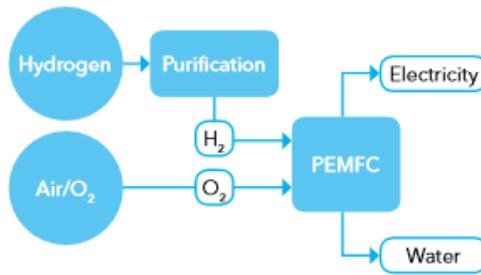
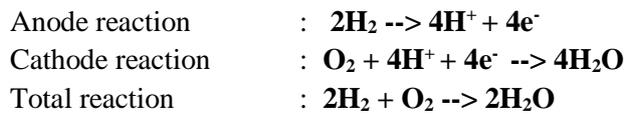


Figure 13 flowchart PEMFC, (Tronstad, Haugom, Langfeldt , Astrand, & , 2017)



### 1.7.1.3 Direct Methanol Fuel Cell (DMFC)

The DMFC cell is a different version of the PEMFC cell. In this cell the used fuel is Methanol. It operates at the lower temperature ranges, 50-120°C, and has a low efficiency (20%). Instead of the injection of hydrogen, methanol is injected into the system. The methanol reacts with oxygen, resulting in carbon dioxide and water as a residue. This is the drawback of the DMFC. It will still emit CO<sub>2</sub>. Another drawback of the DMFC is that, because of the low operating temperatures, there is a lot of platinum needed to function as a electrocatalyst. This will drive up the costs of the cell. (De-Troya, Álvarez, Fernández-Garrido, & Carral , 2016) (Tronstad, Haugom, Langfeldt , Astrand, & , 2017).

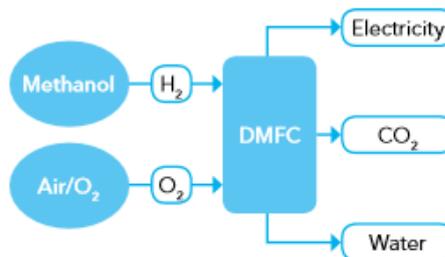
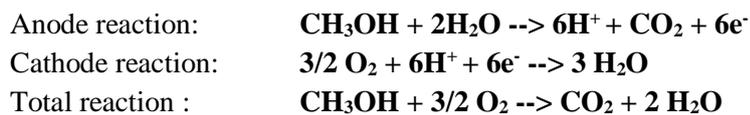


Figure 14 flowchart DMFC, (Tronstad, Haugom, Langfeldt , Astrand, & , 2017)



### 1.7.1.4 Phosphoric Acid Fuel Cell (PAFC)

The PAFC is the oldest and most well developed type of fuel cell, operates in the mid-temperature ranges, this is around 150°C - 200°C. The cell operates like a standard membrane cell, but instead of having a membrane as an electrolyte it has an acid that operates as an electrolyte. The big advantage of having an acid instead of a membrane is that the acid does not react with CO<sub>2</sub>. This will result in diminishing costs for purification of air and the hydrogen production. The PAFC works the same as the PEMFC, the only difference is that the PEMFC needs pure hydrogen. Furthermore, this cell will also need the expensive platinum. (De-Troya, Álvarez, Fernández-Garrido, & Carral , 2016). The higher temperatures in the PAFC, compared to the PEMFC and AFC, make the excess heat from the FC useful for utilisation. Without the waste heat recovery the efficiency of the PAFC is around 40%, adding waste heat recovery the efficiency can be increased to 80%. A drawback of the PAFC is the fairly low power density. This will result in a system that is rather large and heavy. Operating at a higher temperature will cause the system to start up slower than the PEMFC and AFC. (Tronstad, Haugom, Langfeldt , Astrand, & , 2017).

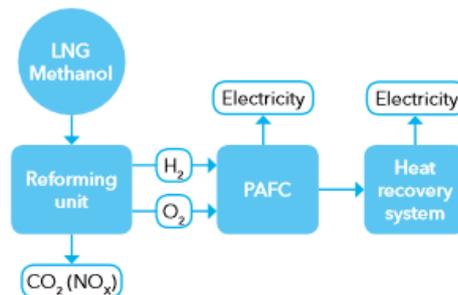
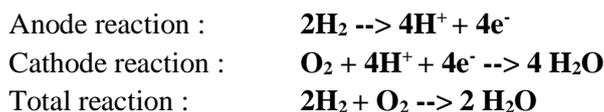


Figure 15 Flowchart PAFC, (Tronstad, Haugom, Langfeldt , Astrand, & , 2017)



### 1.7.1.5 Molten Carbonates Fuel Cell (MCFC)

The MCFC is an example of a cell that operates at very high temperatures. The operating temperatures will be around 600°C - 700°C. With these high temperatures the electrolyte will be more conductive and operate more efficiently. In this cell there won't be any platinum needed to act as an electrocatalyst. Instead the electrolyte that is used is a molten carbonate salt. Normally the anode consists of a nickel alloy and the cathode is a nickel oxide. (De-Troya, Álvarez, Fernández-Garrido, & Carral , 2016) . Because this cell operates at such a high temperature, it is hardly vulnerable to different kinds of fuels. The high temperatures makes it possible to eliminate a fuel to hydrogen reformer, instead the reforming process occurs within the fuel cell, hence the fuel flexibility. It should be kept in mind that using a carbon-based fuel

will result in carbon-based emissions. Another advantage is the lack of air at the anode-side. This means there won't be NO<sub>x</sub> emissions. Same as with the PAFC, the MCFC can have a waste-heat-recovery system. With the emissions from hydrocarbon based or methanol fuels either gas or steam turbines can be used for extra efficiency. This can make the MCFC efficient from 50 – 85%, but only with the use of these GHG-emitting fuels. (Tronstad, Haugom, Langfeldt , Astrand, & , 2017) Another benefit of the MCFC, other than its efficiency, is the low price of the catalyst. Drawbacks are the vulnerability to cycling and slow start-up time. (Tronstad, Haugom, Langfeldt , Astrand, & , 2017).

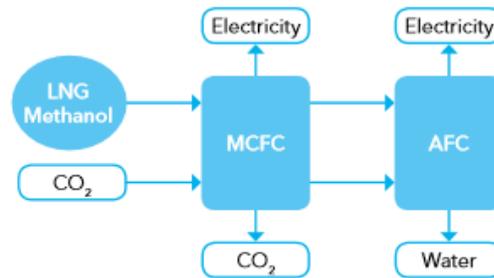
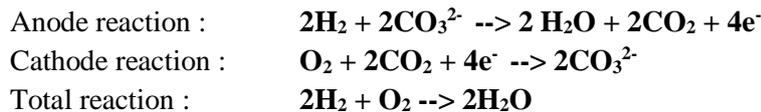


Figure 16 Flowchart MCFC, (Tronstad, Haugom, Langfeldt , Astrand, & , 2017)



### 1.7.1.6 Solid Oxide Fuel Cell (SOFC)

This is the fuel cell with the highest operational temperatures, around 600°C - 1000°C. The electrolyte in this fuel cell is a porous ceramic material. The most common for the SOFC electrolyte is yttrium-stabilized zirconia. The anode material is equal to the ones of the MCFC, nickel alloy, for the cathode lanthanum strontium manganite. (Tronstad, Haugom, Langfeldt , Astrand, & , 2017). The high operational temperatures of the SOFC make it a perfect application for generating on a bigger scale. On-shore installations have proven to easily generate 10MW. In the maritime sector the SOFC hasn't been used as much as on-shore. Module power levels in ships have been made for a capacity up to 60kW. (Tronstad, Haugom, Langfeldt , Astrand, & , 2017) . The SOFC is fuel flexible, it can use pure hydrogen and also carbon-based fuels, same as the MCFC. And equal to the MCFC, the SOFC does not need reformers. High operational temperatures make it possible to internally reform fuels. The cell has a very high efficiency, about 60%. In combination with a gas turbine or waste heat recovery, this number can grow up to 85% efficiency. But the cell has some drawbacks as well. The high operating temperatures cause the start-up procedure to be very long. Besides that the costs will be rather high and corrosion appears at these levels. The biggest advantage of the SOFC compared to the MCFC, is that the cell does not need CO<sub>2</sub> at the cathode side, hence hydrogen is a very suitable fuel for the SOFC. The MCFC and the SOFC are fairly vulnerable to cycling. This means that large differences in energy demands will deteriorate the fuel cell quicker. Preferably both cells want to operate at stable levels. These fuel cells a very

suitable to use in combination with batteries for energy storage. In this way it is possible to lower the thermal strain on the cells. By using batteries it is possible to apply peak shaving. At lower energy demand levels, batteries can be charged. When the energy demand exceeds the operational level, batteries can fill the energy demand gaps. (De-Troya, Álvarez, Fernández-Garrido, & Carral, 2016). (Tronstad, Haugom, Langfeldt, Astrand, & , 2017).

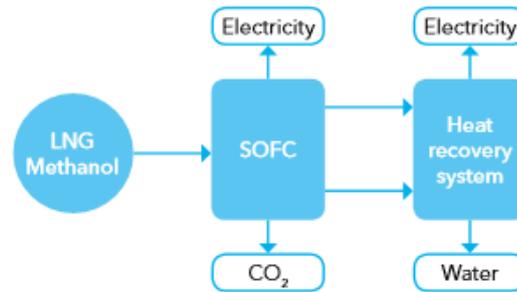


Figure 17 Flowchart SOFC, (Tronstad, Haugom, Langfeldt, Astrand, & , 2017)

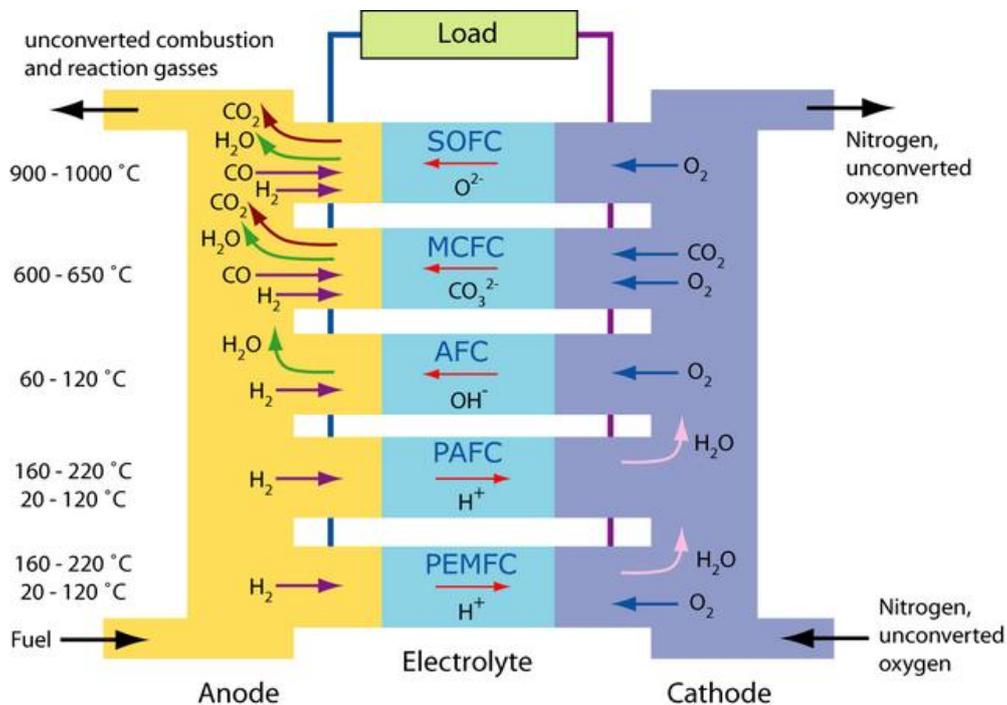


Figure 18 diagram of fuel cell operation, (DoITPoMS, 2018)

The schedule above show the electrochemical reactions of the different fuel cells. From the Anode side the fuel is injected to the system. In most cases this is (pure) hydrogen. In some cases there are

hydrocarbons or carbon monoxides involved. The cathode side has Nitrogen and unconverted Oxygen injected. The electrolyte part show the transported ion. Through the load flow electrons that create the electrical load. (DoITPoMS, 2018).

## **1.7.2 Fuel Cell selection**

In the Appendix 10 a summary of the different fuel cell technologies is published. This is to easily see all the different aspects of the fuel cells and with this summary it can be determined what fuel cell would suit the TSHD the best, in combination with the previously selected fuel. The summary shows different important aspects of the fuel cells. There's been looked at relative costs, modular power levels, lifetime, tolerance for cycling, fuel, maturity, size, sensitivity to fuel impurities, emissions, safety aspects and efficiency. Some of the factors are more important to Van Oord than other aspects.

Looking at the goals for Van Oord and the maritime industry, the most important aspects would be emissions, fuel, sensitivity to fuels, power levels and the efficiency. These aspects (in)directly link to each other. Obviously the other aspects are important as well, but these aspects will most likely improve more easily over time. It is less likely that the fuel sources of the fuel cells will change over time. The quality of the cell is more likely to improve.

For this thesis it is decided that the Solid Oxide Fuel Cell (SOFC) is most likely the best option. This is due to different aspects. First of all the SOFC, like the MCFC, has the best performing output levels. On-shore capacity already match or exceeded the 10MW boundary. (Tronstad, Haugom, Langfeldt, Astrand, & , 2017). This is a promising outlook for the offshore use of this technology. Next to that is the fuel options. Besides that, due to high operational temperatures, the sensitivity to fuel impurities is low, it is possible to apply different kinds of fuels to the fuel cell. Depending on the fuel input, there will or will not be any emissions. The biggest benefit is that Ammonia can directly be injected into the fuel cell. There is no need for an Ammonia reformer, therefore there is less efficiency loss of the fuel. The high efficiency of the cell is also of great importance. Low efficiencies can cause the autonomy of the ships to deplete too much, as refueling would have to happen more regularly.

Obviously there are also question marks or drawbacks. The SOFC is fairly expensive and scores medium on the size of the fuel cell. Also the maturity and lifetime of the fuel cell score moderately. Time and technology development should cause these drawbacks to improve overtime.

# Chapter 2 The Analysis

## 2.1 The Trailing Suction Hopper Dredger

Trailing suction hopper dredgers are vessels that are used for excavation and transportation of materials from the sea floor. This can be sand, clay, gravel or silt. TSHD's are used in various regions of the world, exploiting various projects. This varies from water defense constructions for countries that struggle with rising sea levels, to land reclamation, deepening of channels or creating new beaches. TSHD's consist of a few different components. The trailing suction installation excavates the materials from the sea floor, the dredge pumps accommodate the hydraulic transportation and the hopper is the storage compartment during transportation. After the material is dredged the residual seawater is drained back into the sea. On arrival the TSHD can unload in 4 different kinds of ways. This can be done by opening the hatches in the hull and dropping the material on the seafloor. Another way to drop the sand on the seafloor is by returning the material through the suction pipes. For this process the material needs to be liquified again. The other 2 ways of unloading can be done over the bow of the ship. In this case the material needs to be liquified as well. Through a hose attached to the bow the material can be transported to the exclamation site and sprayed on the new land. The other method is called 'rainbowing', in this case the material is sprayed from the bow into the air and water. After demarcating the fuel and fuel cell, it is needed to determine a suitable ship for the research. At the moment Van Oord is already working on LNG-powered TSHD's. LNG-powered ships already emit significantly less GHG's and are a logical step in the process to Zero-Emission ships. The infrastructure on board is already focused on electricity generation for propulsion and auxiliary components. Next to that, most of the ships in the Van Oord are Diesel-Electric ships. Meaning that the diesel engines generate electricity for the power consumers in the ship. These kinds of ships are also suitable for a retrofit.

In consultation with Van Oord Supervisor J. Tilman it is determined that the HAM 318 is the most suitable TSHD in the Van Oord fleet. The Ham 318 is a Diesel-Electric TSHD that will most likely be retrofitted within the next 5 to 10 years.

### HAM318

The HAM 318 is a 2001 built TSHD from building yard Van Der Giessen-de Noord B.V. in Krimpen aan den IJssel (NL). The ship has been designed by Royal IHC. The HAM 318 sails under the Dutch flag and has Rotterdam as its Port of Registry. (Van Oord , 2014)



Figure 19 HAM 318 in operation at Maldives reclamation zone, (Van Oord , 2018)

## 2.1.1 Dimensions

The HAM 318 has an overall length of 227,20 meters, overall breadth of 32 meters and a moulded depth of 17 meters. From keel to top the HAM 318 reaches almost to 50 meters. The lightweight of the HAM 318 is 22.554 tons. This is the weight of the ship without anything on board. So no fuel, no passengers, no dredged material, totally empty. The Displacement of the ship weighs almost 84 tons. Quick calculation gives us a 61 tons of potential load. (Van Oord , 2014)

The HAM 318 has a Hopper volume of 39,467 m<sup>3</sup> and can dredge up to a maximum depth of 135 meters. The Trailing suction pipes have a diameter of 1.2 meters, the discharging pipes have a diameter of 1.1 meters. The sailing speed of the HAM 318 is loaded 15.5 knots and unloaded 16.5 knots. (Van Oord , 2014)

## 2.1.2 Installed Power

### 2.1.2.1 Diesel

The HAM 318 is equipped with 2x Wärtsilä 12V46C engines, with a rated power of 12,600 kW each. The Auxiliary generator engine is a Wärtsilä 6L26 A, rated on 1950 kW. The Harbour generator engine is a Caterpillar 3512 B, rated on 1257 kW. The Emergency generator engine is a Caterpillar 3406 C, rated at 229 kW. This brings the Total Installed Diesel Power to 28,636 kW. (Van Oord , 2014).

### 2.1.2.2 Dredge Pumps

The HAM 318 has 4 dredge pumps. The inboard DP, Shore DP, Underwater DP and Jet pumps. The inboard DP's are rated at 2x 2759 kW. The Shore DP are rated at 2x 5500 kW. The Underwater DP's are rated at 2x 2500 kW and the Jet pumps are rated at 2x 2150 kW. (Van Oord , 2014)

#### Propulsion

For the propulsion of the ship the HAM 318 has regular propulsion and bow thrusters. The Propulsion power in free sailing mode is rated at 25,200 kW and in Dredging mode this is brought down to 6500 kW. For positioning the bow thrusters are also being used. The bow thrusters are 2x 1500 kW and 1x bowjet of 2250 kW (Van Oord , 2014).

Further specifications of the HAM 318 can be found in the HAM 318 leaflet, which is added to the Appendix [xxx]. Below a sideview blueprint of the HAM 318 can be found. The picture shows the main power consumers of the ship.

1. Main engines PS/SB
2. Propulsion
3. Underwater Dredge Pumps
4. Inboard Dredge Pumps
5. Bow thrusters
6. Jet pumps

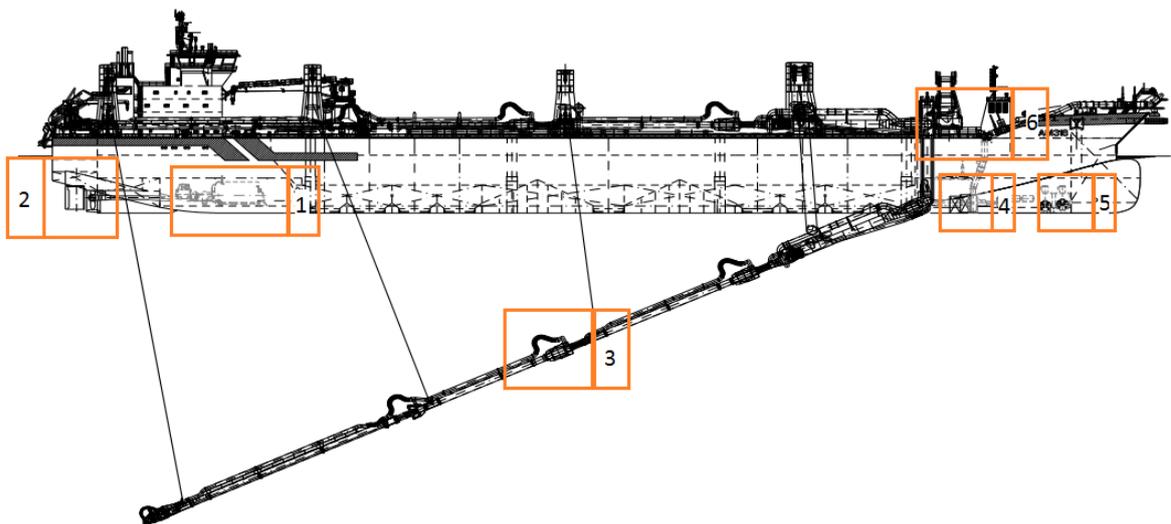


Figure 20 HAM 318 sideview blueprint with power consumers indicated, (Van Oord , 2014)

## **2.2 The Bilbao Project**

This chapter will elaborate on the Bilbao project of Van Oord. The data that has been used for the power demand analysis of the HAM 318 was measured on this dredging project. Therefore a description of the project is needed. The Bilbao project represents fairly average dredging activities, hence the choice for the HAM 318 on this project.

The description is based on the Bilbao transfer sheet of the Production Support department, under supervision of Willem Jumelet, production engineer at Van Oord. The transfer sheet is based on estimations of earlier projects, calculations provided by the client and survey executed by Van Oord.

### **2.2.1 General info**

The Bilbao project is a so-called Reclamation project. Meaning that the project has as goal to reclaim new land. In this case the extension of the Bilbao harbor quay. The project is solely executed by Van Oord. No joint venture, sub-contractor or other charters are being used to build the new harbor facility. The payment is based on In/Out survey conditions. Meaning that before the start of the project a survey will be executed. Based on this In-survey the price of the project can be determined. After finishing the project another survey will be executed, the Out-survey. Comparing both surveys will tell if the estimation was right and whether or not the price needs to be changed.

The dredged material outside the harbor of Bilbao consists of Sand, Mud and Clay and this material is supposed to be discharged through Dump, Pump and Rainbow techniques. As the project developed it became clear that Rainbowning is not allowed in the vicinity. The total dredged volumes reach approximately 6.000.000 m<sup>3</sup>. The material is dredged from an area outside the harbor, depicted in the North Western part of the map in Figure 21. The dredged material will be transported to the reclamation zone, based in the harbor. The reclamation zone is depicted in South-East off the map in figure Figure 21 (Jumelet, 2019)

#### **2.2.1.1 The Dredging area**

The dredging area is located North-West of the Bilbao harbor entrance Figure 21 The current depth of the dredging area varies from -66 meters to -41 meters. The thickness of the layer that has been appointed for dredging varies from ½ meter to 5 meters. The surface area of the dredging area covers roughly 4000 meter x 10.000 meter. The available volume for dredging is 16.000.000 m<sup>3</sup>. Besides the mud, clay and sand there is the possibility of debris in the area. This can affect the capacity of the Ham 318 or even damage the trailing system. (Jumelet, 2019)

#### **2.2.1.2 Reclamation area**

Looking at the reclamation area, the following data was acquired. The sail from the dredging area to the reclamation area is 4.75 nautical miles. The current depth of the reclamation area is roughly 20 meters below sea level. Figure 21 displays the reclamation area. In the South-East corner there is an access possibility. This entrance is 137 meters in width and will be kept open sufficiently with a depth level of -15m. This entry is needed for the HAM 318 to enter the reclamation zone and dump the dredging material. Onshore pumping will occur from outside the reclamation area. (Jumelet, 2019)

### 2.2.1.3 E&E

For the estimation of the quantity of material that needs to be dredged, the Estimation & Engineering department of Van Oord participates in a Tender. Several companies can enrol for a tender in which the estimated time spend, quantity and price are determined. For this chapter we're looking at the quantity and time. The Bilbao project started in October 2018 and was expected to take 15 weeks. The following table shows the Original Awarded Estimates. This will be followed up by the Actual Work estimate. (Jumelet, 2019)

#### Original Award Estimate

|                         | Volume in<br>m3  | %          | weeks       |
|-------------------------|------------------|------------|-------------|
| Dumping                 | 2.139.704        | 34         | 4.2         |
| Rainbow (outside)       | 1.493.278        | 30         | 4.5         |
| Rainbow + dump (inside) | 1.859.154        | 24         | 3.7         |
| Pump                    | 729.320          | 12         | 1.9         |
| <b>Total nett</b>       | <b>6.221.456</b> | <b>100</b> | <b>14.2</b> |

Table 3 Nett Quantity of Original Awarded Estimate, (Van Oord , 2018)

**Gross Quantity:** including 5% losses: **6.548.896m<sup>3</sup>**

#### Anticipated work method:

| Anticipated work method | Depth in m |
|-------------------------|------------|
| Dumping up to           | -11.5      |
| Rainbow (inside) up to  | -3.5       |
| Rainbow (outside) up to | 4.0        |
| Pumping up to           | 6.0        |

Table 4 Anticipated work method, (Van Oord , 2018)

After the Bilbao project was awarded to Van Oord, a change in work method needed to be done. It turned out that Rainbowing was not allowed in the Reclamation Area. These changes led to the following new estimates.

#### Work Estimate

|                   | Volume in<br>m3  | %          | Weeks       |
|-------------------|------------------|------------|-------------|
| Dumping           | 2.139.704        | 34         | 4.2         |
| Pokken + Dump     | 1.508.237        | 24         | 3.6         |
| Pump              | 2.573.515        | 42         | 6.6         |
| <b>Total nett</b> | <b>6.221.456</b> | <b>100</b> | <b>14.4</b> |

Table 5 Nett Quantity of actual Work Estimate, (Van Oord , 2018)

**Gross Quantity:** including 5% losses: **6.548.896m<sup>3</sup>**

**Anticipated work method:**

| Anticipated work method | Depth in m |
|-------------------------|------------|
| Dumping up to           | -11.5      |
| Pokken (inside) up to   | -5.0       |
| Pumping (outside) up to | 6.0        |

Table 6 Anticipated work method, (Van Oord , 2018)

More detailed information on the Dredging and Discharging Parameters can be found in Appendix 1



Figure 21 Port of Bilbao, reclamation and extraction zones, (Jumelet, 2019)

## 2.3 Power Demand Analysis of HAM 318

### 2.3.1 Methodology Power Demand Analysis.

The goal of the Power Demand Analysis is to come to a conclusion on the optimal set of SOFC and Energy Storage Systems (ESS). To determine the optimal set of SOFC and ESS it is needed to analyse where the power demand in the ship is coming from, at what moments during operation the highest power demand is and how much this power demand fluctuates. To come the right conclusion about the power demand a few techniques are being used. For the analysis there has been made use of VODAS data, Simplot software and excel. With these methods a power analysis has been concluded, this has been separated in different categories. In this chapter a brief description of dredging stages will be given. This is followed up by an explanation on the analysed cycles and the groups identified for the analysis.

### 2.3.2 Operational profile of dredging

The operational profile of a dredging vessel is not a rather complicated process. There are different kinds of ships that have different kind of processes considering the dredging. As explained earlier, the HAM 318 is a Trailing Suction Hopper Dredger, and is a self-propelled vessel that can dredge up in-situ material via its suction pipe into its own 'hopper'. For this vessel the standard dredging cycle basically consists of 4 stages. Sailing empty, Trailing, Sailing Full and Discharging. Which will be explained in the following paragraph.

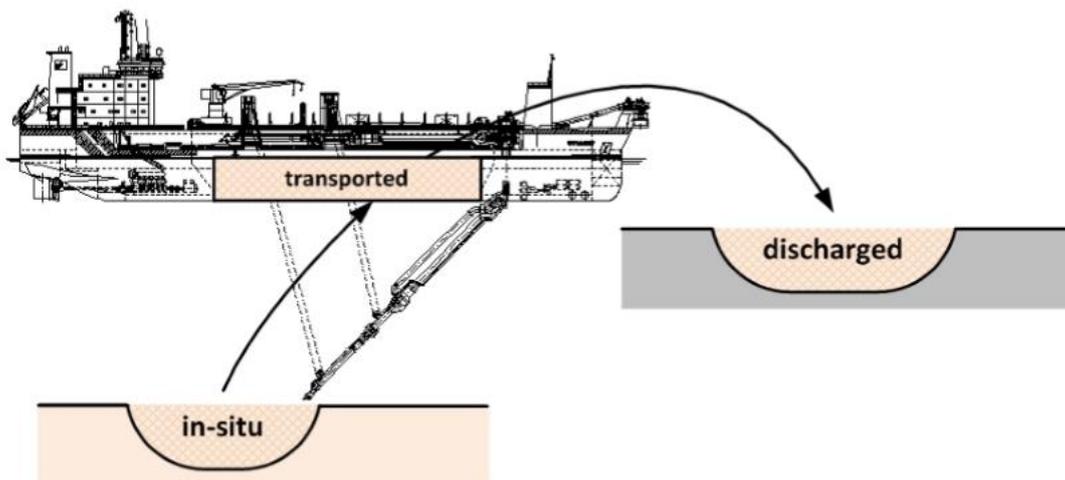


Figure 22 dredging and discharging, made by (Houten, 2013)

The 'sailing empty' stage is self-explanatory. In this stage the TSHD is either sailing from the reclamation area back to the extraction zone or from the harbour to the extraction zone. This is the first

stage in this research, but is not always necessarily the first stage. It depends on what is marked as the first step of dredging. In the 'sailing empty' stage only a few power demanders are being used. This is mainly the propulsion and the bow thrusters. More will be explained in the following paragraphs.

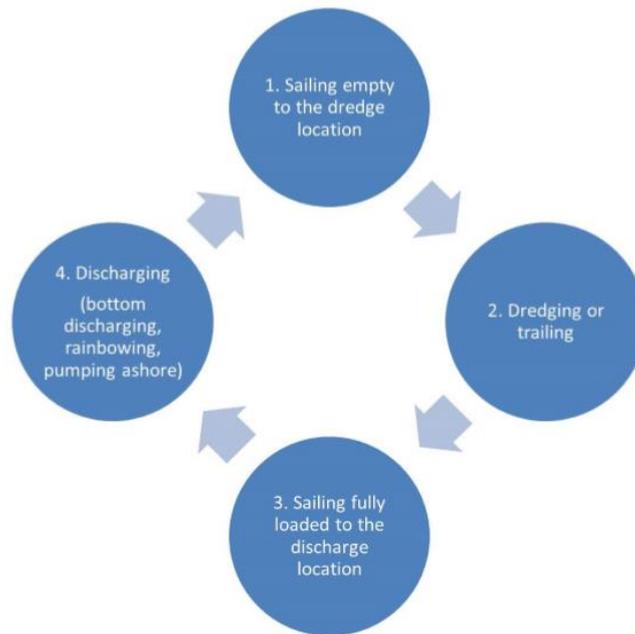
The second stage is marked the 'trailing' stage. The hopper is the main barge where the sediment can be stored. The sediment is being dredged by drag heads that are attached to suction pipes. The drag heads loosen up the sediment with water injection jets and with 'teeth' on the drag heads. The substance of seawater and sand is being sucked up through the pipes and loaded into the barge. Once in the barge the water is extracted from the sediment. This is done because of the volume and weight the water takes up. Once the process is finished the TSHD is ready for the next stage, 'sailing full'

The 'sailing full' stage, is like the 'sailing empty' stage, fairly self-explanatory. The TSHD is loaded with sediment at this point and sets sail to the reclamation zone. Like the first stage, the most power is consumed for propulsion and bow thrusters. Also the injections are being used at the end of the stage. These are being used to re-liquify the sediment. This is needed to finally discharge the sediments. If this has not been done the sediment cannot be transported through the pipes and hoses.

The fourth and final stage is the 'discharge stage'. In the discharging stage the sediment needs to leave the TSHD. This can be done in several ways. This can be done by dumping, rainbowing and shore discharge. Dumping is the easiest, quickest and least power demanding way of discharging the sediment. The sediment in the barge is being liquified and the 'doors' are being opened. These doors can be found in the bottom of the ship and work hydraulically and therefore not counted in the power demand analysis.

Rainbowing is the method for short distant but onshore discharge. It is the method of choice in areas where the water is rather shallow and needs large quantities of sediment. When Rainbowing the TSHD sprays the sand/seawater mixture over the bow into the air. This is a power demanding process with high fluctuations of power demand. Because the mixture does not always apply the exact pressure on the system the power demand fluctuates as well.

The shore discharge method is a popular method when sediment needs to be transported over longer distances. Fluctuating from 100 meters up to a couple of kilometres. For this process a pipe is attached to the bow of the ship. The sediment mixture is pressurized and flows through the pipe to the reclamation area. This too is a power demanding process, but the peaks of the power demand are less fluctuating than it is the case with rainbowing.



**Figure 23 Dredging cycle of a TSHD, made by (Houten, 2013)**

### **2.3.3 VODAS**

For analysing the power demand of the HAM 318 use has been made of data that was extracted from the VODAS database. VODAS, Van Oord Data Acquisition System, is a system that includes all hardware and software to measure signals that are being send from all the applications and equipment on board of the Van Oord fleet and equipment. Every 40 milliseconds signals are being read, edited and send to the main server. The data that is being gathered from the fleet can be used for several applications. This can be process visualisation, process automation, security and alarming, datalogging, process analysis, automatic reporting and process simulation.

The software used in VODAS has a Linux kernel, the rest is an in-house design. The in-house design avoids license cost and forced update patches. Besides that, any adjustments that need to be made can be written by Van Oord itself, this means that the measuring software does not have to be interrupted in operation. The Hardware that is being used for VODAS is also partly in-house built as well as bought from the regular market. (Hordijk, 2019)

### **2.3.4 SimPlot**

To read the measured data and plotting graphs for the research, use has been made of SimPlot.NET software. As the name reveals, SimPlot.NET, is a simulation and plotting software. SimPlot has certain advantages over general spreadsheet applications. SimPlot can easily manage large time series, gives the possibilities of analyzing with extended sets of formula's, generates quick and easy manageable graphs and makes it easier to print and copy graphs. (Paauw J. , Use of SimPlot , 2019)

### 2.3.5 Analyzed Power Groups

For the analysis of the power demand of the HAM 318 several different ‘power groups’ have been analyzed. ‘Power groups’ define the components of the HAM 318 that demand a significant amount of power and are seen as viable for the operation of the HAM 318 on different dredging projects. The power distribution diagram (appendix) shows where the components are placed in the system. Also the specifications are being displayed in this diagram. The power distribution diagram contains the following power groups

- Wärtsilä main Engines PS/SB
- Main generator PS/SB
- Propulsion PS/SB
- Bow thrusters
- Jet pumps PS/SB
- Underwater dredge pumps PS/SB
- Inboard dredge pumps PS/SB
- Auxiliary engine \*
- Harbor engine\*
- Emergency engine\*

power groups with the \* are not displayed in the analysis in the follow paragraphs.

The above listed power groups are the components of the HAM 318 that consume the most and viable power. In the analysis the Wärtsilä main Engines PS/SB, Harbor engine and Emergency have not been taken into account. The reason to keep the Wärtsilä out of the picture is that the Wärtsilä is the accumulated total of the system and does not take the downstream efficiencies into account. Therefore it is more accurate to use the separate components. The Harbor engine is not taken into account as the HAM 318 has not been in the harbor in the sampled time frame. The harbor engine is being used, as the name reveals, in the harbor. Since the HAM318 has not been idle or docked, it is useless to analyze this component. Same holds for the emergency engine. The engine is only being used as a back-up system when the total system collapses. Therefore is not part of the initial system. Even when the conventional system is being replaced by a zero-emission solution, the emergency system will still be the same conventional combustion system.

### 2.3.6 Power diagram HAM318

In Appendix 2 a power distribution diagram can be found. This power diagram displays the power distribution on the HAM 318. This part will give a brief walkthrough of the diagram. Starting at the ‘Propulsion engine PS/SB’ one can find 2 Wärtsilä 12V46C engines which each have a rated power of 12.600 kW. In the diagram the engines are named the propulsion engines, which is a bit misleading as they are not mainly for the propulsion of the HAM 318. The Wärtsilä 12V46C’s are produce mechanical energy for the whole ship. This mechanical energy propels a shaft and gearboxes. The gearboxes split the energy into the actual propulsion nozzle as well as the generator (depicted with a G). The sum of the 2 Wärtsilä 12V46C engines is the total generated and rated power in the HAM 318. This is before efficiency calculations. The efficiency of the Wärtsilä engine itself is rated at 70.3% and has a power factor cos. Phi of 0.81. This can be found in the ‘Bakker Sliedrecht certificate of compliance’ added in Appendix 3.

The total power of both engines is calculated in the ‘Cal 1’ code and is the sum of BOT 347/348 and COT 345/346. As displayed in Table 7. To determine the average power of this engine group, code ‘Cal 1b’ has been created. It measures the average of the Cal1 code over a set time period. Simplot will give the average output in a value.

The next part in the diagram is the Optima nozzle and is named 'Propulsion PS/SB' in this power analysis. This is the actual average power that has been used for propulsion of the ship in time period X to time period X or easily said, for each stage of the cycle. 'Cal 3' is the sum of COT346 and COT 345 and is basically the total generated power minus everything that goes into the 'power plant' HAM 318. COT 345 and COT 346 are indicators for the propeller shafts of the ship on both PS and SB and are expressed in kW's

The Main Generator PS/SB is the sum of both generators and is called 'Cal 2' in the table of formulas. The Main generator is the part just after the gearboxes and is the component that transfers the mechanical power from the Wärtsilä 12V46C into electricity for the HAM 318. The power that is generated is being measured with BOT 348 on starboard and with BOT 347 on portside. The BOT 347/348 express the main generator power in kW's on PS and SB respectively.

Next part in the diagram, that also has been used in the power demand analysis, are the bow thrusters. The bow thrusters are being used to keep the ship in position. Depending on the size and manoeuvrability of the ship, a ship can have multiple bow thrusters. The HAM 318 has 2 bow thrusters that each are rated on 1100 kW. The power demand of the bow thrusters is calculated through the BOT 355 and BOT 356 indicators and are expressed in kW's.

After the Bow thrusters the diagram comes at the most important part of the ship, the money-makers and the part of the ship that makes the ship actually a dredging vessel. These are the pumps. There are 6 pumps on the HAM 318. Jet pumps, Underwater Dredge pumps and Inboard dredge pumps on both portside and starboard side.

The jet pumps inject water into the barge to re-liquify the sediment. This is done with 2x 2150 kW rated pumps on each side of the ship. The power demand for these pumps are being calculated with the BOT 317 and BOT 318 on PS and SB respectively. The power that is being demanded by the pumps is expressed in kW's

The Underwater dredge pumps both have a 2500 kW rated pump on each side of the ship. The power demand of these pumps can be calculated through BOT 279 and BOT 280 and are also expressed in kW's. These pumps are in an alternating connection with the Inboard dredge pumps. This is a hybrid form. When extra power is needed on the inboard pumps or on the underwater pumps the system can switch between the pumps and distribute the power in different directions where needed.

The Last part are the Inboard dredge pumps. The pumps have a double engine on each side of the ship, resulting in a total rated power of 4 x 2750 kW and the possibility to power up with another 2500 kW on each side, by re-directing the Underwater dredge pumps capacity. The inboard dredge pumps power demand can be calculated by BOT 249 and BOT 250 and are also expressed in kW's.

In Table 7a list of all the Cal-codes or formulas is presented. These are all the formula's that have been used for analysing the power demands of the HAM 318.

### **2.3.6.1 COT/BOT**

The COT and BOT abbreviations stand for 'Computer Output' and 'Berekende Output' respectively. 'Berekende Output' is Dutch for the calculated output. Both are indicators and read or calculate the output that the signals within the boat send to the VODAS. BOT and COT are roughly 40 year old indicators and exist from the beginning of the computer area. Since then the abbreviations have never

been changed. Each component in the Ham 318 that uses energy or electricity have there own signal indicator. In this way the behaviour of the HAM 318 can be analysed for different kinds of purposes. (Paauw J. , COT/BOT, 2019)

### 2.3.6.2 Cycles and timetables

For the power demand analysis in this thesis it was needed to demarcate a certain period of time that represents average dredging behaviour. As explained in the previous chapter, the Bilbao dredging project has been determined and used as representative. To gather sufficient and representative data 10 cycles have been used. These cycles consist each of 5 stages and are continuously back to back measurements. In Appendix 4 Stage times and cycles for each stage of the dredging cycle are displayed. They show for each stage the corresponding cycle number, day of the month, start time, end time, total time in minutes and the relative part of an hour. All time measurements took place in October 2018.

| Code           | Name                                 | Formula   | Datatype |
|----------------|--------------------------------------|---|----------|
| <b>Cal 1</b>   | Main engines PS/SB                   | bot347 + bot348 + cot345 + cot346   | Value    |
| <b>Cal 1b</b>  | Avg of Main engine PS/SB             | Avegl(Cal1,datetime(x),datetime(x))   | Value    |
| <b>Cal 2</b>   | Main generator                       | bot347 + bot348   | Value    |
| <b>Cal 3</b>   | Propulsion PS/SB                     | cot345 + cot346   | Value    |
| <b>Cal 4</b>   | Bow thrusters PS/SB                  | bot355 + bot356   | Value    |
| <b>Cal 5</b>   | Auxiliary engine                     | bot349  | Value    |
| <b>Cal 6</b>   | Jet pumps PS/SB                      | bot317 + bot 318  | Value    |
| <b>Cal 7</b>   | Underwater Dredge pumps PS/SB        | bot279 + bot280   | Value    |
| <b>Cal 8</b>   | Inboard Dredge pumps PS/SB           | bot249 + bot 250  | Value    |
| <b>Cal 11</b>  | Accumulated Power of all Auxiliaries | bot317 + bot 318 + bot249 + bot250 + bot279 + bot 280 + bot255 + bot256 +bot349                   | Value    |
| <b>Cal 12</b>  | Cal 11 + propulsion                  | bot317 + bot 318 + bot249 + bot250 + bot279 + bot280 + bot255 + bot256 + bot349 + cot345 + cot346 | Value    |
| <b>Cal 99</b>  | Average over x-time of x-group       | avegl(Calx,datetime(x),datetime(x))   | Value    |
| <b>Cal 88</b>  | Average boat speed x-stage           | avegl(cal881,datetime(x),datetime(x))   | Value    |
| <b>Cal 881</b> | Boat speed                           | bot965  | Value    |
| <b>Cal 343</b> | Average fuel cons. Day-x             | avegl(cal343, datetime(x),datetime(x))  | Value    |

Table 7 Cal Codes for SimPlot

### 2.3.7 Stage analyses of HAM 318

In the following chapter the results of the Power Demand Analysis have been presented. This has been done for each stage of the dredging cycle; Sailing Empty, Trailing, Sailing Full, Dumping and Shore Discharge. Each stage has a description of what has been measured and the possible meanings of the results. The Power Demand Analysis has been followed up with a paragraph about ‘ The New Dredge Cycle’. In this paragraph it is attempted to come up with an average off all cycles, to get a clear view on the Power Demand of the HAM 318 over a certain amount of time. The results have been compared to the parameters of a regular dredge cycle following the guidelines of the Bilbao transfer sheet. Of this comparison a corrected dredging cycle has been generated. This has been done to make sure that the measured data is not too divergent compared to the standards of the company.

### 2.3.8 Stage 1 – Sailing Empty

This graph in Figure 24 Stage 1 - Sailing Empty - Accumulated Avg kW's shows the average kW's of each group of energy producers on board during the ‘sailing empty’ stage. The main engine PS/SB is the accumulated energy consumption of the total system. This is because these are the producers of all energy on board. Part of the generated energy from the main engines goes to the propulsion nozzles and the rest powers an onboard generator that produces electricity for the rest of the ship.

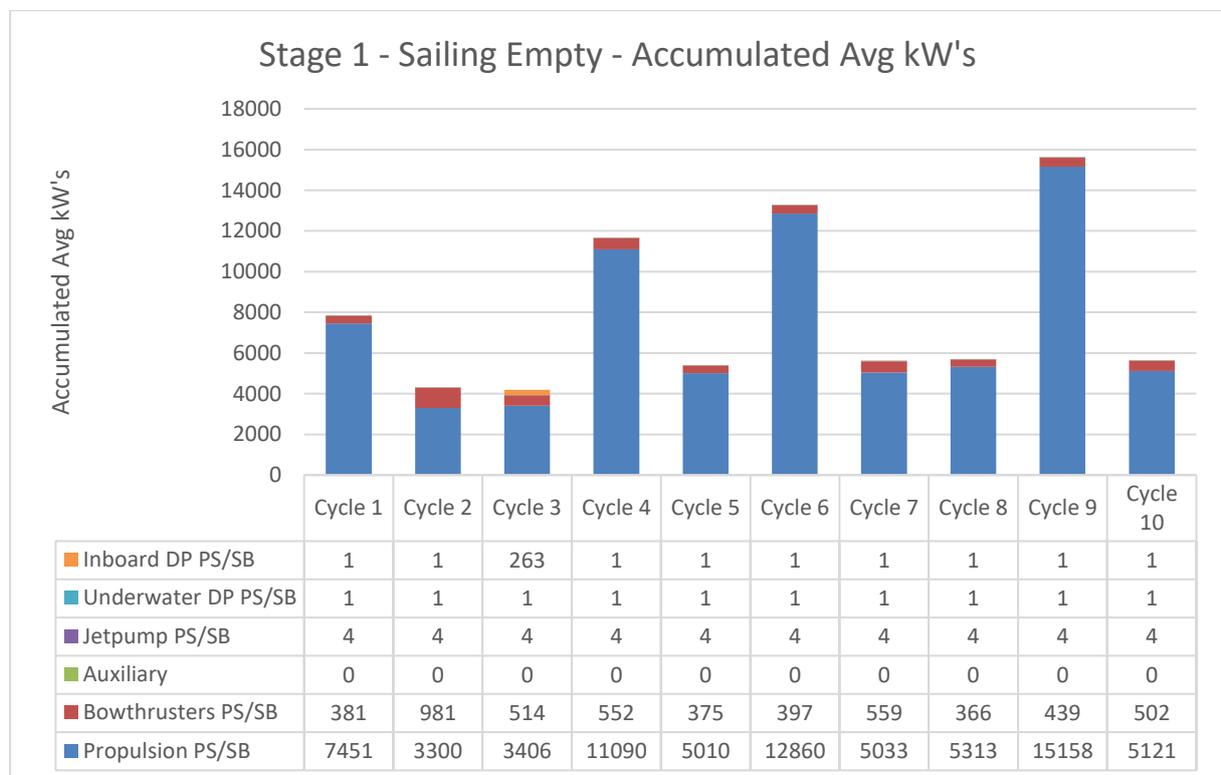


Figure 24 Stage 1 - Sailing Empty - Accumulated Avg kW's

As we can see the average power used over all the cycles in the sailing empty stage is fairly steady. The most outlying cycle is the 3<sup>rd</sup> cycle. In this cycle one can see that other than the normal generators the Inboard Dredge Pumps are also being used. This is not expected when the boat is sailing, as the dredging equipment is not needed in this process. The most likely reason for the use of the Inboard Dredge Pumps is that they are being used to rinse out left over dredging residue. In this case that is a mixture of Sand, Mud and Clay. It is likely that this mixture stick to the bottom and doors of the barge. When there is too much residue left over, the capacity of the barge decreases. For this process a peak power demand of roughly 1300 kW is used Figure 25. Over the total cycle it levels out to an average of 260 kW.

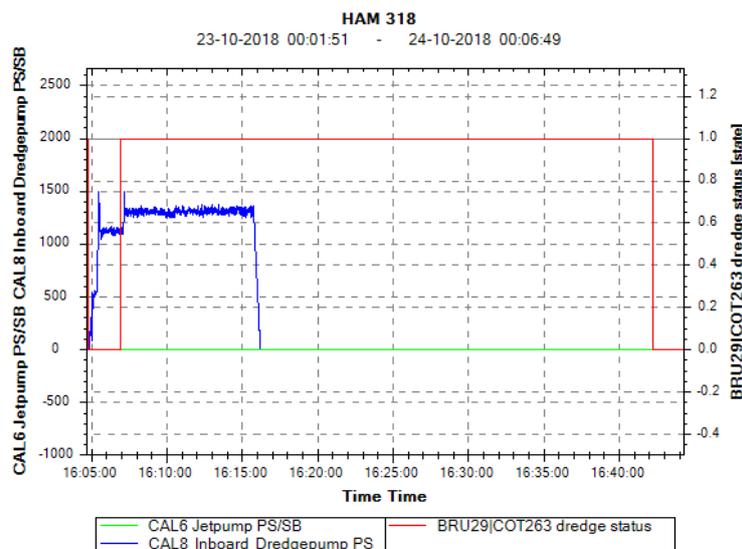


Figure 25 Inboard dredgepump power demand

There are 3 other cycles that have symptoms of an outlier. These are the 4<sup>th</sup>, 6<sup>th</sup> and 9<sup>th</sup> cycle. Taking a look at the generating groups one can conclude that the propulsion of the ship in these cycles increases with respect to the other cycles. There can be different factors that can be the reason. For example changing weather or tidal changes. As a cycle lasts on average about 8 hours, it is rather unlikely that tidal change causes the increase. The tide changes every 6 hours and there is no consistency in the fluctuations of the dredging cycles. Weather patterns could be a reason. But looking at the stage-times of the cycles, it shows us a more reasonable explanation. In the 4<sup>th</sup>, 6<sup>th</sup> and 9<sup>th</sup> cycle the sailing times are significantly shorter. An average of about 20 min in comparison to the standard 30/40 min (Cycle times -Appendix 4). The shorter stage-times, in this case sailing from the discharge location to the extraction location, indicates that there have been higher boat speeds and thus more power demand. Higher boat speeds are probably caused by trying to make up for delays. These delays generally occur at the connecting and disconnecting of the discharge hose.

To defend the hypothesis that the ship has sailed at a higher speed than normally, 2 graphs have been added. The first graph (Figure 26) shows the boat speed in the 8<sup>th</sup> cycle, under 'normal' circumstances and the second graph (Figure 27) show the boat speed in the 9<sup>th</sup> cycle, under 'other' circumstances. The ships reaches a speed of 8 and 13 knots respectively.

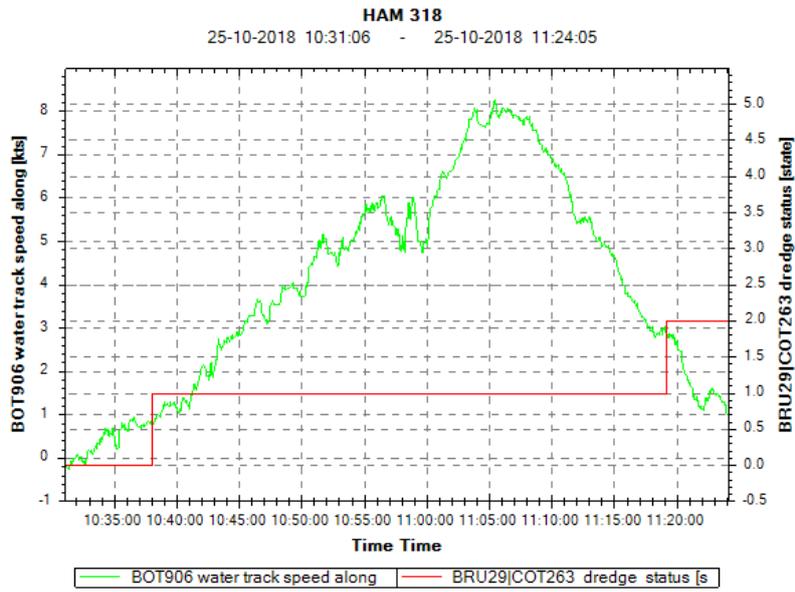


Figure 26 STW, speed through water, 8<sup>th</sup> cycle 'normal'

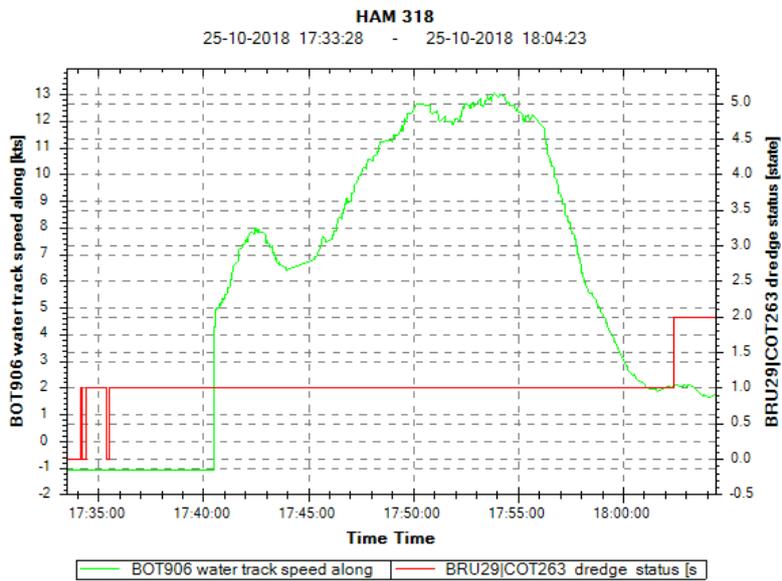
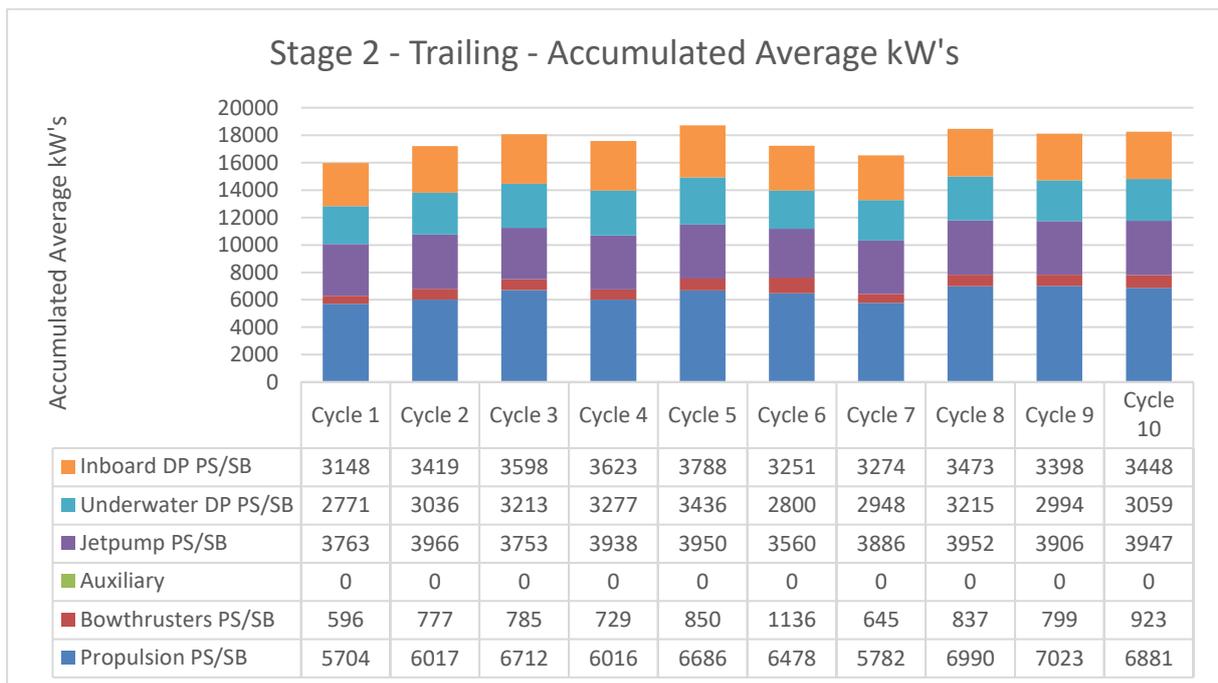


Figure 27 STW, Speed through water, 9<sup>th</sup> cycle, other

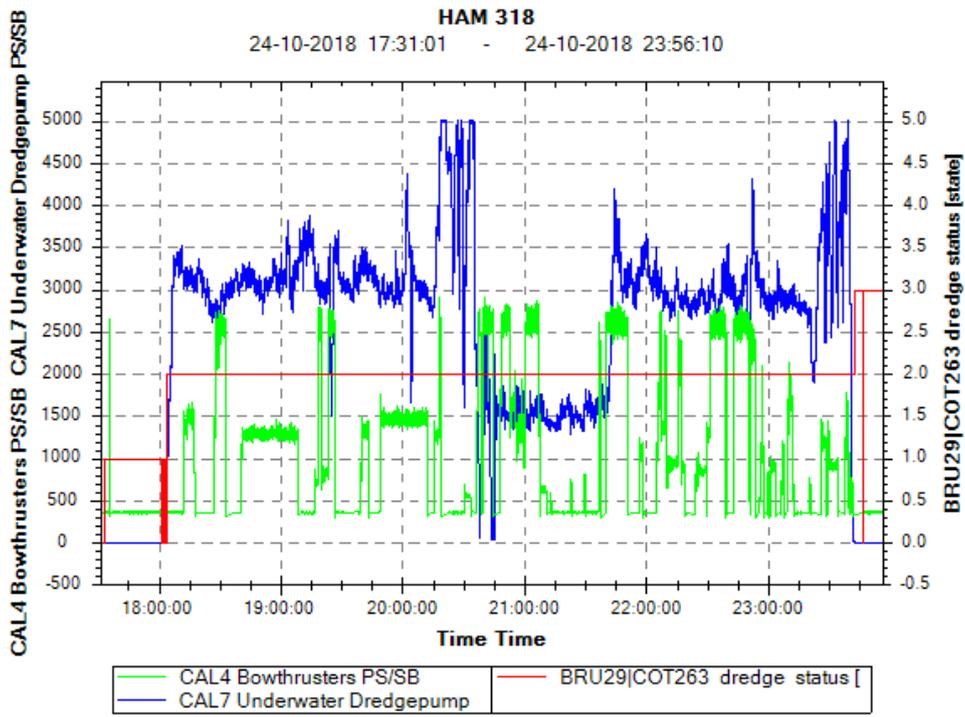
### 2.3.9 Stage 2 – Trailing

In Figure 28, the Trailing stage is displayed. Compared to the first stage, there is a steadier power demand visible. There is more consistency in both the actual demand as in the group that is demanded in this stage. The accumulated power demand fluctuates between the 16.000 and 18.000 kW and comes from the same groups at each cycle. From the Simplot data and the excel data there can't be any unusual conclusions drawn.



**Figure 28 Stage 2 - Trailing - Accumulated Average kW's**

If we take a closer look at the 6<sup>th</sup> cycle one can see a slight difference in the power demand distribution. In the case of cycle 6 one can see that there has been a bit higher power demand from the bow thrusters PS/SB and a bit lower power demand from the Underwater Dredge pumps PS/SB. A credible reason for this change can be a change in weather or temporarily heavier sea state. The bow thrusters keep the ship in place during the trailing phase. When the ship needs to maneuver more, there is an increase of power demand from the thrusters and the ship temporarily decreases the power demand from the Underwater dredge pumps. Figure 29 shows the change in the power demand for the Underwater dredge pumps. The sudden drop in power demand in the blue line and the increase of power demand in the green line point out the maneuvering of the ship.



**Figure 29** power demand bow thrusters and Underwater dredgepumps

### 2.3.10 Stage 3 – Sailing full

The third stage of the dredging cycles is the sailing full stage. In this stage the Ham 318 sails from the extraction zone to the discharge zone. The draught of the ship in this phase is, obviously, deeper than in the sailing empty stage. Therefore more power is needed to displace the ships weight from point A to point B. More power, on average, is demanded in this phase. This can be seen in the graph for the average power distribution. Figure 30

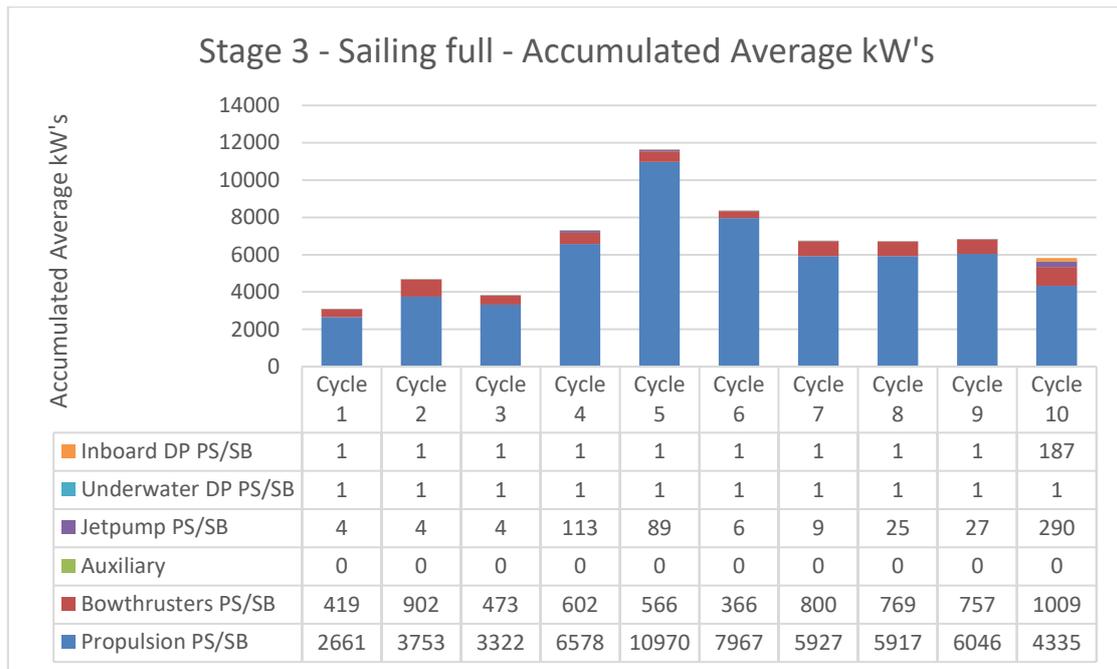
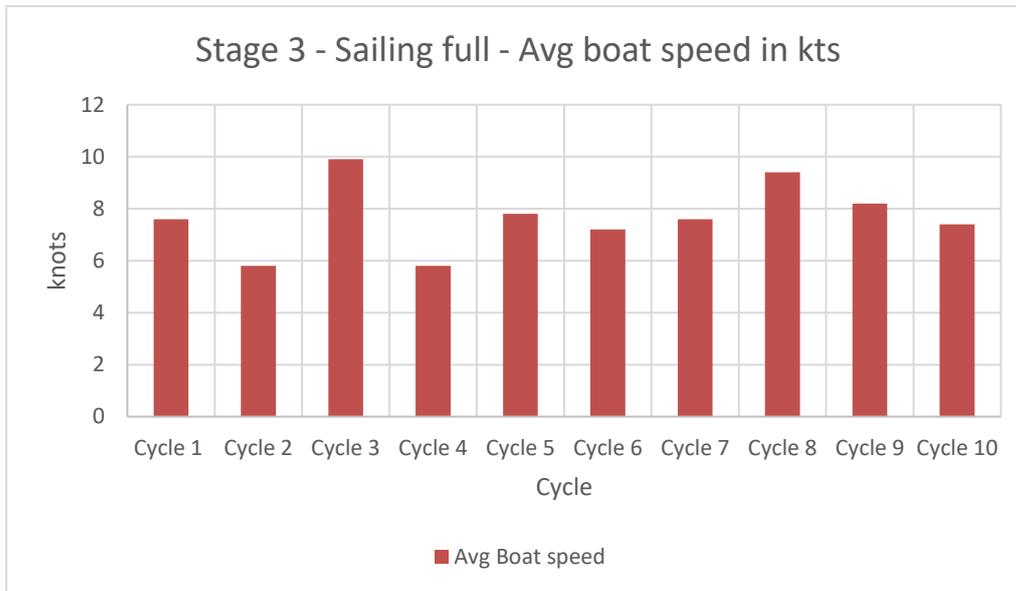


Figure 30 Stage 3 - Sailing Full - Accumulated Average kW's

In general the power distribution is somewhat stable. Generating around 4.000kW in the first 3 cycles. The last 5 cycles have an average of around 7.000kW's. There is a clear peak in the 5<sup>th</sup> cycle. In this cycle the propulsion almost reaches an average of 11.000 kW's. There is no clear reason for this sudden increase in power. If we plot a graph with the average boat speed of the HAM 318 during stage 3 for every cycle, one can see that there is hardly a relationship between the demanded power of for propulsion and the average boat speed of the HAM 318 in the 3<sup>rd</sup> stage. Moreover, the highest average boat speed is recorded in the cycle with the lowest average demand of power.

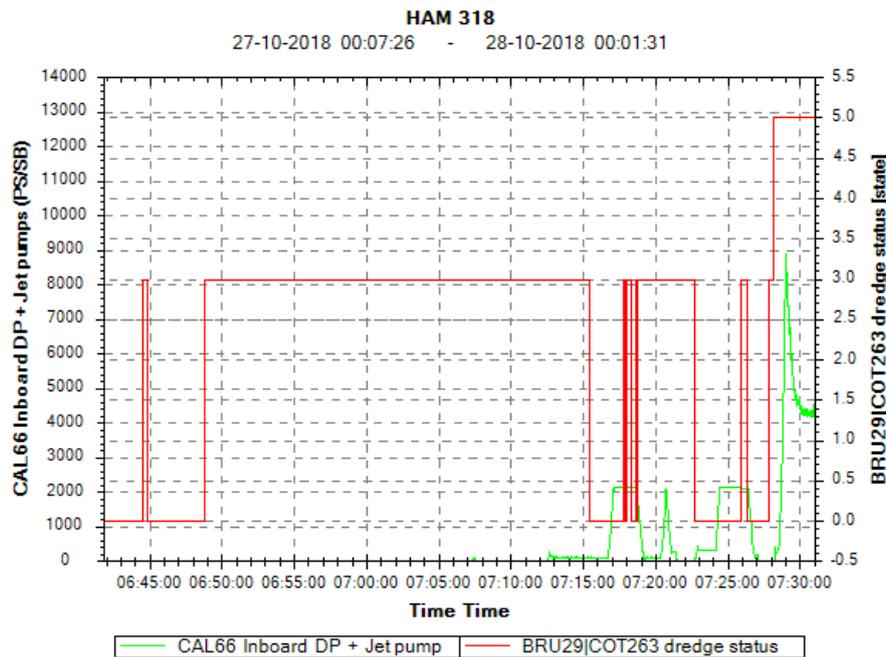


**Figure 31 Average Boat speed per cycle in stage 3**

Other than the observation of the insignificance of the relation between demanded power for propulsion and the average boat speed of the HAM318 in the ‘sailing full’ stage, there is not a remarkable difference of power demand over the total of 10 cycles in the ‘sailing full’ mode. The only thing that may draw some attention is the increase of power demand of the Inboard dredge pump PS/SB and Jet pump PS/SB in the 10<sup>th</sup> cycle. On average these are roughly 200kW and 300kW respectively.

When the HAM318 switches from the ‘sailing full’ status to the ‘shore discharge’ status the ship prepares for the unloading of the dredging material. To unload the material, the mixture needs to be liquified again. For the liquification of the material the Inboard dredge pumps and the Jet pumps are being used. The most likely thing that has happened, is that the pumps were already in use before the ship actually went into discharging mode. The liquefaction phase generally demands a lot of power. The average power demand value in this case is rather low. The peak of power demand is for a short period of time and at the end of the cycle. By dividing the total power demand over the total time of the stage the average demanded power is found, hence the low value for the Jet pump and Inboard dredge pump groups.

The attached Figure 32 shows the accumulated power demand of both the Inboard dredge pump PS/SB and the Jet pumps PS/SB for the 10<sup>th</sup> cycle. Stage 3 of this cycle runs from 06:50 till 07:30. In this period, at the end of the stage, the power demand indeed increases. This points out the start of the liquefaction process. This supports the explanation.



**Figure 32 Inboard dredge pumps + Jet pumps**

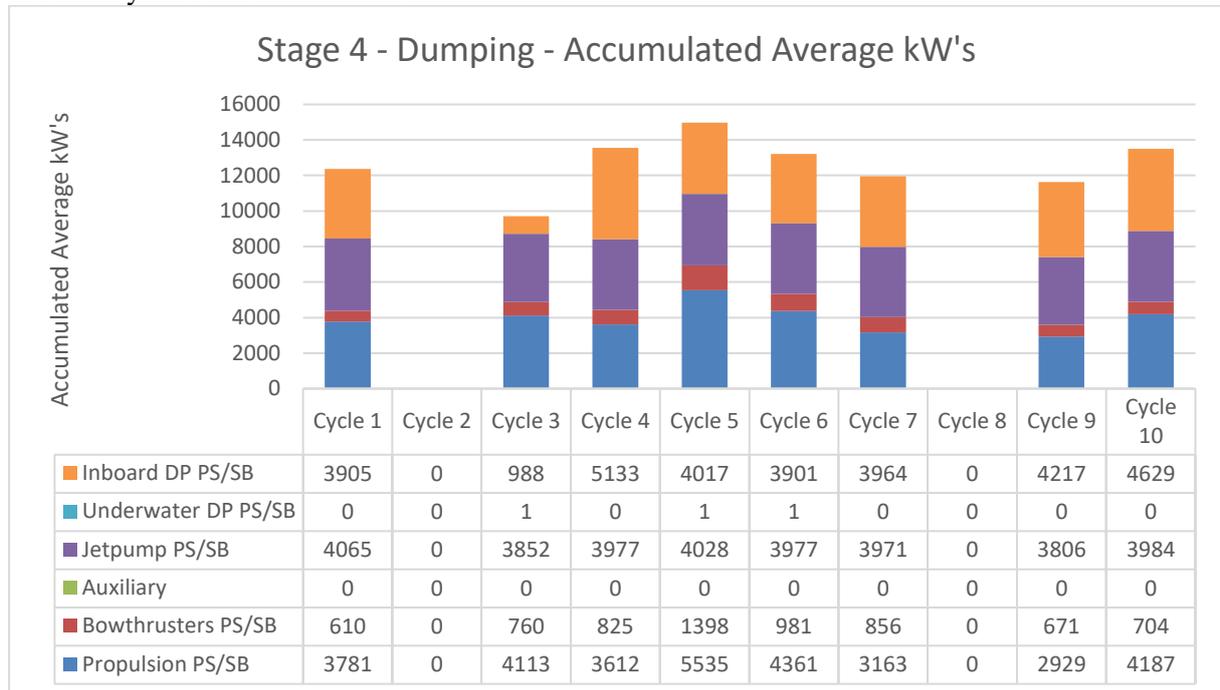
### 2.3.11 Stage 4 – Dumping

As described in 2.3.2 there are different kinds of discharging of the dredged material. The 4<sup>th</sup> stage is the dumping phase. In the case of the Bilbao project there is hardly any dumping involved. Dumping in this project is mainly to get rid of the last residues in the barge of the TSHD. Stage 4 in this project is only used straight after stage 5, the shore discharge. The average time of stage 4 in the Bilbao project is roughly 10 to 15 minutes. In these 10 to 15 minutes the left over material is being liquified again and the barge is rinsed out. For this process the Inboard dredge pumps and the Jet pumps are being used. At the end of the stage the bottom doors of the barge are hydraulically opened. To close the bottom doors the boardnet of both PS and SB are needed to electrically close them. The power demand of the boardnet is not taken into account in this research, as the signals of the boardnet are not measured.

Looking at the Accumulated Average kW's of the 4<sup>th</sup> stage there are no real significant deviations from the average or median of the average demanded kW's (Figure 33). Cycle 2 and cycle 8 are missing in this graph. In cycle 2 and cycle 8 there has not been any dumping involved, hence the lack of data. After the discharge stages in cycle 1 and 7 the HAM 318 straight away returned to the extraction zone. The reason for this could be either a delay in one of the previous stages, or insufficient left over residue in the hopper itself. Rinsing out the hopper, opening and closing the hopper doors costs time. The risk of a delay outweighed the extra loading capacity, therefore it is likely that the crew of the HAM 318 decided to sail back to the extraction zone and skip stage 4 in these cycles.

The 5<sup>th</sup> cycle of the 4<sup>th</sup> stage shows an above average power demand. The bow thrusters and propulsion PS/SB demand slightly more power than on average. Changing sea state or weather is the

most likely reason for the deviation.

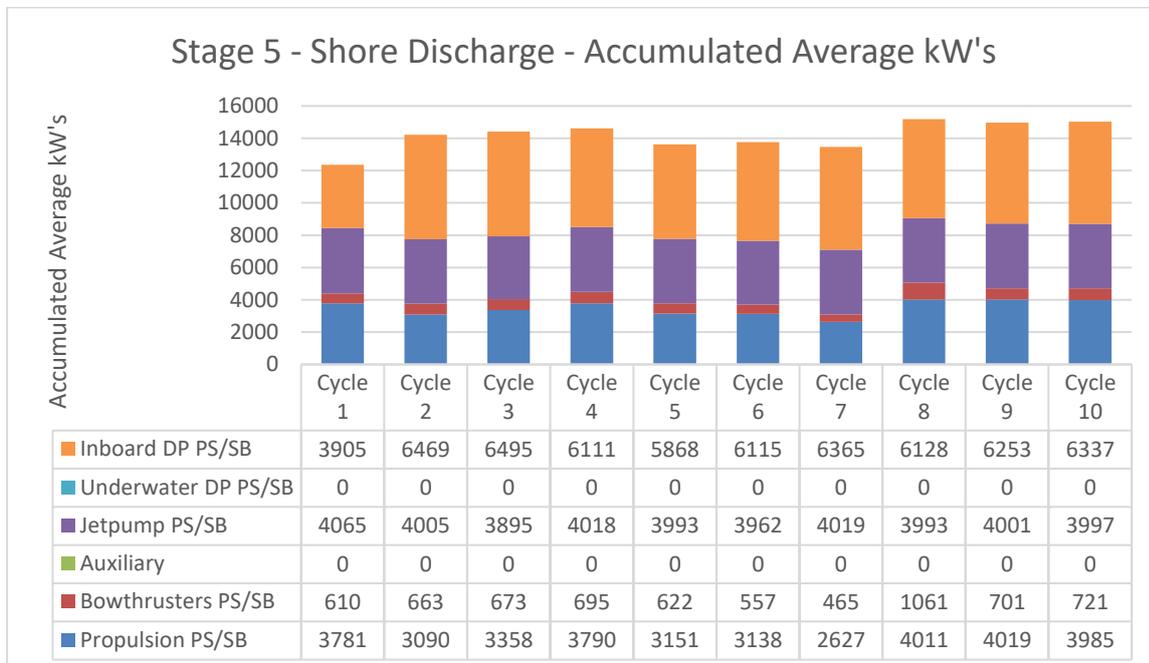


**Figure 33 Stage 4 - Dumping - Accumulated Average kW's**

### 2.3.12 Stage 5 – Shore Discharge

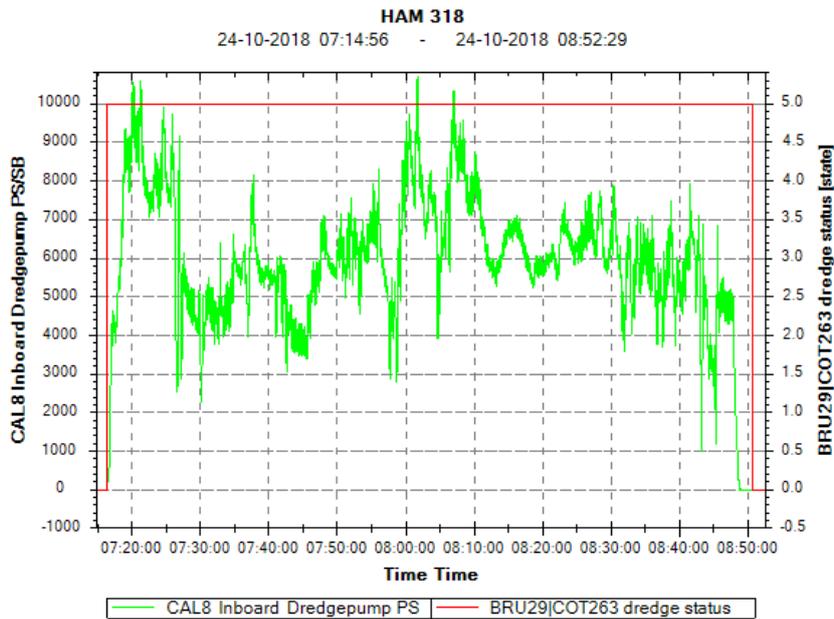
The 5<sup>th</sup> stage of the dredging cycle is the concluding stage. At this point all the dredged material is being discharged at the discharge zone. For the case of the Bilbao project, discharging is done through Rainbowing, Pumping and ‘Pokken’. Later in the project Rainbowing became forbidden and just ‘Pumping’ and ‘Pokken’ were left over.

Having a look at the Accumulated Average power demand (Figure 34), it gives the impression that the discharging stage is a fairly consistent one when it comes down to power demand. Over all the 10 cycles there are no real inconsistencies and roughly all the groups demand the same average power over each cycle. Only in the 8<sup>th</sup> cycle one can observe a higher than average power demand for the bow thruster group. The bow thrusters are, as mentioned before, used for the positioning of the ship. An increase of power demand for these bow thrusters are due to the increasing of position correction in that specific phase.

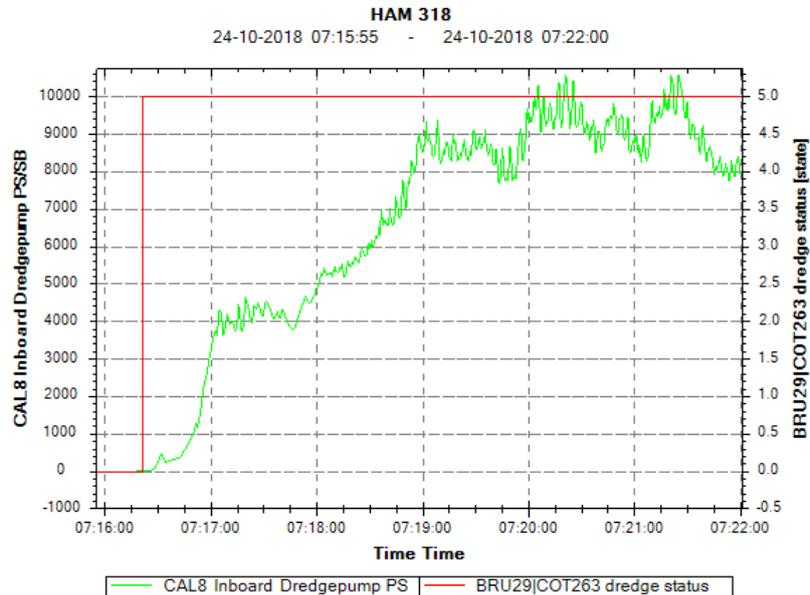


**Figure 34 Stage 5 - Shore Discharge - Accumulated Average kW's**

The impression of a consistent power demand for the discharging stage is slightly deceiving. Discharging dredged material is highly power intensive and very fluctuating in power demand. The attached (Figure 35) shows the fluctuations of the Inboard dredge pumps in the 4<sup>th</sup> cycle, October 24<sup>th</sup> 07:20 – 08:50. Here one can see that the power demands fluctuate between 1000kW's up to 10.000 kW's within a short amount of time. With the biggest change being at the start of the dredging stage. Here the Inboard dredge pumps increase the power demand from 0kW's to almost 11.000 kW's within 5 minutes. This can be observed in the second attached Figure 36.



**Figure 35 Inboard Dredge pumps**



**Figure 36 Loadstep Inboard Dredge pumps**

These serious fluctuations in power demand are the biggest challenges that need to be overcome to figure out the feasibility of a zero-emission TSHD solution. An electrical system that cannot meet the demands will fail and causes the system in general to crash. Hence the research into a hybrid system, where SOFC's and Energy Storage can complement each other and cause the system to operate properly.

### 2.3.13 'The New Dredge Cycle'

Now that we know the average power demand of the 5 different stages over 10 different cycles. It is possible to set-up an average 'Power Demand' for this particular time frame in this particular Bilbao project. In this 'New Dredge Cycle' it is attempted to display the most accurate averages of each power group for each stage. After plotting this graph, a closer look will be taken into the most fluctuating power demand stage. Under the guise of 'a system is as strong as its weakest link' it is important to identify the right stage. If the hybrid system cannot meet the fluctuations in demand, the system will crash and the Ham 318 will not be able to operate.

#### Method for NDC

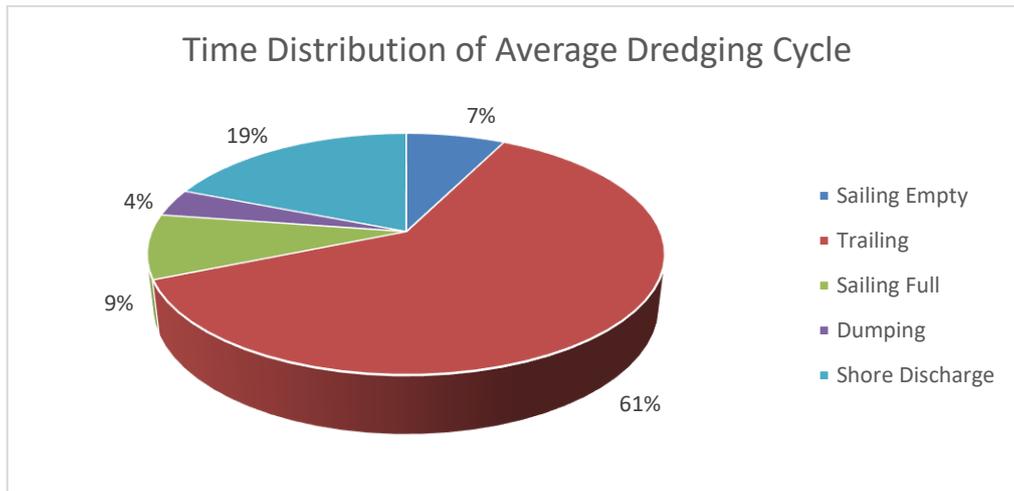
To calculate the new average dredge cycle for the Bilbao all the cycle and stage times have been transferred from the NC-file in Simplot to Excel. This is all done by hand as there is no possibility to convert the NC-data to a CSV-file. In Appendix 4 the stage and cycle times have been displayed. The appendix shows the start and end time of each stage and how many minutes this actually is. Summing up all the stage-cycle times and dividing them by 'n-cycles' gives the average time for a stage. As mentioned in the Parameter sheet of the Bilbao project, the total cycle time should be 469 minutes. The results will likely deviate from the parameter (expected) values. To plot a hypothetical and plausible Average dredging cycle, 3 different time distributions will be showed. The distribution of the Average Dredging Cycle, the Parameter Dredging Cycle and the Corrected Average Dredging Cycle. Based on the CADC a new graph with the 5 dredging stages will be plotted.

#### 2.3.13.1 Time Distribution of Average Dredging Cycle

The Average Dredging Cycle (ADC) shows, as the name reveals, the average times of dredging stages of the sampled dredging cycles. These are cycles 1-10 for each stage. The 2<sup>nd</sup> and 8<sup>th</sup> cycle of the Dumping stage (4) are not taken into account, as there was no dumping involved in these cycles. To calculate the average time that was spent on each stage, all the stage times were added up and divided by n-cycles, an Arithmetic mean.

$$\text{Average Dredging Cycle} = \frac{1}{n} \sum_{i=1}^n a_i = \frac{a_1+a_2+\dots+a_n}{n}$$

The results can be found in Table 8. The relative distribution of the stages are displayed in Figure 37 **Error! Reference source not found.** The distribution shows that in the sample of the dredging cycles the trailing time was almost 60% of the total cycle time. Sailing full and Sailing empty almost took the same amount of time. The sailing full stage obviously being slightly longer as the TSHD has more weight to displace over the same distance. Discharging the dredged material almost took up 20% of the total cycle time. Roughly 3 times as short as the trailing time. The average relative dumping time took only 4% of the time. The time spend in the 4<sup>th</sup> stage is not necessarily used as actual dumping, but is used to clean the hopper.



**Figure 37 Time Distribution of Average Dredging Cycle**

### 2.3.13.2 Time Distribution of Parameter Dredging Cycle

The Parameter Dredging Cycle (PDC) is the expected dredging cycle for the Bilbao project. In Appendix 1 the parameters for the project are displayed. In this sheet the estimated times for the different dredging stages, hopper specifications, fuel types and other data can be found. The sheet shows 3 different dredging scenarios and the corresponding stage times. For the Bilbao project a DUMP, Rainbow/DUMP and PUMP scenario have been made. Ultimately the PUMP scenario was chosen. Appendix 1 shows the data that corresponds with the PDC. The missing of stage 4, the dumping stage, stands out. Using a PUMP scenario normally does not include any dumping. As explained earlier, there has not been actual dumping involved, but the Ham318 has been in that stage for cleaning reasons. Therefore dumping has been taken into account for the calculation of the distribution, although the value of dumping is '0'.

The expected distribution of the PDC shows that under normal scenario circumstances, in a PUMP scenario, the distribution is as follows. A little bit more than half of the time in a dredging cycle is expected to be used for trailing. Roughly 20% of the time is being used for Sailing Empty and Sailing Full together and the leftover 30% is the actual Shore Discharge.

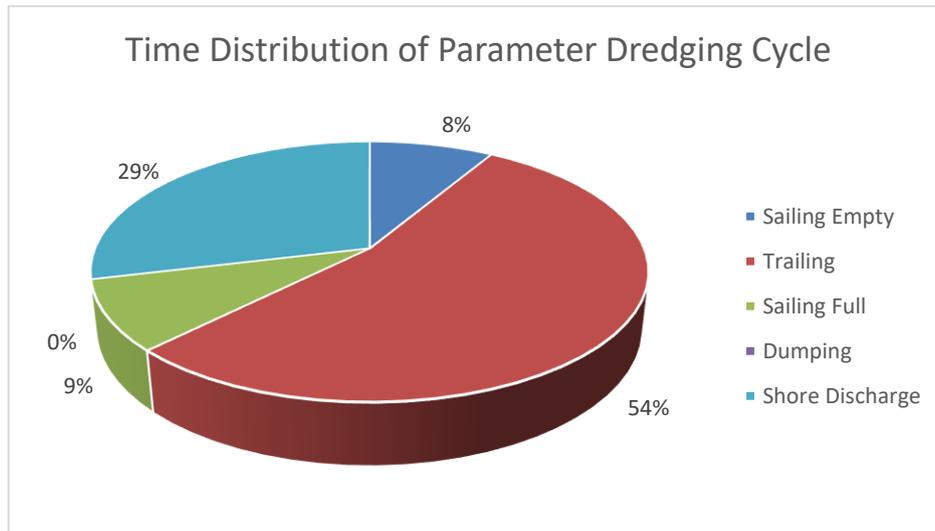


Figure 38 Time Distribution of Parameter Dredging Cycle

### 2.3.13.3 Time Distribution of Corrected Average Dredging Cycle.

The Corrected Average Dredging Cycle (CADC) is the cycle that is being used for the research. This is the basis for determining the optimal set of SOFC's in a hybrid system. This cycle is made up out of the ADC and PDC. The measured ADC and the expected PDC have been compared and from this conclusions a fictive cycle has been developed. The CADC has corrections for the measured cycles included. If the ADC and PDC are compared, one can see that some stages deviate from the expectation. The measured 'Sailing empty' stage is on average 10 minutes too short. The sailing full stage is also lacking an average of 6 min too short. The real significant difference can be found in the Shore Discharge stage. The expected time spend in this stage is 43 minutes longer than the observed in the ADC. The same problem can be seen in the Dumping stage. Dumping was not expected, but it was measured.

Explanations for deviations.

- Sailing empty/full: the deviation in the 1<sup>st</sup> and 3<sup>rd</sup> stage are most likely occurred to inaccurate demarcation of the status in Simplot. The 'status' signals are not always being read. The failing of the 'status' recognition causes the exclusion of data for that particular timeframe. In this case a shorter amount of time has been measured, resulting in shorter stage times.
- Shore Discharge: The shortage of time in the Shore Discharge stage is most likely due to the exclusion of 'connecting and disconnecting'. This is in the sample not included in the timeframe as it is not seen as a stage in the dredge cycle. It should be included in the Shore discharge stage. The left over missing minutes in the cycle are probably also due to the lacking accuracy of demarcation.
- Dumping: As mentioned before, there was not 'Dumping' expected in the parameter sheet. On the other hand, it was measured in the sample cycles. For this research it has been included.

## The Corrections

The differences between the expected and actual cycle times have been overlaid and modified to come to a new CADC. For the sailing empty stage an extra 5 min were added to the stage time average. The trailing stage remained the same, this also holds for the dumping stage. For the average Shore Discharge phase a new time value has been set up. As seen in the table the missing 63 minutes, minus a correction of 10 minutes, were added up to the Shore Discharge stage. This results in a CADC for Shore Discharge of 130 minutes.

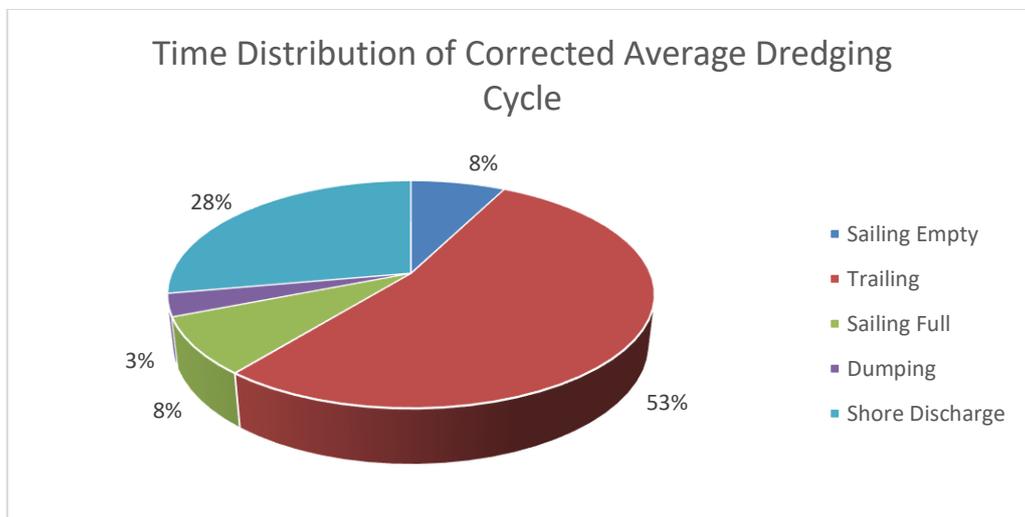


Figure 39 Time Distribution of Corrected Average Dredging Cycle

| Name            | Avg of DC's in Min | % ADC | Parameter DC | % Par | Corrected Avg DC | % Corr |
|-----------------|--------------------|-------|--------------|-------|------------------|--------|
| Sailing Empty   | 30                 | 7.4%  | 40           | 8.5%  | 35               | 7.5%   |
| Trailing        | 249                | 61.3% | 253          | 53.9% | 249              | 53.3%  |
| Sailing Full    | 35                 | 8.6%  | 41           | 8.7%  | 38               | 8.1%   |
| Dumping         | 15                 | 3.7%  | x            |       | 15               | 3.2%   |
| Shore Discharge | 77                 | 19.0% | 120          | 25.6% | 130              | 27.8%  |
| Connecting      | x                  | x     | 15           | 3.2%  | x                | x      |
| Sub total       | 406                |       | 469          |       | 467              |        |
| Parameter       | 469                |       |              |       |                  |        |
| Missing         | 63                 |       |              |       | 2                |        |
|                 |                    |       |              |       |                  |        |

Table 8 results of average DC, parameter DC and Corrected Avg DC

### 2.3.14 The CADC

In Figure 40 the share of each stage of the dredging cycle and the according average kW's are displayed. This is the CADC, corrected average dredging cycle. This cycle is based on the 10 measured cycles and the parameter values for the expected dredging cycle.

Each stage of the cycle is displayed and has the size of its relative contribution. The wider the column, the more time it accounts for over the total cycle. The height of the column represents the average Power of the stage.

The graph helps in determining the optimal set for the SOFC hybrid system. Based on the information, value and shapes of this graph, one can identify the most important and demanding stage in the dredging cycle.

Determining the optimal set of SOFC and storage system is a tough question. The considerations that need to be taken into account differ from technical performance to financial factors. If too many Fuel cells or storage capacity is installed the price could be too high to be economically viable. On the other hand, if the technological performance demands are not met, there is no chance of success at all.

Besides that the system should be able to deliver enough power and energy over time (kWh) it is also important that the hybrid system can comply with the load step. This means that the system should be able to deliver enough power over a short amount of time and capture energy in times when the demand is lower than the supply, in also a short amount of time.

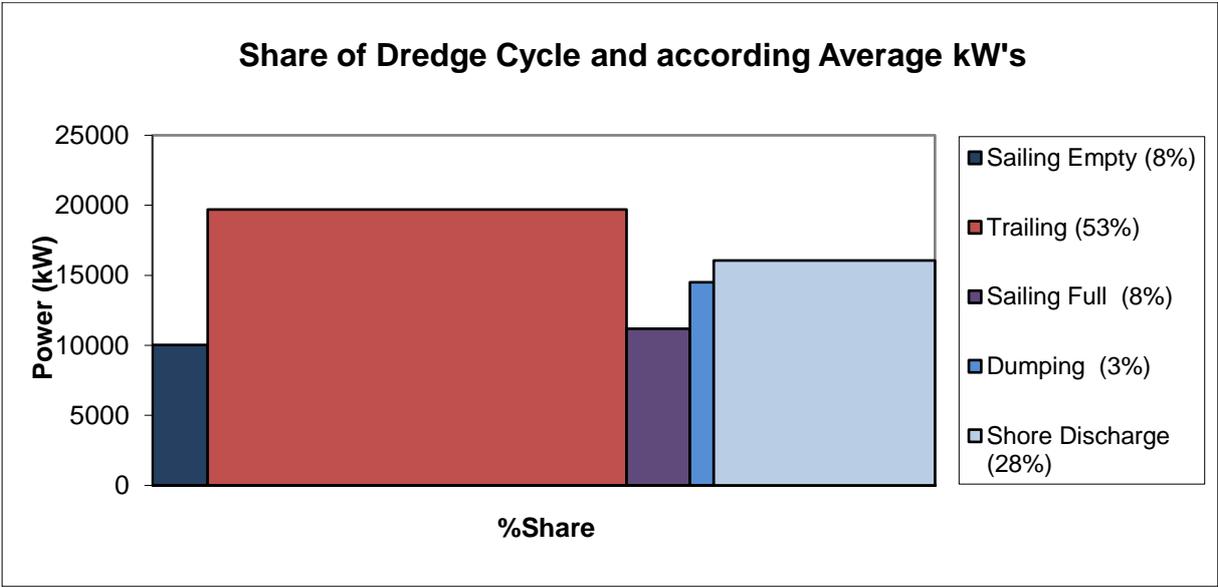


Figure 40 Share of Dredge Cycle and according Average kW's

### 2.3.15 Optimal set of SOFC system

For the determination of the optimal set of SOFC. A calculation needs to be made based on the total average kW demand, weighted for the time % share. The total average kW's over the 10 dredging cycles will be used as the set amount of SOFC. The total average kW's is based on the generated power from the group 'Main engines PS/SB' . After this has been done it is possible to determine the kWh potential for each stage. This means that the difference of the installed SOFC power and the average kW for the stage is the 'gap' that can charge or discharge the Battery Storage systems.

#### SOFC

For the amount of power needed for the SOFC the following calculations have been made. The results can be found in Table 9 To determine the installed set of SOFC the total average of the 'Main engines PS/SB' for each stage in all 10 measured cycles have been used. The averages of the 'Main Engines PS/SB' can be found in the appendix 'kW's Bilbao'. The total average 'Main engines PS/SB' of each stage have been multiplied by the average minutes calculated in the CADC-cycle. The totals for each stage have been summed up and divided by the total minutes of the CADC. This results in a total average power of 17099 kW of SOFC that need to be installed.

| Main Engines PS/SB | Avg kW-stage | CADC min | kW * min |
|--------------------|--------------|----------|----------|
| Stage 1            | 10028.2      | 35       | 350987   |
| Stage 2            | 19693.9      | 249      | 4903781  |
| Stage 3            | 11187.1      | 38       | 425110   |
| Stage 4            | 14504.5      | 15       | 217568   |
| Stage 5            | 16061.3      | 130      | 2087969  |
| Total              |              | 467      | 7985414  |
| Installed SOFC     |              |          | 17099    |

Table 9 Determination of SOFC power, power demand per stage corrected for time

## 2.4 The Hybrid and Energy Storage System

In this chapter the potential Hybrid and Energy Storage System will be discussed and determined. For the fluctuations in power demand there is a solution needed. This can be found in a power balancing energy storage system. The ESS will work together with the SOFC's in a hybrid system. To get to the point of the decision which ESS to use, the following steps will be taken. An explanation of the different kinds of technologies will be given. These technologies include a battery system, flywheel system and a system of Supercapacitors. These are ought to be most suitable for the maritime industry. Nevertheless, they do differ from each other. Through a Multi-Criteria Analysis a decision will be made. The choices for the different of the criteria in the analysis will be discussed, followed by the explanation for the weighting of the factors.

The literal translation or definition of a hybrid system is: *"a dynamical system that exhibits both continuous and discrete dynamic behavior"*. (Heemels, Lehmann , Lunze, & De Schutter, 2016).

This explanation is rather abstract and for this thesis it needs to be redefined to a sentence that is more applicable for power generation in the maritime industry. This could turn into a definition somewhat like the following.

*“A hybrid ship is a ship that generates energy, stores energy and optimizes power control in an efficient way to reduce fuel costs, maintenance and emissions while guaranteeing safety and performance”*

For this thesis a hybrid system is regarded as a combination of Ammonia fueled Solid Oxide Fuel Cells in combination with an Energy Storage System, this system still needs to be defined in the following paragraphs. The ESS part of the hybrid system could exist of a chemical, electrical or mechanical solution. This could be either flow batteries, lithium-ion batteries, flywheels or supercapacitors. Other possibilities for an ESS are already excluded beforehand. During the desk research it became clear that there is a rather large variation in the possibilities and solution for ESS. The vast majority of these were not applicable or even close to being suitable for this research. The 4 most feasible solutions will be discussed.

## **2.4.1 Energy Storage Systems**

For the Energy Storage System of the hybrid configuration there are multiple options possible. ESS can be found in the form of a battery back-up systems, capacitors, flywheels or even in a different form of hydrogen technology. The latter of these will not be discussed in thesis as it is not to be expected to be efficient to have 2 different hydrogen systems and hydrogen storage solutions on the TSHD. (Paauw J. , 2019)

In the literature review the possibility and technologies of a battery system have briefly been discussed. There is broad spectrum of different kind of battery technologies, of which just a few are suitable for the maritime industry. This is due to capacity, energy density and other technical limitations. In DNV GL's article, *“the future is hybrid”*, (Mollestad, E; Valoen, L. O., 2017) a wide variety of ESS have been tested or discussed. Looking at the needs for our system, the most suited technologies appear to be flow batteries, lithium-ion batteries, flywheels or supercapacitors.

### **2.4.1.1 Lithium-ion**

A battery is an electrochemical device that stores electrical power through chemical reactions. On both sides of a battery there are electrodes, anodes and cathodes. These are needed to electrically cause a chemical reaction that can either charge or discharge the device. The electrolyte in the battery is a catalyst for the electrochemical reaction. In a lithium-ion battery this is a gel polymer. The charging and discharging of a lithium-ion battery is explained in Figure 41.

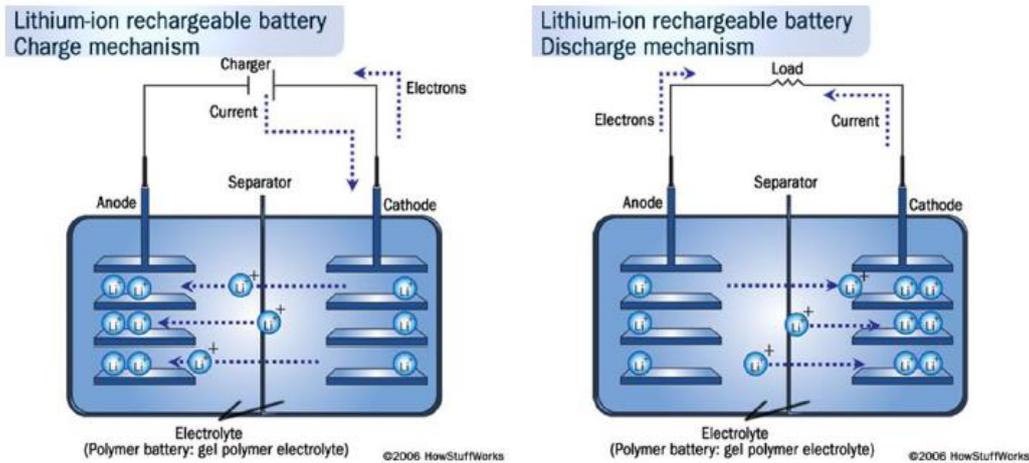


Figure 41 Lithium-Ion (dis)charge mechanism; (Mjos, et al., 2016)

How much energy can be stored and how quickly it charges and discharges depends on different compositions and chemistry of the device. In the maritime industry battery systems are relatively large. The connection of battery cells together makes it possible to capture large amount of energy. The battery management system, BMS, can operate the cells in a comprehensive way. Generally there are 3 different kinds of forms that battery cells are produced. These are cylindrical, soft pouch or prismatic. Each have a different way of how they are enclosed, ventilated or have a mechanical current interruption device (CID). This creates certain safety features that can either be positive or negative. DNV-GL describes the characteristics of the cells as follows.

| Property                                  | Cylindrical                          | Soft Pouch                              | Prismatic                            |
|---|--------------------------------------|---|--------------------------------------|
| Enclosure                                 | Steel or Aluminium                   | Multi-layer laminate pouch              | Aluminium Plastic Steel              |
| Cell vent mechanism                       | Fixed direction at specific pressure | Packaging failure vents at low pressure | Fixed direction at specific pressure |
| Mechanical current interrupt device (CID) | Can be included in header            | Non-existent                            | Can be included in header            |

Table 10 Battery characteristics; (Mjos, et al., 2016)

### Battery Chemistries

The quality of a battery is determined by its longevity, consistency, energy density and safety. However, the positive electrode side of the battery is the most defining of the performance of the device. This is also often the part where the battery gets its name from. The composition of the material is decisive for the power, energy and lifetime of the battery. The most common chemistries are the following

- Lithium cobalt oxide ( $\text{LiCoO}_2$ ). This chemistry has a high energy density, which is beneficial. On the other side the cycle life and power rates are rather low with this cathode. On the safety aspect it does not perform well. At high temperatures the battery releases oxygen. This can result in fires or thermal runaways.
- Lithium manganese oxide spinel ( $\text{LiMn}_2\text{O}_4$ ) The spinel structure gives high power capabilities. Next to that the thermal stability is also beneficial. Drawbacks are the marginal energy capacities and the fairly short cycle at higher temperatures.
- Nickel manganese cobalt oxide, ( $\text{LiNi}_{1-x-y}\text{Mn}_x\text{Co}_y\text{O}_2$ ) The nickel manganese cobalt cathode is the most used combination for large applications. The combination of these 3 elements generate high power densities, energy densities and scores well on the safety aspects.
- Lithium iron phosphate ( $\text{LiFePO}_4$ ) This cathode is significantly different to the other forms. Its structure exists from phosphorous-olivine layers instead of metal oxides. This causes a lack of oxygen on the cathode side, reducing potential risks of thermal runaway. On the other side  $\text{LiFePO}_4$  has a lower voltage and lower energy levels.

#### 2.4.1.2 Flow batteries.

Flow batteries are electrical storage devices that are a solution between fuel cells and regular batteries. The flow battery exists of 2 electrolyte tanks and a reactor in the middle to connect the electrolyte tanks. Electricity is generated in the same way as a fuel cell. The flow reactor has a positively charged cathode and a negatively charged anode and a membrane in between these electrodes. The liquid electrolyte is pumped through the reactor and the ions that exchange between the anode and cathode generate electricity. The electrical current is created by the ion flow through the microporous membrane. This chemical reaction is a reduction oxidation reaction, redox reaction. The most common electrolyte material and reaction is the Vanadium Redox flow battery and will be used for this thesis. Other electrolyte materials for flow batteries are the Zinc-Bromide (Zn-Br), Iron-Chromium (Fe-Cr) and Polysulfide-Bromide (PSB) technologies. (Battery University , 2019) (Nguyen & Savinell, 2010)

The amount of energy that can be stored in the system is fully dependent on the size and volume of the Electrolyte tanks. The bigger the tanks, the more energy can be stored. In this way the flow battery is rather interesting for multiple energy demanding auxiliaries. But there are more advantages to this technology. Because the electrolyte and electroactive materials are not stored within the system, the power and energy can be decoupled of each other. In this way storage can easily be upgraded, or the flow reactor can be easily upgraded if needed. (Battery University , 2019) (Nguyen & Savinell, 2010)

### 2.4.1.3 Flywheels

A flywheel is a device that can store kinetic energy for a certain amount of time. The kinetic energy is 'stored' in a rotating object. Generally this is in a disk shape. When energy needs to be stored the device will accelerate the flywheel, or rotor, to a high speed. By keeping this high speed steady the energy will be stored as a rotational energy. When the energy is needed from the system the rotational energy can be transferred in either electrical or mechanical energy. The extraction of the energy from the flywheel will cause the rotor to decelerate. The rule of thumb here is; the higher the speed of the rotor the more energy is stored in the system. (Zhou, Benbouzid, Charpentier , & Scuiller , 2013).

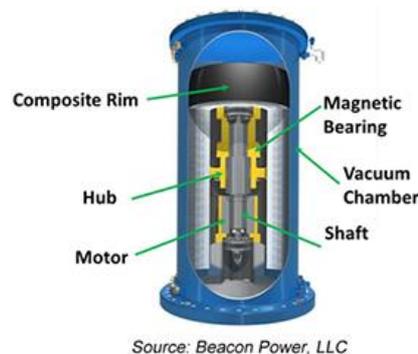


Figure 42 Flywheel; Beacon Power LLC, (Zakeri & Syri , 2015 )

Flywheels can roughly be separated into 2 different categories. Low and High speed. Low speed fly wheels going slower than 10.000 rpm and high speed faster than 10.000 rpm.

A typical flywheel system is displayed in Figure 42. The power that a flywheel is based on the rpm a flywheel can produce and how much friction is involved. To avoid too many losses due to friction, flywheels operate in a vacuum. The rotating part in the cylinder can be made of different materials. For low-speed flywheels this is steel, high-speed flywheels are generally made out of composite. The bearings in the low-speed flywheels have generally a bit more friction than the bearing in the high-speed flywheels. The composition of a heavier rotational device and more friction in the bearing results in a 5-30 Wh/kg energy density for low-speed flywheels and around 100Wh/kg energy density for the high-speed flywheels. (Hadjipaschalis, Poullikkas, & Efthimiou, 2009) the low-speed flywheels produce more power but over a shorter amount of time than the high-speed flywheels. In this article (Makbul, Hiendro, & Twaha, 2015) a bigger single flywheel system have been reported, generating little over 1 MW for a brief 15 sec. Also flywheel farms have been described. Providing 20 MW for a duration of 15 minutes. (Doucette & McCulloch, 2011)

In general there are advantages and disadvantages for the flywheel energy storage systems (FESS). The key advantages of the FESS is the rather high cycling time, this gives the FESS a rather high lifetime of roughly 30 years before it needs to be replaced. Also low maintenance makes the lifetime fairly long. Next to that the FESS has a high energy density and efficiency, it can quickly charge and discharge without too many losses. The efficiencies of flywheels are around 85%-97%, which is very high. High energy density and efficiency is favorable for an energy system with a lot of power demand fluctuations. . (Hadjipaschalis, Poullikkas, & Efthimiou, 2009) (Doucette & McCulloch, 2011). There is a major drawback in the flywheel technology, which can be a deal breaker for the decision on the

ESS for the TSHD. This is the self-discharge rate of FESS. With a 20% loss per hour the system cannot contain energy over a longer period of time. On the other hand, for the short term solution it is promising technology.

Flywheel costs.

The cost of the flywheel technology is fairly fluctuating. The costs depend on the materials used and which company made them. In the research “*electrical energy storage systems: a comparative life cycle cost analysis*” (Zakeri & Syri , 2015 ) an financial assessment of a wide variety of ESS has been made. The research found that the high-speed flywheels can have as much as 500% more costs than the low-speed flywheel technology. This wide variation is due to the different kinds of materials and techniques that are being used by different manufacturers of flywheels. Zakeri’s research they found that the purchase cost of low-speed flywheels are averaged on €290/kW and that the cost of installation is set at €19/kW. This comes down to a TCC of €309/kW. In comparison, high-speed flywheels have an average TCC of €867/kW. The literature research pointed out that the lifetime of flywheel systems is roughly 15-20 years. The replacement cost are based on a 10-year period and range from €85 - €216/kW, averaging out on €151/kW. (Zakeri & Syri , 2015 )

#### 2.4.1.4 Supercapacitors.

Capacitors are electronic components that can store electrical energy in an electric field for a certain amount of time. This process is also called the capacitance effect. The capacitor exist from 2 ‘plates’, or conductors. The 2 conductors are negatively and positively charged and are being separated by a so called dielectric, this is comparable with an electrolyte in for example fuel cells or how a battery system works. The capacity of a capacitor is expressed in Farad and depends on the ratio of charge (Coulomb) and Voltage (V) and can be written down in the following formula.

$$Q = CV = \frac{A\varepsilon}{d}V$$

In this formula the charge (Q) is the Capacitance effect (C) times the Voltage (V). The Capacitance (C) equals the Area (A) between the 2 conductors times the permittivity of the dielectric ( $\varepsilon$ ) which should be divided by distance (d) of the 2 conductors. (Vazquez , Lukic , Galvan , & Franquelo , 2011 )

Super and Ultra capacitors are similar to regular capacitors, the only difference is that Super and Ultra capacitors can deliver more power and energy.

Besides that, Super- and Ultracapacitors are energy storage devices that are capable of delivering power at much higher rates than regular lithium-ion batteries can. On the other hand, supercapacitors cannot store energy as good as regular lithium-ion batteries. (Zakeri & Syri , 2015 )

Storing the energy in the (Ultra)capacitors is done by physical separation of the electrical charges. The positively charged on one end of an electrode and the negatively on the other side. By doing this there is no chemical reaction to the electrodes. This has substantial benefits for the performance of the Ultracapacitors. (Zakeri & Syri , 2015 )Both the energy efficiency as well as the Power density of the

capacitors is rather high. Energy Efficiency is measured around 95% and the Power density reaches up to 4000W/kg. (Vazquez , Lukic , Galvan , & Franquelo , 2011 )

Another benefit of physical separation of the charges is that the cycle life of the capacitors is high. The Ultracapacitors can easily exceed 50.000 cycles before they need to be replaced. (Vazquez , Lukic , Galvan , & Franquelo , 2011 )

Drawbacks of the ultracapacitor technology is the Energy density of the system. The beforementioned separation of charges and no chemical reaction make it impossible to save more Energy in the capacitor. Overall this charge separation means that the capacitor can quickly take up and release power and energy, but cannot store it over longer periods of time. (Zakeri & Syri , 2015 ) (Vazquez , Lukic , Galvan , & Franquelo , 2011 )

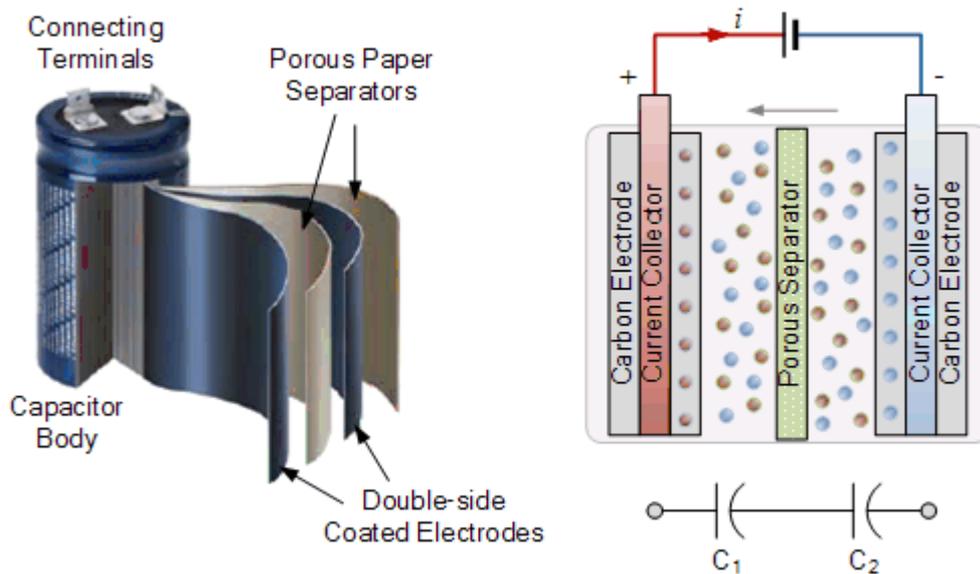


Figure 43 Ultra Capacitor, schematic mechanism (Vazquez , Lukic , Galvan , & Franquelo , 2011 )

## 2.4.2 Technology costs

### Flywheel costs

The cost of the flywheel technology is fairly fluctuating. The costs depend on the materials used and which company made them. In the research “*electrical energy storage systems: a comparative life cycle cost analysis*” (Zakeri & Syri , 2015 ) a financial assessment of a wide variety of ESS has been made. The research found that the high-speed flywheels can have as much as 500% more costs than the low-speed flywheel technology. This wide variation is due to the different kinds of materials and techniques that are being used by different manufacturers of flywheels. Zakeri’s research they found that the purchase cost of low-speed flywheels are averaged on €290/kW and that the cost of installation is set at €19/kW. This comes down to a TCC of €309/kW. (Abele , Elkind, Intrator, & Washom, 2011 ) In comparison, high-speed flywheels have an average TCC of €867/kW. The

literature research pointed out that the lifetime of flywheel systems is roughly 15-20 years. The replacement cost are based on a 10-year period and range from €85 - €216/kW, averaging out on €151/kW. (Zakeri & Syri , 2015 )

### Ultracapacitors

The costs concerning Ultracapacitors are not very well described in the literature review of Zakeri. There is little known about the cost price of this technology on a high power scale. The price of ultracapacitors on low scale are more often described. But these figures cannot be used for the application on large scale. The reviewed articles set the total capital cost of the technology around and average of €229/kW. (Inage , 2009)

### Flow batteries

The price of the vanadium redox flow battery technology (VRFB) is going through some promising times. The research and development on new materials and configurations contribute to a diminishing cost price and an increasing performance (Lloyd, Vainikka, & Kontturi, 2013). The price of the power conversion technology in the VRFB ranges from €424 - €527/kW. This is just the system itself and not the total capital cost of a flow battery system. Other costs include the storage section, fixed and variable O&M and replacement cost. For the storage section the price is determined on €467/kWh. The O&M are split up in to cost parts. The fixed and variable. The fixed costs are determined at €8,5/kW-yr and the variable costs are set on €0.9/MWh. The last cost item is the replacement cost, these are based on an every 8 year replacement period and with a use of 365-500 cycles per year and are set on €130/kW. Doing the math and adding all these items up the research sets the TCC on a total of €1360/kW. (Kear, Shah , & Walsh, 2012 )

### Li-ion

For the lithium-ion battery solutions the same outcome holds as with the VRFB solution. At the moment the technology of the Li-ion are heavily developing and the storage and power capacities of the technology keep on improving. For this research a TCC of €2512/kW will be used. This TCC is build up out of several factors. Of which not all are being described in the article of Zakeri. Zakeri accounts the PCS, power conversion system, for €463/kW and this already includes a Balancing of Plants of €80/kW. The storage section of the battery is set on €795/kWh and the O&M cost are set on €6.9/kW-yr and €2.1/MWh for Fixed and Variable respectively. The 5 year replacement of the application, based on 365-500 cycles per year are set on an annual cost of €369/kW. (Chen , et al., 2009)

| Technology                               | Min                   | Avg  | Max  | Min                        | Avg  | Max   |
|--|-----------------------|------|------|----------------------------|------|-------|
| <b>Total Capital Cost of ESS systems</b> |                       |      |      |                            |      |       |
|  | TCC power rating €/kW |      |      | TCC storage capacity €/kWh |      |       |
| <b>Li-ion</b>                            | 2109                  | 2512 | 2746 | 459                        | 546  | 560   |
| <b>VRFB</b>                              | 1277                  | 1360 | 1649 | 257                        | 307  | 433   |
| <b>Ultracapacitors</b>                   | 214                   | 229  | 247  | 691                        | 765  | 856   |
| <b>Flywheel</b>                          | 590                   | 867  | 1446 | 1850                       | 4791 | 25049 |

Table 11 Overview of the Total Capital Cost of ESS technology

| Technology                            | Fixed (€/kW-yr) | Variable (€/kW-yr) |
|---------------------------------------|-----------------|--------------------|
| <b>Operation and Maintenance Cost</b> |                 |                    |
| <b>Flywheel</b>                       | 5.2             | 2                  |
| <b>VRFB</b>                           | 8.5             | 0.9                |
| <b>Li-ion</b>                         | 6.9             | 2.1                |
| <b>Ultracapacitors</b>                | ?               | ?                  |

Table 12 Operation and Maintenance Cost of technologies

In Table 11 an overview of the Total Capital Cost per unit of power rating and per unit of storage capacity are summarized. Table 12 depicts the fixed and variable operational and maintenance cost of the ESS technologies.

From this data we can tell that the Ultra capacitors have the lowest cost when it comes down to the Total Capital Cost per unit of power rating. This means it has the lowest price per kW. Li-ion being the most expensive per unit of power. Li-ion scores worse than other options due to the fact that the power output of batteries is in general lower than the power output possibilities for other ESS technologies.

The Total Capital Cost per unit of storage see a slightly different composition of technology performance. When it comes down to energy capacity (€/kWh) the best performing technology is the Vanadium Redox Flow Battery. This technology has an energy storage capability that reaches up to months, due to both technology as well as the volume of the energy storage. (Figure 47) Therefore the €/kWh is lower than other technologies as the other technologies have storage durability's that are much lower than VRFB. A shorter durability and energy storage volume will cause the TCC per unit of storage capacity to increase. This results in a rather expensive TCC for the flywheel technology. Flywheels discharge rather fast and cannot storage energy for a long period of time. Therefore the high TCC and wide range of the TCC for €/kWh.

### 2.4.3 Multi – Criteria Analysis

To determine the optimal solution for the back-up of the power fluctuations, there will be a multi-criteria-analysis (MCA) executed in the next chapter. This multi-criteria analysis is mainly based on qualitative outputs and some quantitative outputs. Therefore there will be no scoring or weighting included. Instead the decision will be based on the best interest and best practice for Van Oord. What factors are most important to the company and success of the system. In this MCA 4 options for the hybrid system will be tested. To decide which system is the most suitable for this research different factors will be weighted. These factors include Power, Energy, Volume/size, Weight, Lifetime, Costs and Charge/Discharge time.

## Power

The Power parameter represents the maximum power, in both charging and in discharging, that can be reached by the certain technology. It is both the average as well as the peak power that the technology can deliver. The power of the technology needs to be sufficient to account for sudden peak fluctuations, therefore the power sum of the SOFC and the ESS cannot drop below its peak. Power is expressed in kW's

## Energy

The energy parameter is also referred to the energy capacity of the ESS. It is the quantity of energy that is available when the ESS is fully charged. Which can be expressed in Wh, kWh or MWh. For this thesis this will be kWh. The energy that actually can be used from the ESS is limited by the capacity the technology has to be depleted or discharged. This basically means that the usable energy is 100% of the capacity minus the minimum depth of discharge, also known as the efficiency of the ESS. When the ESS is charged too quickly or discharged too quickly the efficiency of the ESS can be negatively affected. Resulting in less efficiency or shorter lifetime. This will indirectly lower the overall performance of the ESS.

## Efficiency

The efficiency of the ESS technology is obviously important as well. The efficiency is the ratio between the energy that is stored in the ESS and the energy that is released by the ESS. Expressing the efficiency in this way is a bit simplistic. As the formula does not account for losses in other kinds of ways. This could be a loss in charging or self-discharging. The efficiency rating should be as high as possible. This would mean the ESS hardly has any losses in self-discharging or the transfer of energy. Volume/weight

As the name of the parameter indicates. The volume/weight of the ESS is referred to in this aspect. The volume/weight can be expressed in different ways. This could be  $\text{kg/m}^3$ ,  $\text{kW/m}^3$  or  $\text{kW/kg}$ . This will be determined later in the analysis. The most likely expression of the criteria will be  $\text{kg/m}^3$ .

## Lifetime

The lifetime criteria of the system is also rather relevant for the succession of the ESS technology. Lifetime is mostly expressed in years and/or cycles of the system. This will also be used as an indicator in this research. The lifetime can be a deal breaker or maker for the feasibility study. When the lifetime decrease to rapidly or is too short in general, the overall cost or ROI can be too high or unfavourable.

## Costs

The cost of the ESS will be indicated in this criteria. This will expressed in price/kW of the system. This is a rather rough indication as the total cost of an ESS is hard to determine. There are obviously articles that publish competitive prices, but the relevance of these numbers cannot always be guaranteed. The numbers do help to give a proper indication of the price.

## Charge/Discharge

The time an ESS needs to charge or discharge is also a quite essential criteria. Looking at the power demand fluctuations in paragraph 2.3, it shows us that the dredging stage, which was studied, accounts

for roughly 50% of the time. So 50% of the time the ESS is being charged and 50% of the time it is being discharged. The time of discharge and charge should fit within the boundary limits of the dredging profile.

The best interest for Van Oord would be a system that is capable of load stepping between the different dredging stages. The system should be able to cover the load demands as analysed in the Power Demand Analysis. Next to that it would be convenient that the system is not too expensive, to what extent that is possible. Because of the abovementioned criteria, a closer look will be taken into the Power and Energy possibilities as well as the costs.

**2.4.3.1 Power demand**

To come to the right decision which ESS solution to work with, we will need to a closer look at the characteristics of the ESS solutions. The characteristics have been described in the previous paragraph and summarized in Figure 47 . The criteria's for the ESS have also been described in the previous paragraphs.

The technical demands for the ESS lie mostly in the Power output. The ESS will need to be able to meet the load step that occur in the power demand. As depicted in Figure 44 Power demand Main engines PS/SB the fluctuations in power demand in a short amount of time is clearly visible. Figure 45 Power demands Main Engines PS/SB, zoomed in is a zoomed in example of the prior Figure 44 Power demand Main engines PS/SB. The orange square marks the zoomed in area. The zoomed in area shows that the power demand can fluctuate from approximately 19.000 kW at point 05:15:50 to almost 24.000 kW at point 05:16:05. This is an increase of roughly 5.000 kW within a time window of only 15 seconds. This is a serious demand of power output within a short amount of time. The ESS will need to be able to meet this demand, if not, the system will collapse and the ship won't be able to operate. Therefore we are looking for an ESS with a high energy density. The higher the energy density, the more kW's are included per kg of the system. If the density is not high enough the system will not be able to meet the power demand and can be rather heavy or rather voluminous.

| Technology       | Power Density | total kg's    |
|------------------|---------------|---------------|
| Li-ion           | 360 W/kg      | 14278         |
| VRFB             | 80 - 150 W/kg | 64250 - 34266 |
| Ultra-Capacitors | 4000 W/kg     | 1285          |
| Flywheel (steel) | 1000 W/kg     | 5140          |
| Flywheel (comp)  | 5000 W/kg     | 1028          |

Table 13 Power densities of ESS technologies

The above depicted Table 13 the total amount of kg of each ESS, based on their Power Density (W/kg) The calculation was based on the maximum peak power in the system. This peak is relative to the total installed SOFC capacity, 5140 kW.

$$\frac{5140 \text{ kW}}{\text{Power density} \left( \frac{W}{kg} \right)} = \text{total kg's of ESS}$$

Based on this calculation it can be concluded that the Ultra-Capacitors and the Flywheel technologies have the lowest total weight of the system and most likely also the least volume. In the case of power

demand these technologies outperform the Li-ion and VRFB technology.

**2.4.3.2 Energy demand**

The energy supply capabilities are also relevant for the succession of the system. Over a short amount of time the ESS should be able to deliver enough energy to keep the system running. To sketch a rough estimation of the amount of energy that is needed to be delivered, the following calculation has been made. From the tested dredging stage a certain, or representative, peak has been tested. In this peak the total demanded energy has been calculated. With this information and the knowledge of the energy density of the ESS possibilities, the weight of the ESS can be calculated.

In Figure 45 Power demands Main Engines PS/SB, zoomed in one can see a zoomed in graph, this represents the tested peak in the power demand. The blue line represents the average power demand in the tested dredging stage and also the installed amount of SOFC's. The purple line represents the highest peak demand in the total stage. The black line depicts the average power demand over the tested peak, which is being described.

To know how much energy is demanded in the tested peak, the following steps need to be taken.

$$\frac{\text{Average power demanded in test peak}}{3600 \text{ sec}} = \text{kWs (kilowatt per second)}$$

$$\text{kWs} * \text{duration of test peak} = \text{demanded energy during the peak}$$

This will give the following outcome

$$\frac{21923 \text{ kW}}{3600} = 6 \text{ kWs} \rightarrow 6 \text{ kWs} * 89 \text{ seconds} = 550 \text{ kWh}$$

With this information the calculation of the weight/energy density of the ESS can be made

$$\frac{\left(\frac{\text{demanded energy during peak}}{\text{energy density of ESS}}\right)}{\text{Efficiency of ESS}} = \text{kg of ESS}$$

Inserting the details, that are published in Table 14, into the formula gives the following results.

| Technology       | Energy Density | Efficiency | total kg's  |
|------------------|----------------|------------|-------------|
| Li-ion           | 100 - 200 Wh   | 70 - 85%   | 3235 - 7857 |
| VRFB             | 27668 Wh       | 80%        | 25          |
| Ultra-Capacitors | >50 Wh         | 95%        | >11580      |

|                         |           |     |                |
|-------------------------|-----------|-----|----------------|
| <b>Flywheel (steel)</b> | 5 - 30 Wh | 95% | 19290 - 115790 |
| <b>Flywheel (comp)</b>  | >50 Wh    | 95% | <11580         |

**Table 14 Energy densities, efficiencies and kg's of different ESS**

The outcomes of the formula for the total kg's of ESS that are needed to meet the energy demand for such a peak as the one used for the example show the following results. As can be seen, the VRFB outweighs the other technologies by a significant amount. This looks promising, but is misleading. The energy capacity of the VRFB is totally depending on the volume of the system. In this peak it therefore, will 'lose' 25 kg of the stored capacity. Using a VRFB for the total system during this peak will require a much larger system. As it will drain energy quicker during peak than it will store during the dip. If a VRFB is the most suitable candidate for the ESS the weight of the system needs to be more accurately calculated.

#### Cost

Furthermore it would be convenient if the ESS is not too expensive. This, in combination with an ESS that needs to have the capability to deliver a lot of power, means that we are looking for a system that has a low TCC per kW. This TCC should be complementary with the lifetime or cycle life of the ESS. If an ESS system is cheap, but the lifetime or cycle life is not ideal, it means that the system will be replaced relatively often. Resulting in a high price after all. Looking at Table 15 for the cost per kW, the Ultracapacitors have the lowest TCC. Besides the lowest TCC the Ultracapacitors have the longest lifetime. Figure 47. In the case of lifetime it is not convenient to look at the cycle life of the technologies. The cycle life of each technology differ a lot from each other. This does not necessarily mean that their life time is longer as well. Flywheels and Ultra-Capacitors cycle more often than VRFB or Li-ion batteries, resulting in higher cycle life.

#### Decision

Based on the beforementioned criteria for the right ESS technology, to back-up the power fluctuations in the trailing stage of a dredging cycle. It has been determined that the Ultra-Capacitors are the most favourable technology to meet the demands of the system. In Appendix 5 positive/negative scheme ESS technologies another brief review of pro's and con's has been depicted to back-up the decision. At the fluctuation and ramp-up speed of power it seems favourable to use the Ultra-capacitors as the ESS technology. The Ultra-Capacitors can quickly take up and release power and energy in short amounts of time. It is a fairly cheap solution for stabilisation of the system at the determined power levels, and it has a low volume/weight density, causing it not to take up to much space in the TSHD.

Next to the back-up for power fluctuations, it is important that energy can be stored as well. As determined in the Power Demand Analysis, the SOFC stack system capacity is set on 17099 kW. This means that during certain stages energy can be stored and certain stages energy needs to be released. For the storage of energy it seems that, of the 4 technologies, the Li-ion battery system is the most suitable. The TCC of the storage capacity is one of the lowest of the 4 technologies. Next to that the energy density of a Li-ion system scores relatively well, same holds for the duration of storage. As the Flywheel and UC's can only store energy for a rather limited amount of time, it seems that the Li-ion system is more favourable.

| Technology                               | Min                   | Avg  | Max  | Min                        | Avg  | Max   |
|--|-----------------------|------|------|----------------------------|------|-------|
| <b>Total Capital Cost of ESS systems</b> |                       |      |      |                            |      |       |
|  | TCC power rating €/kW |      |      | TCC storage capacity €/kWh |      |       |
| <b>Li-ion</b>                            | 2109                  | 2512 | 2746 | 459                        | 546  | 560   |
| <b>VRFB</b>                              | 1277                  | 1360 | 1649 | 257                        | 307  | 433   |
| <b>Ultracapacitors</b>                   | 214                   | 229  | 247  | 691                        | 765  | 856   |
| <b>Flywheel</b>                          | 590                   | 867  | 1446 | 1850                       | 4791 | 25049 |

Table 15 Total Capital Cost of ESS systems for power and energy

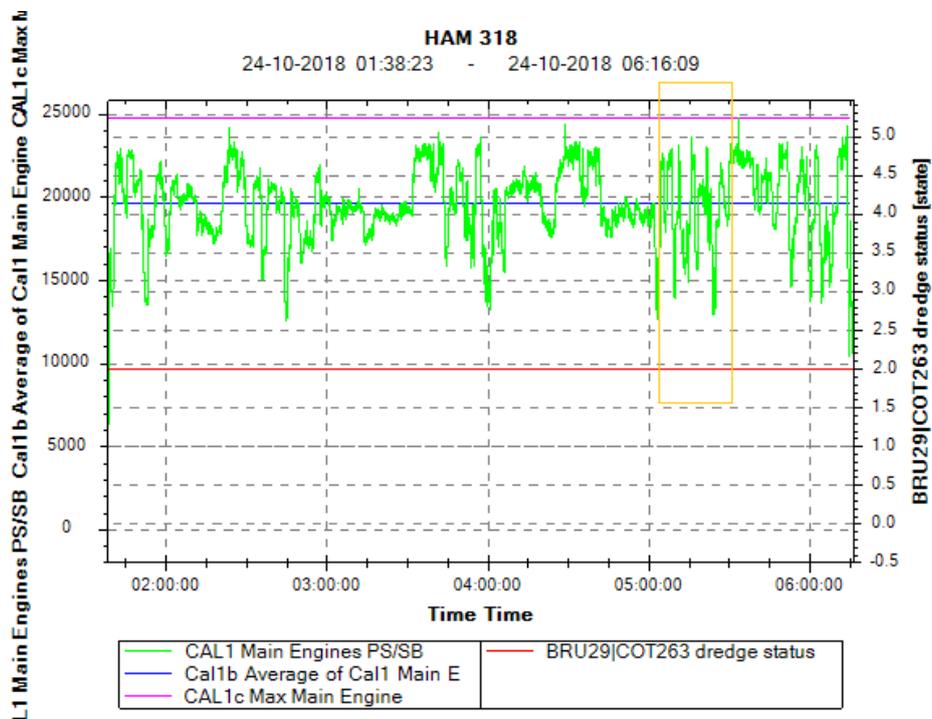


Figure 44 Power demand Main engines PS/SB

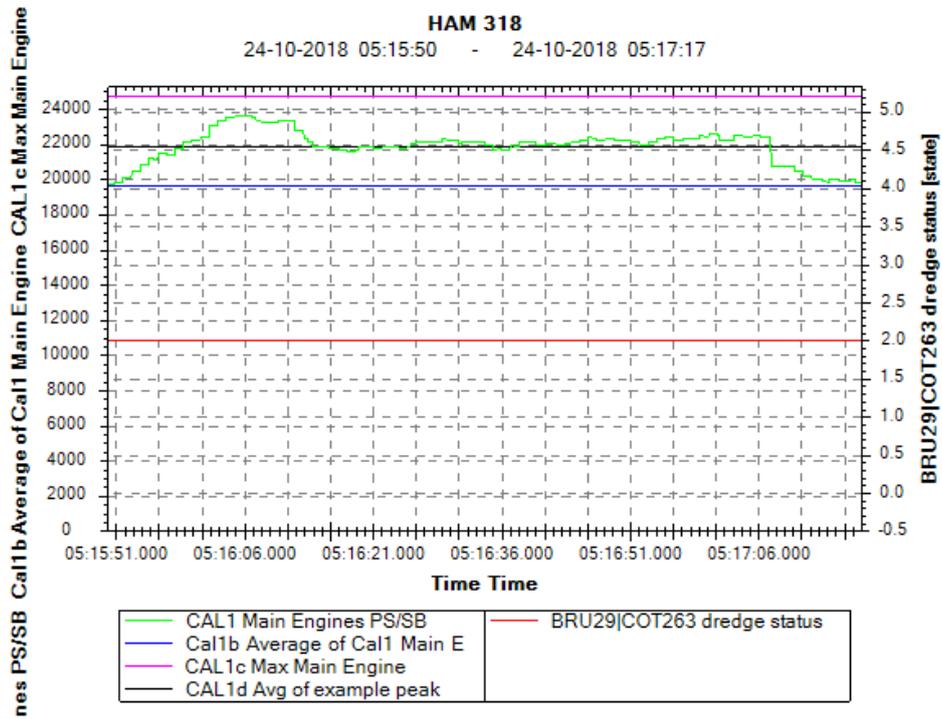


Figure 45 Power demands Main Engines PS/SB, zoomed in

| <i>Technology</i>       | <i>Energy Efficiency</i> | <i>Energy Density</i> | <i>Power range</i> | <i>Power Density</i> | <i>Lifetime</i> | <i>Cycle Life</i> |
|-------------------------|--------------------------|-----------------------|--------------------|----------------------|-----------------|-------------------|
|                         | (%)                      | (Wh/kg)               | (MW)               | (W/kg)               | (years)         | (cycles)          |
| <i>Li-Ion</i>           | 70-85                    | 100 - 200             | up to 0.01         | 360                  | 5-15            | 500-2000          |
| <i>VRFB</i>             | 80                       | 27668                 | 0.03 - 3           | 80-150               | 5-10            | 16000             |
| <i>Ultracapacitors</i>  | 95                       | <50                   | up to 0.3          | 4000                 | 10-20           | >50.000           |
| <i>Flywheel (steel)</i> | 95                       | 5 - 30                | up to 0.25         | 1000                 | 15-20           | >20.000           |
| <i>Flywheel (comp)</i>  | 95                       | >50                   | up to 0.25         | 5000                 | 15-20           | >20.000           |

| <i>Technology</i>       | <i>Self Discharge</i> | <i>Total Capt Cost</i> | <i>Fixed O&amp;M</i> | <i>Storage</i> | <i>(Dis)charge time</i> |
|-------------------------|-----------------------|------------------------|----------------------|----------------|-------------------------|
|                         | (per 24h)             | (€/kW)                 | (€/kW-yr)            | Durability     |                         |
| <i>Li-ion</i>           | 0.1 - 0.3 %           | 2512                   | 6.9                  | min - days     |                         |
| <i>VRFB</i>             | Negligible            | 1360                   | 8.5                  | hours - months |                         |
| <i>Ultracapcitors</i>   | 20 - 40 %             | 229                    | ?                    | sec - hours    | instantly               |
| <i>Flywheel (steel)</i> | 100%                  | 309                    | 5.2                  | sec - min      | instantly               |
| <i>Flywheel (comp)</i>  | 100%                  | 867                    | 5.2                  | sec - min      | instantly               |

Figure 46 Energy Storage Systems - Characteristics

## 2.5 The Retrofit

In this chapter a hypothetical retrofit is being presented. The calculated and determined technologies will be discussed and presented. This is followed up by the storage system on the potential retrofit of the HAM 318 and the new power distribution on board.

### 2.5.1 The Solid Oxide Fuel Cell and Ammonia

As determined in an earlier chapter, the Solid Oxide Fuel Cell, is the most applicable fuel cell technology for the demands of Van Oord and the zero-emission goals. Especially the fuel flexibility of the technology is highly interesting. This is because of different reasons. The fuel flexibility of the SOFC makes it possible to use different fuels for this cell. This can be hydrocarbon based fuels, but more interesting, hydrogen based fuels. Ammonia is such a hydrogen based fuel that is suitable for the SOFC. The combination and operation of the two, SOFC and Ammonia, will be discussed in this chapter. This is based on research of Cinti et al. and will be backed with articles that confirm some findings or statements. Giovanni Cinti has done research in the field of Solid Oxide Fuel Cells and the use of Ammonia. In “*SOFC operating with Ammonia: Stack test and system analysis*” (Cinti, Discepoli, Sisani, & Desideri, 2016) Cinti studied the potential energy vector Ammonia as a fuel for SOFC’S. Cinti found that Ammonia could guarantee high electrical efficiencies and carbon free solutions. For the research a design was made of a thermodynamic model of a complete SOFC system. The results of the research showed that ammonia as a fuel in a SOFC is the most efficient form of hydrogen based fuels.

As briefly described in paragraph 1.7.1 about the different fuel cell technologies, fuel cells work following the method of fuel inlet at the anode side and air inlet at the cathode side. In the case of Ammonia and SOFC there is another process and that is the cracking of the Ammonia. Normally, cracking of Ammonia occurs before entering the fuel cell, but due to its high operating temperatures and the nickel based anode cracking is possible within the cell. Nickel is a catalyst in the cracking of Ammonia, hence the internal cracking at the Anode side. After cracking the hydrogen can be used in the SOFC and the nitrogen can return into the atmosphere. Next to that, the Ammonia cracking is an endothermal process. This means that the heat is inside the cell and keeps the cell cooler than with hydrogen. This is an interesting process, because it means that the air inlet temperature does not have to be heated. In the case that the air inflow needs to regulate the temperature inside, it would mean that efficiency losses will occur.

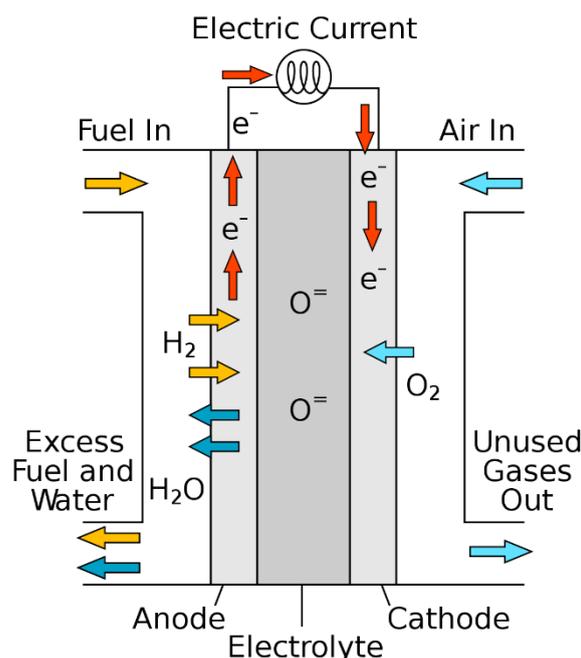


Figure 48 Schematic of SOFC process

### The Cell structure

The SOFC itself exists from 4 layers. These are the anode, cathode, electrolyte and the interconnection. The anode and cathode form a sandwich around the electrolyte. On the outside of this 3-layer form the interconnections can be found. These are needed to stack the cells into a bigger system, hence the name, interconnections. The thickness of the layers of the cell differ from each other. The anode is 700  $\mu\text{m}$  thick. The cathode is 50  $\mu\text{m}$  thick and the electrolyte, in this case the solid oxide, is only 10  $\mu\text{m}$  thick. (Scataglini, et al., 2017)

The anode is made out of a cermet, this is a mix of ceramic and metal. For the anode nickel has been mixed with the ceramic that also is being used for the electrolyte, Ytria Stabilized Zirconia (YSZ). The YSZ has been added to avoid excessive growth of Nickel on the anode side. This could cause the cell to be less efficient.

The electrolyte, as briefly mentioned before, is made out of YSZ and is about 10  $\mu\text{m}$  thin. The electrolyte has the task the let oxygen molecules migrate from the cathode to the anode side of the SOFC. In other words, from the air side to the fuel side. The electrolyte should have a high ionic conductivity and no electrical conductivity to make this migration possible. Furthermore, the the layer needs to have a high density to guarantee that there is no short circuit with reactive gasses. The thinner the electrolyte layer is the lesser resistive losses will occur. (Scataglini, et al., 2017)

The Cathode is made out of lanthanum strontium manganite (LSM) and is 50  $\mu\text{m}$  thick. Basically the layer is made out of lanthanum manganite and is being dipped into strontium to improve the conductivity of the cathode. The cathode is the oxygen side of the cell, therefore it is important that the chemical and structural stability is guaranteed since very high operational temperatures are being reached.

The interconnects are the parts that connect the cells with each other. This is called stacking and makes the SOFC scalable. In this way more power can be produced as the cells stack up and the SOFC system grows larger. The interconnect is made of metals or alloys, for example stainless steel so it is compatible in terms of chemical stability and mechanical compliance. The thermal stresses in the process need to be dealt with to avoid inefficient operation of the cell. (Scataglini, et al., 2017)

### Structures

The SOFC has been developed in 2 different ways. These are the tubular and planar structures. This has been done with the motivation to minimize losses due to electric resistance, how to seal the anode and cathode compartments and the ease of manufacturing. Figure 49 depicts the cross section of a tubular SOFC. The round and tube shaped SOFC consists of 3 layers. The outer layer being the Anode (fuel electrode), the middle layer the electrolyte and the inner layer the Cathode (Air electrode). Air flows through the centre of the pipe and the fuel along the outer layer towards the next tubular cell. The planar structured SOFC has the same anode, cathode and electrolyte, but is shaped differently. In this case the cell has a flat layered structure, as depicted in Figure 50. The planar SOFC can have different shapes. This includes either rectangular, circular or squared. (Yuan, 2008)

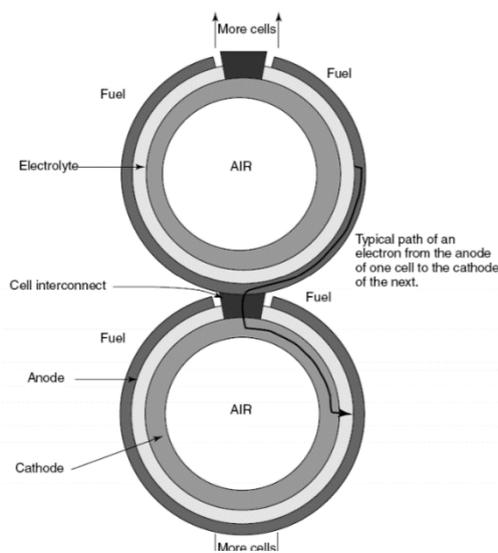


Figure 49 cross section of tubular SOFC

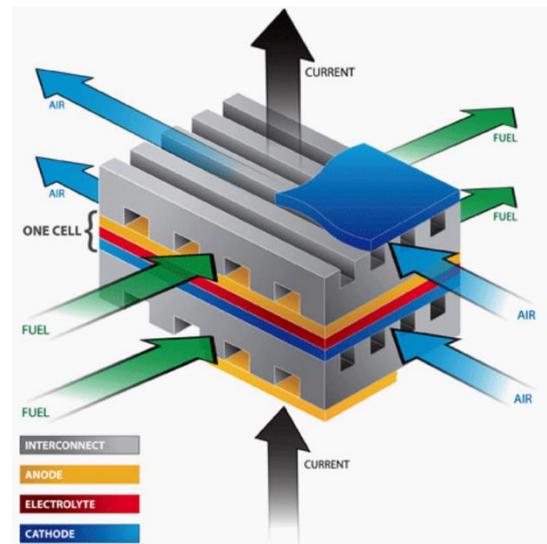


Figure 50 Planar SOFC mechanism

### Challenges

There are some challenges that the SOFC has to deal with. Due to the exposure to high operating temperatures the SOFC has to deal with thermal stresses. The high temperatures in the SOFC causes the materials to expand and shrink when the temperature changes. The expanding and shrinking of the materials can cause cracks. These cracks have a direct impact to the lifetime of a SOFC. Gas leakage and structure instabilities are a direct cause of a mechanical failure of the system. (Xu, Li, Yang, & Andersson, 2016)

### The Cinti Research

In Cinti's research; *"SOFC operating with Ammonia: Stack test and system analysis"* (Cinti, Discepoli, Sisani, & Desideri, 2016). Cinti succeeded in a theoretical and experimental study in which he proved that Ammonia is a very suitable fuel for the SOFC stack system. He proved that with the internal cracking of Ammonia an efficiency of 22% can be achieved for the SOFC. The earlier mentioned 60%-85% in combination with a gas turbine and waste heat recovery can be reached with hydrocarbon based fuels. (Cinti, Discepoli, Sisani, & Desideri, 2016)

The goal of Cinti's research was to perform a SOFC study at system-level. For this, Cinti made a thermodynamic model. With this thermodynamic model Cinti scoped on the evaluation of the energy equilibrium and the effect of ammonia on the cathode inlet flow. With this model Cinti calculated the current density of the fuel inlet flow rate and the fuel utilization. Next to that Cinti calculated the efficiency with pure Ammonia and the power output with certain fuel flow rates. Cinti used the following formula for this.

$$J = \frac{U_f * F * n * n_{fuel}}{A * n_{cell}}$$

In which  $U_f$  is the fuel utilization,  $F$  is the Faraday constant,  $n_{fuel}$  is the molar fuel gas flow,  $A$  the cell area and  $n_{cell}$  is the number of cells and  $n$  the mole of electron available for each mole of inlet fuel (this being  $n=2$  for hydrogen).

To let the SOFC stack system operate in a equilibrium a few steps need to be taken. The operational temperature of the system lies around 750C. Both the air inlet flow and the fuel inlet flow need to be

heated to a temperature of 700C. The outlet temperature of the SOFC is 800C. To reach these temperature the inlet fuel and air flow are pre-heated in 2-stage heating. Figure 51 shows the Schematic system of the model. In the schematic model, 4 Heat—Exchangers are depicted (HE1,2,3,4). HE-1 is both a heat exchangers as well as an evaporator. The HE-1 heats up fuel at the inlet from ambient conditions with the outlet exhaust temperatures from the SOFC. These temperatures are around 330C. HE-4 operates in the same way as HE-1 but instead of heating up the fuel, it heats up the air inlet flow. Further in the schematic model HE-2 and HE-3 are found. These are the high temperature heat exchangers and bring the fuel and air up to higher temperatures for both the anode and cathode side respectively. (Cinti, Discepoli, Sisani, & Desideri, 2016)

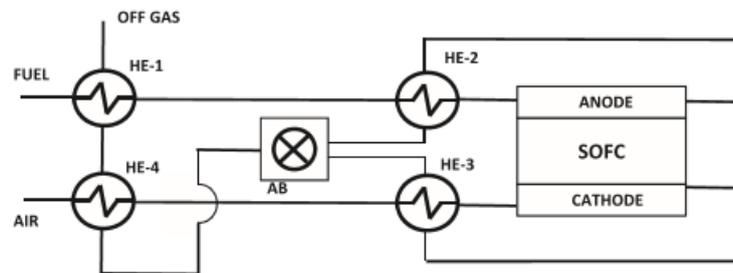


Figure 51 Schemataic SOFC model, (Cinti, Discepoli, Sisani, & Desideri, 2016)

The main findings of the Cinti research, that are important for this thesis, are the successful evaluation of using Ammonia in a SOFC stack cell and system. Cinti tested and succeeded both experimentally as well as theoretically. The efficiency of the cell increased to 22% with an power output of 75W for a 4 layer stack of SOFC's.

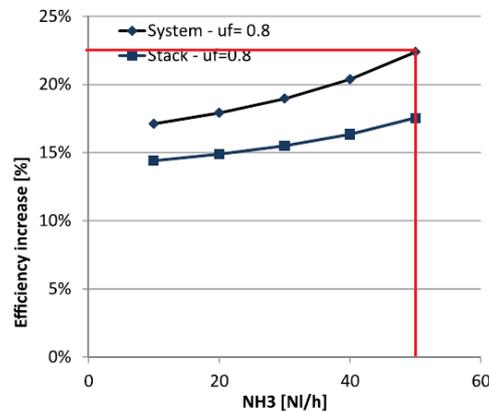


Figure 52 Efficiency and NH3 flow rate, (Cinti, Discepoli, Sisani, & Desideri, 2016)

Figure 52 shows the Ammonia flow rate at the 22% efficiency rate. It shows that at that efficiency and power level, the Ammonia flows with a rate of 50 Nl/h. This means that 50 Normal litres of Ammonia are needed to generate 75W of energy. Normal litres stand for the flow rate of a gas at 0°C and 1 atm. Under these circumstance Ammonia is a gas. In storage Ammonia is a liquid and therefore a calculation is needed to determine the amount of kg's of Ammonia that has been consumed. To calculate the consumed Ammonia, the specific volume of Ammonia is needed. The specific volume Ammonia is 1.3m<sup>3</sup>/kg. (Toolbox, 2019). Or 1300 litres per kg of Ammonia. This will give the following calculation.

$$\text{Hourly consumption of Ammonia (kg)} = \frac{50 \text{ Nl Ammonia(g)}}{1300 \text{ litres}}$$

$$= 0.038462 \text{ kg Ammonia (l)per hour}$$

This number equals a power output of 75W. As described in the conclusion on the Power Demand analysis the HAM 318 will need the SOFC system to operate on a fixed level of 17099 kW per hour. To calculate the total consumption of Ammonia on an hourly base the following steps need to be taken. The total Power Demand needs to be divided by the output of the tested stack system in the Cinti research, 75W. This number will be the amount of stack cell systems needed. Multiplying this by the hourly Ammonia (l) will give the total hourly consumption rate of Ammonia in liquid form.

$$\begin{aligned} & \text{Total hourly consumption rate NH}_3 \text{ (l)} \\ &= \frac{\text{Total Power Demand}}{\text{Power output Cinti Stack}} * \text{hourly Ammonia (75W)} \end{aligned}$$

Gives us

$$\frac{17099 \text{ kW}}{75 \text{ W}} * 0.038462 = 8768,82 \text{ kg per hour or } 8.77 \text{ metric tonne}$$

## 2.5.2 Battery Storage

In Table 16 the results have been depicted of the battery storage calculation. For each stage the average power of that stage over 10 cycles has been given. The installed SOFC power minus the average demanded power for that stage is the delta kW. Multiply the delta kW by the time that this power is demanded will give the potential kWh for that stage. If the number is positive it means that the ESS can store energy for that time period. If the number is negative it means the ESS will discharge energy to meet the demand.

| total avg per stage | Stage-kW | Installed kW | Delta kW | Time in min | kWh potential |
|---------------------|----------|--------------|----------|-------------|---------------|
| stage 1             | 10028.2  | 17099        | 7070.8   | 35          | 4125          |
| stage 2             | 19693.9  | 17099        | -2594.9  | 249         | -10769        |
| stage 3             | 11187.1  | 17099        | 5911.9   | 38          | 3744          |
| stage 4             | 14504.5  | 17099        | 2594.5   | 15          | 649           |
| stage 5             | 16061.3  | 17099        | 1037.7   | 130         | 2248          |

Table 16 (dis)charge potential for battery storage

## 2.5.3 Ammonia storage

The storage of Hydrogen as well as Ammonia can be done in pressurized tanks. This is normally done in a Cryogenic tank, also known as a type C-tank. The C-tank is an insulated tank that is fitted with a valve to release vaporized gas. The insulated tank is needed to keep the temperature low at the required level.

At the moment of writing Van Oord is working on a LNG-TSHD, the ZSH 7.0. This ship will operate solely on LNG. LNG needs to be stored at low temperatures, of  $-162^{\circ}\text{C}$  and at a pressure level of 6.5 bar. These LNG-tanks of Wärtsilä could also be used for the storage of Ammonia.

These LNG fuel storage tanks are single-walled IMO type-C tanks with polyurethane and polymeric coating and consist of different parts. For example the TCS. The Tank Connection Space is the area built around the tank penetrations and is built to contain any leakage and contain the hazardous areas. The Bunker Station is an assembly of valves and instrument and are delivered as a skid mounted unit. The skid mounted unit is the interface towards the fuel supplier for the filling of the LNG fuel storage tanks onboard. And lastly there is a control and automation system, the Process Control Cabinet. This system is designed for the primary process and safety control functions of the fuel system and comes with a control panel with all the certified alarms and indicators.

Tank specifications.

As mentioned before, the tank is a IMO type C tank. Meaning it is used for cryogenic purposes and complies with the standards set by the IMO. The design lifetime is 20 years and the tanks operate in ambient air temperatures between  $-20^{\circ}\text{C}$  to  $+45^{\circ}\text{C}$ . The dimension of the type C tank are 18.8 meters in length with a diameter 6.8 meters. This is excluding the insulation. The inner tank geometric volume at ambient levels is  $640\text{m}^3$ . Figure 53 shows the side view of the discussed type C tank. (Wärtsilä, 2019)

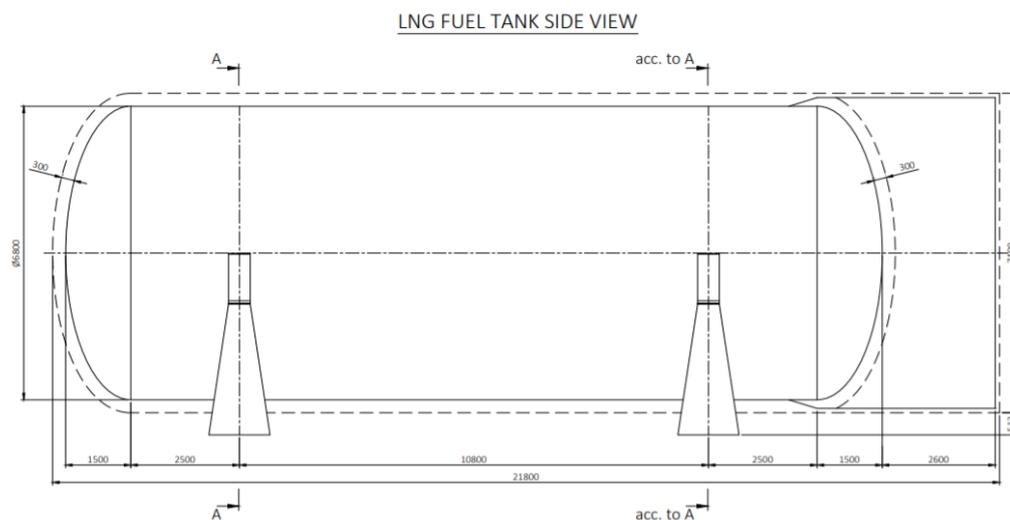


Figure 53 Wärtsilä LNG fuel tank side view, (Wärtsilä, 2019)

Ammonia onboard HAM 318.

To store Ammonia onboard of the HAM 318 these IMO type C tanks could be used as well. Figure 54 shows the situation onboard of the ZSH 7.0 LNG powered TSHD. For the HAM 318 a same fuel storage construction could be made, a solution where the Ammonia is stored upper deck. In the case of the HAM 318 3 of such IMO type C tanks should fit.

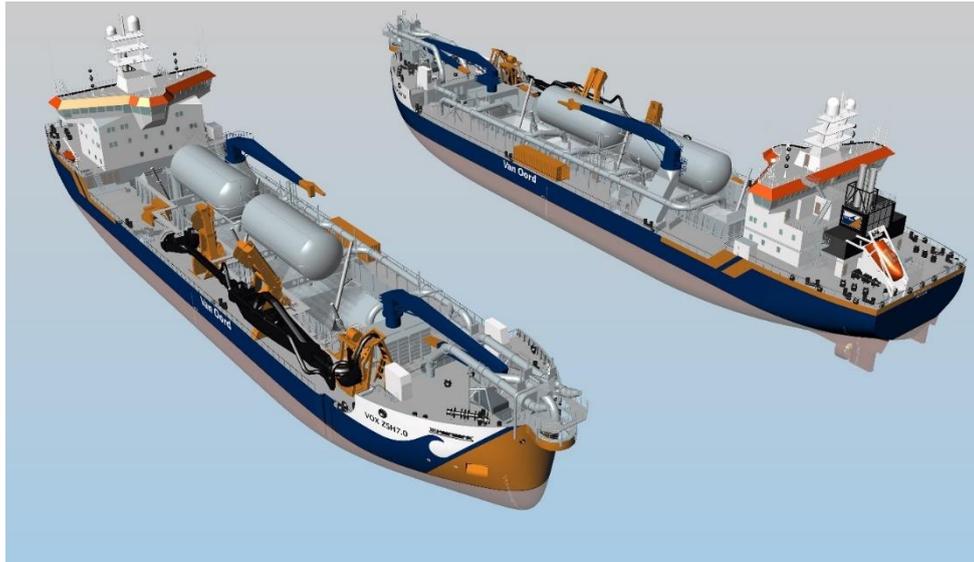


Figure 54 ZSH 7.0 LNG powered TSHD Van Oord, (Van Oord , 2018)

To know how much Ammonia could be stored in the case of an instalment of 3 IMO type C tanks, we assume that the exact same tanks as for the ZSH will be used. This means a total of  $3 \times 640 \text{ m}^3$  of storage space is available. It has to be noted that in the real situation, different sizes are available. This could result in a more favorable capacity. To calculate the potential capacity under these circumstances, it is needed to know the liquid density of Ammonia. This liquid density is  $682.8 \text{ m}^3$  under  $-34^\circ\text{C}$  and 1 atm. See paragraph 1.6 for Ammonia in liquid state. (Toolbox, 2019) This will result in the following storage capacity.

*Total Storage Capacity = Liquid denisty of Ammonia \* Geometric Volume of Type C tanks*

Which equals

$$\textit{Total Storage Capacity KG} = 682.8 * (3 * 640) = 1.310.976 \textit{ kg or } 1311 \textit{ metric tonne}$$

Looking at the consumption rate of Ammonia through the SOFC stack system of the Cinti Research, the autonomy of the HAM 318 can be calculated. This autonomy only holds under the described conditions, where 3 IMO type C tanks are installed with a total capacity of 1311 metric tonne.

*Autonomy of HAM 318 operating on Ammonia fed SOFC stack system*

$$= \frac{\textit{Fuel storage capacity}}{\textit{hourly fuel consumption}}$$

Which results in

$$\frac{1311 \textit{ metric tonne}}{8,76 \textit{ tonne per hour}} = 149.66 \textit{ hours of operation}$$

The Autonomy of the HAM 318, under the conditions of the discussed storage capacity and SOFC stack system, will equal 149.66 hours of straight operation at equal power demand.

## 2.5.4 Power distribution

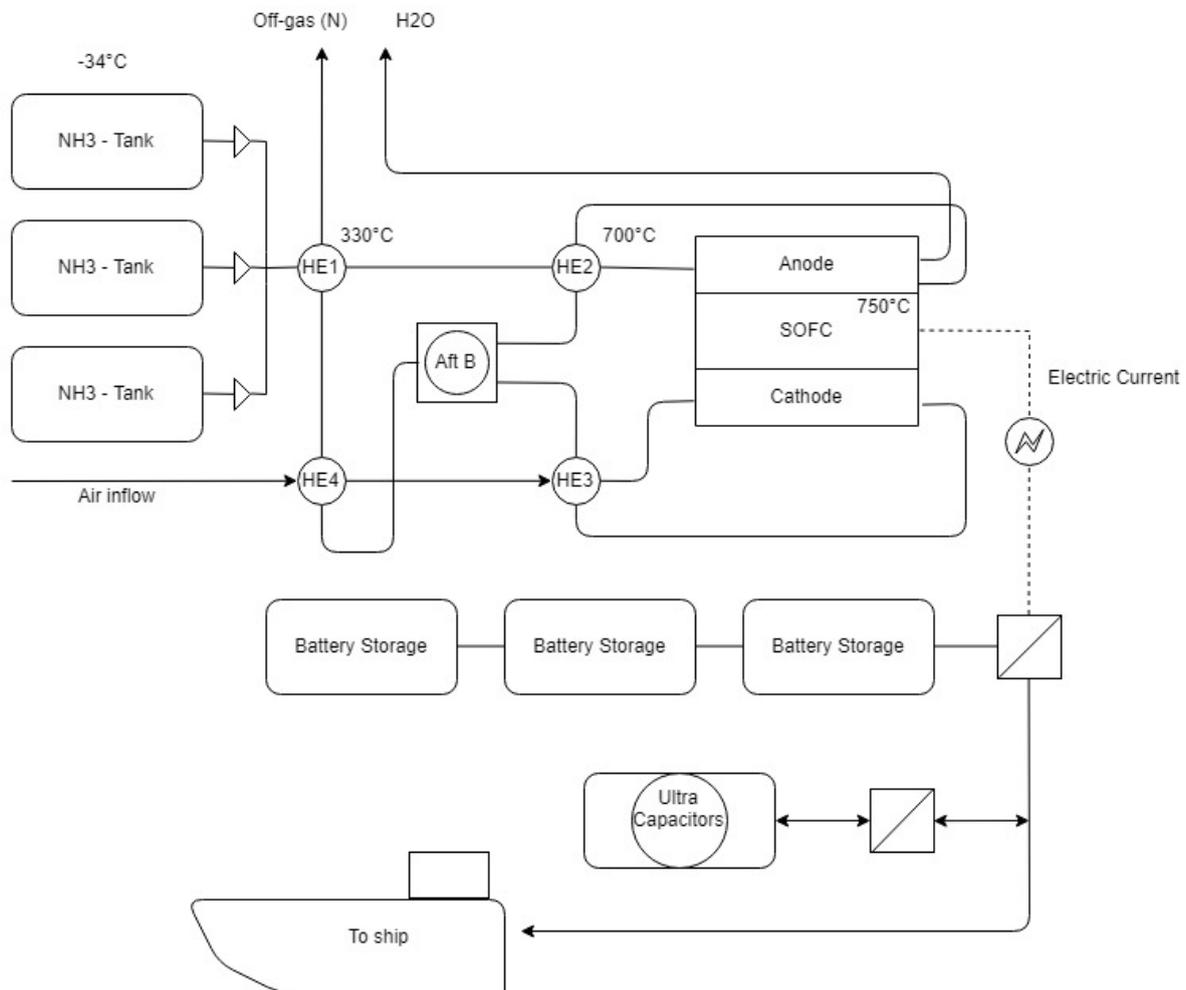


Figure 55 New Power Distribution Flow diagram

New Power Distribution Flow diagram.

With the introduction of the new Zero-Emission technologies on the HAM 318 a new Power Distribution Flow Diagram has been made. This is to give a schematic overview of the new distribution before entering the grid of the HAM 318. This diagram does not replace the existing diagram as in Appendix 2, but will solely replace the Main Engines PS/SB in the diagram.

Starting at the left top corner at the NH<sub>3</sub>-tanks, the diagram flows to the end at 'To Ship'. The Ammonia storage consists of 3 IMO type-C tanks, as described in the Ammonia storage paragraph. The Ammonia leaves the tanks through the throttle valves. The throttle valves make sure that the Ammonia is brought into the system under the right pressure. When leaving the tanks, the liquid Ammonia changes into a gaseous state.

After leaving the throttle valves the Ammonia reaches Heat Exchanger 1, HE1. At this point the Ammonia is in the first stage of pre-heating, as described in the Cinti Research. The Ammonia reaches a temperature of 330°C and is heated by residual heat from the SOFC and electrical heating. After this point the Ammonia flows into HE2, where it goes into the second stage of pre-heating. The temperature at this point will be 700°C.

After HE2 the Ammonia will reach the Anode side of the SOFC stack system. On the Anode side in the SOFC the process of electricity generation will start, as described in the paragraph 1.7.1.6, the Ammonia is split into Hydrogen and Nitrogen. The Hydrogen will create an electrical current by reacting to the Oxygen ions that entered the Cathode side. Nitrogen will leave the SOFC stack system at the end of the Anode side and will turn out in an off-gas. Before leaving the system the residual heat of the Nitrogen will be reused in the HE2, 4 and 1.

At the same moment that Ammonia enters the system, air will flow into the system as well. Same as for the fuel, air will be pre-heated in HE4 and HE3 and will enter the SOFC stack system at the Cathode side. The operating temperature in the SOFC stack system will reach around 750°C, depending on the power demand, air and fuel inflow.

On the end of the Cathode side H<sub>2</sub>O will leave the SOFC stack system as a result of the process of electricity generation. The H<sub>2</sub>O, like the Nitrogen will flow back and out of the system, but not before being used as a pre-heater in HE3 and HE4. The Afterburner, named Aft B in the diagram, has been installed in case the fuel does not reach complete combustion. If the complete combustion will not occur it need to be burned after to make sure that no emissions will occur.

The electrical current that leaves the SOFC stack system is DC. The dotted line ends up in a converter and distributor. At this point the electrical current converts into AC if it flows through to the ship or remains DC to flow into the Battery Storage system. In cases where all the energy from the SOFC stack system is needed for the HAM 318, the electrical current will directly flow through. In times when the energy demand is lower than the production level of the SOFC stack system the converter/distributor can flow energy system into the Battery Storage system. When the energy demand is higher than the production level of the SOFC stack system the Battery System will be discharged. In this case energy comes from both the SOFC stack system directly as well as from the Battery storage system.

The Ultra-Capacitors are installed to cover very quick peaks and lows in the grid of the HAM 318. The Ultra-Capacitors are linked to the AC distribution of the HAM 318 grid. This is done to quickly discharge the UC's in cases when a sudden peak occurs in the system. Same holds for a sudden drop in the energy balance. The UC's will then quickly charge to avoid a collapse of the system. This Power Flow Diagram could be seen as a replacement for the present Wärtsilä 12V46C. A more thorough research of the feasibility is needed to calculate the balancing possibilities.

## 2.6 The Cost Estimation

### 2.6.1 Introduction

The dredging industry is a rather capital intensive industry that is most of the times executed with a few main pieces of marine construction equipment or vessels. Van Oord as a company, like other dredging and offshore contracting companies as well, have to deal with projects in rather inhospitable environments. In these inhospitable environments there are many different aspects that can differ from location to location. Think of weather patterns, sea state, different soil and dredging material. To know which equipment to use or how to tackle different projects, site investigation has to be executed. Site investigation is a relatively expensive process. High construction risks, working conditions and other potential difficulties of obtaining site information can drive up the costs.

The dredging industry is also a large international marketplace and contractors work worldwide. It often happens that multiple organizations form consortiums to tackle large projects. When projects are very large it can be convenient to form these consortiums to avoid or diminish financial and technical risks. These mega-project have a lot of hurdles of which finance is one of them. Offshore contracting companies, consultants, clients, project financiers, insurers and other stakeholders all need to be able to calculate as accurately as possible the planned cost of projects. Because of this need for accurate calculations there has been a method developed to establish potential capital and related costs of various types of equipment and dredging vessels.

This method has been developed by CIRIA. CIRIA is an non-profit association for the construction industry. They gather information and perform research for companies in this construction industry, such as the dredging and offshore contracting industry. Their report "*A guide to cost standards for dredging equipment 2009*" will therefore also be a guideline for this research. Their report and cost standards can provide insight into the capital and some of the related costs of the dredging and offshore contracting industry. (Bray , 2009)

### 2.6.2 The financial research

The financial research of this thesis is executed on the basis of a comparison of the 'Business As Usual' situation (BAU) versus the 'Clean Future' situation (CF). In this comparison there will be looked at the CAPEX and OPEX of both solutions, which will be followed up by a comparison of the BAU fuel vs the CF fuel.

Firstly the BAU situation will be described. Based on the CIRIA report the BAU CAPEX/OPEX will be determined for the HAM318 TSHD. The Capex BAU exists multiple aspects such as the investment costs of the engine system that is built in the HAM318 TSHD at the moment. Secondly, the OPEX of the BAU needs to be determined. This will be set on the CIRIA report OPEX calculations. Lastly the CAPEX/OPEX of the BAU system will be transformed into a unit of measurement. This unit will be expressed in €/operational hour.

For the 'Clean Future'-situation the cost determination will be done slightly differently. As there is not much known about the commercial price structure of the SOFC system, a different approach will be held. "A Direct Manufacturing Cost Model for Solid-Oxide Fuel Cell Stacks" from Scataglini et al will be used as a basis to determine the cost of the new SOFC system. In this article the authors developed a model to determine the manufacturing price of a SOFC stack. Together with the price of the determined amount of ESS it will form the CAPEX of the new technology. Determining the

OPEX is done due to the use of a 3-point method. As the setting of both technologies has never been done before on such a big scale it is not clear or almost impossible to determine the OPEX of the new 'CF'-situation. The 3-point method will set an OPEX on certain levels of the BAU OPEX. This will be scenarios where 75%, 100% and 200% of the BAU OPEX form the CF-OPEX. Same as in the case of the BAU CAPEX/OPEX . the CF-CAPEX/OPEX will be transformed into a unit of measurement, €/operational hour.

### Fuel Price

After determining the cost of the technologies it is time to take a closer look at the costs of the BAU-fuel and the CF-fuel. In this research HFO and Ammonia, respectively. For both types of fuel the same unit of measurement needs to be taken into account. First the fuel prices will be determined for each technology. This will be followed up by a caloric comparison, which will be expressed in a KJ/kg. In this way the price per kg of both technologies can be compared.

### Parameters CIRIA

In the CIRIA cost standard report certain parameters were determined for the operational behaviour of all the different kinds of dredging vessel that operate in the dredging scene. For the Trailing Suction Hopper Dredgers this was determined for the following parameters. These can be found back in the CIRIA report, but are also summarized below. (Bray , 2009)

- Service life : 18 years
- Service hours : 168 hours per week
- Residual value : 10% of V
- Utilisation period : 33 weeks per year
- D+i : 9,647% of V per year or 0.292% per week

### 2.6.3 ‘Business As Usual’

#### Cost-model CIRIA

Explain the cost standards as described in the CIRIA report, of HAM318

The aim of the basic cost standards from CIRIA is to indicate the value of the used equipment. This is done in a refined but clear way, meaning that the calculations of the cost standards are not executed too detailed by CIRIA. This is done to avoid inaccuracies in calculations, the framework is therefore given in a somewhat simple way.

The framework from CIRIA is based on technical, statistical and economic data. It exist from Standard Values (V), standard rates for depreciation and interest (D+i) and the standard rates for maintenance and repair (M+R).

#### 2.6.3.1 CAPEX

The CAPEX is based on the cost of a retrofit of the present engine system in the HAM 318. Meaning that the following calculated CAPEX would be the investment cost of a new engine in the HAM 318. For a price indication Mr. Dirk Heidelberg of Wärtsilä engines have been contacted. Van Oord’s fleet is mainly supplied by Wärtsilä engines and therefore it is more than reasonable that a new conventional combustion system would also be supplied with a Wärtsilä engine system.

Mr. Heidelberg supplied the following cost of Warstila systems Table 17 Wärtsilä cost table. In the Table 17 one can find what the price per kW would be depending on the size of the system. So for example when a 1000 kW system would be installed, the price per kW is €460/kW and so on. To determine the kW price of a new to build in system the price needs to be extrapolated from the supplied data.

| Reference system | Power | Price | Unit |
|------------------|-------|-------|------|
| 1000             | kW    | 460   | €/kW |
| 1800             | kW    | 310   | €/kW |
| 2800             | kW    | 290   | €/kW |
| 3800             | kW    | 240   | €/kW |
| 7500             | kW    | 195   | €/kW |

Table 17 Wärtsilä cost table

As mentioned in the HAM 318 chapter, the installed engine system in the HAM 318 are 2x Wärtsilä – 12V46C engines which have a rated power of 12.600 kW each. To determine the right price a graph has been plotted (Figure 56) and the regression line has been drawn. For the determination of the regression the first datapoint has been deleted of the calculation. This datapoint is determined as an outlier that can interfere with the actual regression. The kW price of a 1000kW system is relatively more expensive. The initial price of a basic engine is always higher as the price of other parts of the engine have a relatively higher share in the total price. Building a bigger engine does not mean there are more parts needed than the with the initial basic engine. Therefore it is more accurate to delete the outlier and use the regression formula that is now depicted in the graph. The regression formula of the line is:

$$Y = 351.95e^{(-8e - 05x)}$$

To determine the €/kW (Y) for a 12.600 kW system the equation needs to be solved for Y when X equals 12.600 kW.

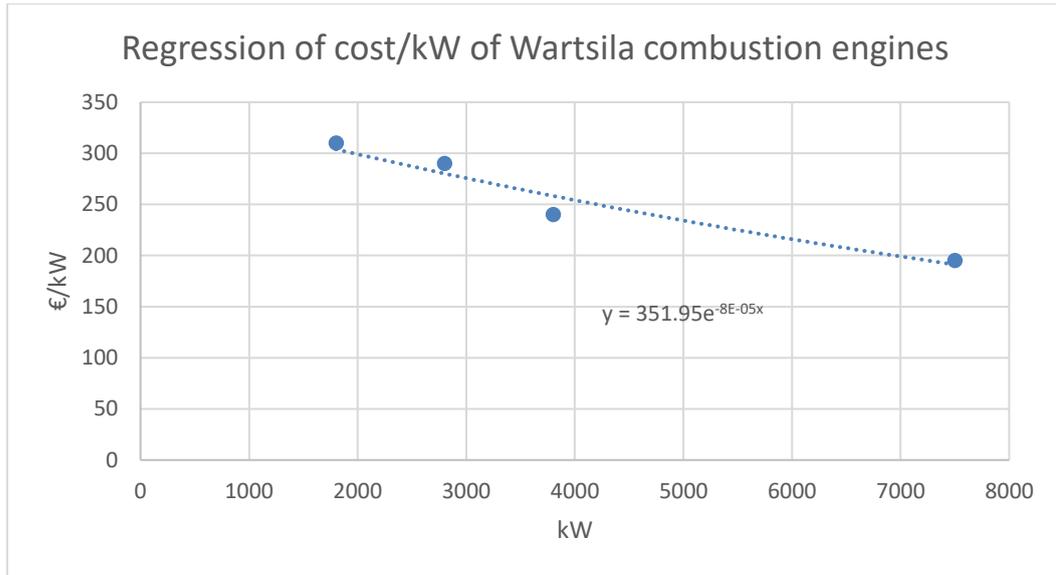


Figure 56 Regression of cost/kW of Wärtsilä combustion engines

Filling 12.600 kW in for X results in the following outcome.

$$Y = 351.95e^{-8E-05 \cdot 12600} = 119.5 \text{ €/kW}$$

For the total system of 2 Wärtsilä 12V46C, with a rated power of each 12600 kW, this will result in a price of:

$$\text{Total price of 2x Wartsila 12V46C} = 119.5 * (12600 * 2) = \text{€ 3.011.400, -}$$

This Total price of the Wärtsilä system is based on the cost of the engine itself. This is excluding transport, installation and cost of extra materials that are needed to get the engine up and running and the ship ready to go. Wärtsilä indicated that generally speaking the price should be doubled to come to a lumpsum price of the engine system. Therefore the price of €6.022.800 will be maintained as the aim price for the CAPEX of the BUA-situation. (Heidelberg & Tilman, 2019)

To calculate the hourly rate of the Wärtsilä 12V46C system, the total CAPEX will be divided by the operational condition parameters of CIRIA. This being 18 years, 33 weeks and 168 hours. This gives us a hourly rate of €60,40.

| Time          | €         |
|---------------|-----------|
| <b>Total</b>  | 6022800.0 |
| <b>Annual</b> | 334600.0  |
| <b>Weekly</b> | 10139.4   |
| <b>Hourly</b> | 60.4      |

Table 18 BAU CAPEX per time period

### 2.6.3.2 OPEX

To determine the OPEX of the HAM318 a closer look has been taken to the cost standard tables of CIRIA. Looking at the TSHD table one can find all the values that correspond for TSHD's with different hopper volumes. Ranging from 900 m<sup>3</sup> to 45.000m<sup>3</sup>. For each of these volumes the according costs, values, installed power, lightweight and displacement can be found back in Appendix 6 CIRIA cost standard table for TSHD based on hopper . As mentioned in the HAM 318 chapter the volume of the hopper is 39.467 m<sup>3</sup>. As this specific volume can not be found in the table, an interpolation have been made to determine the specific factors. In table Table 19 the results of the calculations can be found.

| Hopper Volume | Displacement at dredging mark | Value (V) <sup>d</sup> | Costs per week (D+i) | Cost per week (M+R) | M+R per Week |
|---------------|-------------------------------|------------------------|----------------------|---------------------|--------------|
| m3            | tonnes                        | €                      | €                    | €                   | % of V       |
| <b>39467</b>  | 92733                         | 236859120              | 691628.63            | 223697.797          | 0.105469     |

Table 19 Interpolated cost considering HAM 318 hopper volume

This table tells us that the total value of the TSHD with the according volume has a value of almost 237 million and have a weekly depreciation and maintenance/repair cost of roughly 690.000 and 224.000 respectively. These depreciation and maintenance/repair cost will be used as the operational expenditure of the TSHD and therefore will also be used for the 3-scenario method in the OPEX for the CF-approach. The depreciation cost and maintenance/repair cost have been used as a OPEX cost standard as these are the only know OPEX cost within the company and are also market competitive prices. The OPEX have been recalculated to an hourly rate. This levelized cost makes it easier to do comparisons. The hourly OPEX can be found in Table 20 below.

| Cost per week            | €      |
|--------------------------|--------|
| <b>D + I</b>             | 691628 |
| <b>M + R</b>             | 223697 |
| <b>Total weekly cost</b> | 915325 |
| <b>based on 168h</b>     | 168    |
| <b>Hourly OPEX</b>       | 5448.4 |

Table 20 hourly OPEX BAU

### 2.6.3.3 HFO

For the determination of the fuel consumption of the HAM318, use have been made of Simplot. In Simplot the data from the NC-files, that have also been used for the power demand analysis, can be used to determine this consumption. In Simplot the formula has been set up for the consumption. This is abbreviated to CAL343 and can be found back in the formula table in Table 7.

Below the formula of the Average fuel consumption is depicted in blue. The actual fuel consumption of the PS + SB main engines is depicted in green. The average fuel consumption of the HAM 318 was determined on 0,95 Kg/s over the total measured timeframe.(Figure 57) This is the timeframe of all the 10 dredging cycles as discussed in the power demand analysis.

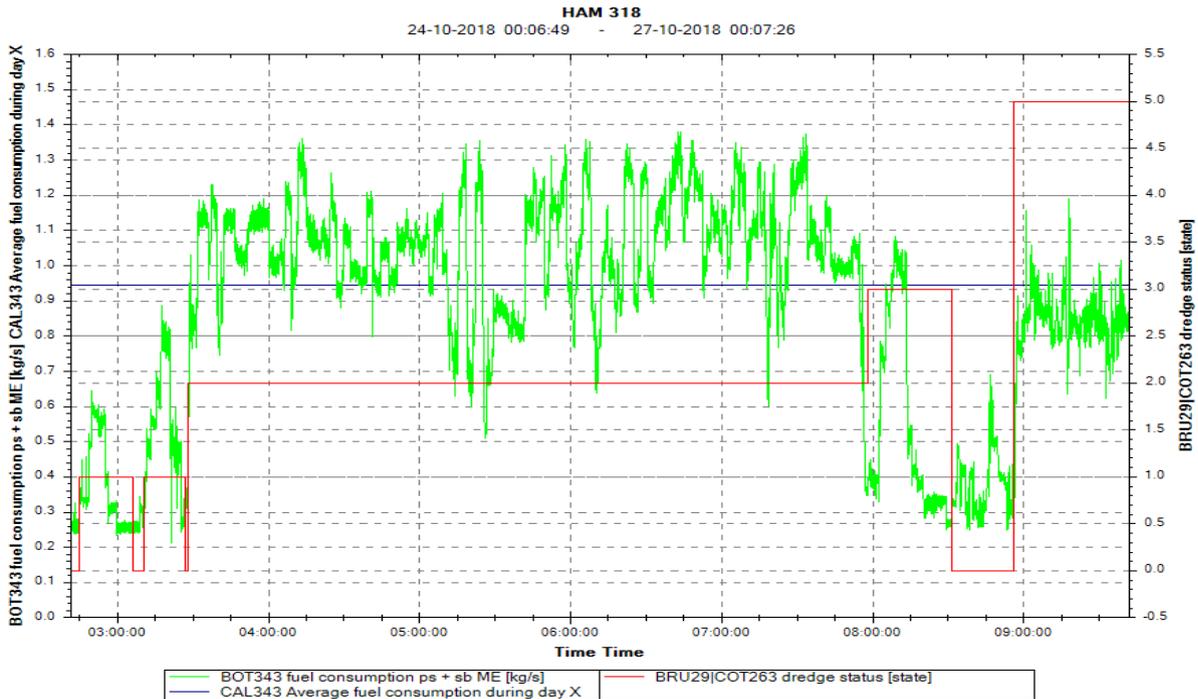


Figure 57 HAM 318 Average fuel consumption, graph extracted from SimPlot

Multiplying the average fuel consumption by the amount of seconds in 1 hour gives the average fuel consumption per hour. This results in the following formula.

$$\text{Hourly fuel consumption} = 0,95 \text{ Kg per second} * 3600 = 3420 \text{ kg fuel per hour}$$

The operational hour consumption is 3420 kg, or also known as 3.420 Metric ton.

#### Present autonomy HAM 318

It is needed to compare the possible autonomy of the HAM 318, operating on an Ammonia fed SOFC stack system, to the present situation. In this present situation the HAM 318 is operating on HFO. The HFO bunker capacity of the HAM 318 equals 2832 m<sup>3</sup>. (Van Oord , 2014). To know the total weight of HFO on board, the storage capacity needs to be multiplied by the density of HFO. The HFO density is 991kg/m<sup>3</sup>. This will give the following result.

$$\text{Total onboard HFO in kg} = \text{HFO denisty} * \text{Storage Capacity}$$

Which gives

$$991 \text{ kg m}^3 * 2832 \text{ m}^3 = 2,806,512 \text{ kg or } 2806 \text{ metric tonne}$$

As described in the fuel consumption of the BAU situation, the average fuel flow rate of the HAM 318 equals 3,420 metric tonne per hour. This means that, if the tanks would be able to be fully consumed, the autonomy of the HAM 318 at present equals:

$$\frac{2,806 \text{ metric tonne}}{3.420 \text{ hourly consumption}} = 820.46 \text{ hours}$$

The CIRIA report parameters determined that a full operational week equals an amount of 168 hours. Therefore, an autonomy of 820.46 hours, will make the HAM 318 capable of operating:

$$\frac{820.46}{168} = 4.88 \text{ weeks}$$

#### 2.6.3.4 Fuel price

To know the fuel cost per operational hour, data about the fuel price is needed. This data has been extracted from the database of shipandbunker.com. Ship & Bunker is the news and intelligence hub for the Maritime Fuel Industry and provides stakeholders with relevant information considering Maritime Fuel topics.

The data on fuel prices that has been used can be found in (Ship and Bunker - Fuel prices , 2019). The most important ports that distribute the fuel have been taken into account. Ports of interest are Singapore, Rotterdam, Houston, Hong Kong, Istanbul, New York, Pireaus and Gibraltar. Next to that the price of the Global 20 ports, APAC, EMEA and Americas have been taken into account. The prices as provided are a snapshot of the 22-april day price. The prices are published in \$/metric ton. To know the € price per metric ton a conversion rate of 0.89 \$/€ has been used. This is the conversion rate on 22<sup>nd</sup> of April as well and is provided by Xe.com. (Xe.com, 2019). The average of all the prices has been taken as a measure for the fuel price. The average price of 1-metric ton of fuel is \$400,76. (Ship and Bunker - Fuel prices , 2019)

The fuel price per operational hour will therefore come down to:

$$\text{Fuel price per operational hour} = €400,76 * 3,420 = €1370,60$$

## 2.6.4 ‘Clean Future’

### 2.6.4.1 CAPEX

#### SOFC CAPEX

As described in the prior chapter on the SOFC technology and the cost of the system, the capex is based on the manufacturing cost model of Scataglini et al. In October 2017 Scataglini et al published a direct manufacturing cost model for Solid-Oxide fuel cell stacks. This rather complete research identified the major contributors to the fuel cell manufacturing costs and examined the influence of production volume and stack size. They have modelled the manufacturing costs as a function of net electricity capacity in kWe for annual production volumes up to 50.000 systems a year. The outcome of this model showed an overall stack manufacturing cost range from \$5,387 kWe<sup>-1</sup> to \$166 kWe<sup>-1</sup>. The cost of the SOFC stack and the relation between the capacity of the system and the production levels of the system are depicted in Appendix 7.

The cost analysis model of Scataglini

The model that has been developed by Scataglini, to calculate the manufacturing costs of the SOFC stack system, finds its origins in the lack of information on the cost price of the SOFC system. As is mentioned in his paper, there are numerous studies on the automotive application but not a general cell manufacturing cost model. *“In the literature there is either a too narrow scope in terms of the components in the cell, not detailed enough system characterization or lack in the assessment of modelling the cost”* (Scataglini, et al., 2017).

Scataglini took a few steps to get to his model, which will not be discussed too broadly. First the research team determined the system boundaries and identified the stack components. This was followed up by the determination of what components to produce themselves or what to buy. Eventually they decided to buy all the components, as it is more likely that other manufacturers will do this as well. Lastly a manufacturing process was designed. With these steps the model was established, with the manufacturing costs as an output. In this model the costs for capital, operation and management (O&M), labour, materials, scrap and factory costs were included. Other components of the model were discount rate, inflation rate and the lifetime of the product.

For the total cost manufacturing of the SOFC Scataglini adopted an annualized cost manufacturing tool. In this tool the sum of all the component cost were annualized to determine the annualized cost for different capacity outputs and production levels.

$$C_y = C_c + C_r + C_{oc} + C_p + C_{br} + C_i + C_m - C_s - C_{int} - C_{dep}$$

| Abbr        | Cost              |
|-------------|-------------------|
| <b>Cy</b>   | total annualized  |
| <b>Cc</b>   | Capital           |
| <b>Cr</b>   | replacement       |
| <b>Coc</b>  | operating         |
| <b>Cp</b>   | property tax      |
| <b>Cbr</b>  | building          |
| <b>Ci</b>   | tool insurance    |
| <b>Cm</b>   | maintenance       |
| <b>Cs</b>   | end of life value |
| <b>Cint</b> | income tax        |
| <b>Cdep</b> | depreciation      |

Table 21 Abbreviations of Cost formula Scataglini

The abbreviations and symbols that are being used in this model are depicted in Table 21. For each of the cost components a certain parameter is set. These parameters can be found in Appendix 8.

#### CAPEX cost determination

Based on the direct manufacturing cost model that Scataglini developed, it is now possible to determine the CAPEX of the SOFC part for the cost analysis. The results from Scataglini's research are published in Table 22. The results are arranged and sorted by the Power capabilities of the system and by the number of produced systems on annual base. As described in 2.3.15 the TSHD will need 17099 kW of installed SOFC power. Logically the highest System Power/kWe will be taken into consideration for the CAPEX determination. To cover 17099 kW, 69x 250kWe systems will be needed. The price per kWe-1 depends on the annual production output. For different output levels there are different prices. Looking at Table 22 gives us information about the kWe-1 price. (Scataglini, et al., 2017)

Table 22 mentions 2 different design of SOFC stacks, Base and Alternative. Both stacks are technically identical. The only difference of stacks lies in the way the stacks are interconnected and framed. The base design consists of a SS441 interconnect and the alternative design consists of a Crofer 22 APU. This results in a thickness and weight of 630 $\mu$ m/247 grams and 315  $\mu$ m/123 grams respectively. Both stacks have a cell surface of 100x100mm.

| System Power/kWe | Systems/year | Stack cost base design \$/kWe-1 | Stack cost alternative design \$/kWe-1 | Cost increase % |
|------------------|--------------|---------------------------------|--|-----------------|
| 250              | 100          | 249                             | 274                                    | 10              |
| 250              | 1000         | 181                             | 204                                    | 13              |
| 250              | 10000        | 167                             | 190                                    | 13.7            |
| 250              | 50000        | 166                             | 189                                    | 13.9            |

Table 22 SOFC manufacturing cost according production level and system power

An annual production level of 50.000 systems, with a base design stack will have the lowest price of \$166 kWe<sup>-1</sup>. The highest price for a stack of SOFC's is \$274 kWe<sup>-1</sup>, based on 100 systems of 250 kWe<sup>-1</sup> on an annual base. For this research a price of both \$249/kWe<sup>-1</sup> and \$274/kWe-1 will be retained. The motivation for this lies mainly in the expected production volume of the systems. As it is not clear how many systems are being sold on an annual base, one cannot assume that production levels will reach the most favorable level, of 50.000. Therefore it is safer to expect that the output levels will not exceed much more than the order for a hypothetical to-build-ship, that needs 69 units of 250kWe<sup>-1</sup>. (Scataglini, et al., 2017)

The total SOFC CAPEX for the 'Clean Future' – scenario will therefore be set on the following price

| Parameter   | Value | Unit     | Total \$ |
|-------------|-------|----------|----------|
| SOFC        | 17099 | kW       |          |
| Base design | 249   | \$/kWe-1 | 4257651  |
| Alt design  | 274   | \$/kWe-1 | 4685126  |

Table 23 SOFC manufacturing cost of 2 designs

## ESS CAPEX

The Energy Storage System on the HAM 318 will exist from 2 different storing technologies. These will be the Lithium Ion battery system for the long term energy storage and the Ultra Capacitors system for the short term high power storage. The Battery storage system will support the SOFC system for the long run power fluctuations. This means that in times when there is excessive energy, the batteries will charge and store energy. In times of high demand the battery system will discharge and support the SOFC system. The Ultra capacitors will help the total power generating system when power demand fluctuate heavily over short amounts of time, for example during the trailing and shore discharge stages.

### **Battery storage**

In the earlier chapter on Energy Storage System calculations have been made on the potential energy charge and discharge of the hybrid system. As the SOFC operates on a fixed level, the excessive energy can be stored to be used in a later stage. Looking at Table 16 we can see that the charge and discharge is roughly stable. With a highest discharge of energy of 10.769 kWh, the trailing stage is very power demanding. To cover the energy needs in this stage a battery capacity of a somewhat equal amount needs to be installed. There it has been decided that 11.000 kWh of installed battery capacity is needed. As Van Oord currently isn't working with large scale battery capacity, there isn't a main supplier of these batteries. Therefore the price estimation will be based on the literature that has been used in the ESS chapter, (Zakeri & Syri , 2015 ). As Zakeri described, a TCC of energy storage devices have been made. For the lithium-ion batteries the €/kWh came down to an average of €546/kWh. Multiplying this price with the needed energy storage capacity will give us the following outcome.

$$TCC = €546 * 11.000 kWh = €6,006,000$$

This is a rather large amount of money. It needs to be taken into account that this is the Total Capital Cost and includes all the cost that are covered with the purchase, installation and delivery of the battery storage system. Next to that it also covers the balancing of plant cost, these are for example wires, computers, stabilizer and monitors.

### Dimensions

The dimensions of the battery system are hard to determine. This really depends on the (dis)charge power, energy density and the voltage. In this thesis this has not been taken into account and therefore need further research to find the optimal system.

### **Ultra-Capacitors**

As determined in the earlier chapter about the ESS, 5000 kW's of Ultra Capacitors will be needed to cover the heavy power fluctuations during certain dredging stages. The UC's that will be used for this process are the same UC's that are being used in 'Werkendam' another the Cutter Dredger in the Van Oord fleet. These UC's are built by AEP International, a hybrid power specialist. AEP has provided Van Oord with the Cell Pack V2 on the 'Werkendam', the same UC's that are being used for this thesis. The Cell Pack V2 (picture) are cost efficient, High-capacity and low internal resistant UC's that have a flexible configuration possibility. These UC's are also being used for power grid stabilisation and as braking energy recuperation systems. The characteristics can be found in Appendix 9.

The Cell Pack V2 is a 33 kg UC pack with the dimensions 600x436x167mm and has an energy density of 4,4 Wh/kg. The rated current of the pack is 100 rms and can peak to 2000 A for <1 sec or 750 A for <5 sec. For the calculation and determination on how many Cell V2 packs are needed the rated current pack of 100 A will be used. (AEP hybrid power , 2019)

The formula for Power in kW is known as

$$kW = Amp * Volt$$

Or

$$P = I * V / 1000$$

Knowing a 5000 kW system is needed and that the rated voltage output of a 6-serie stack is 780V(Appendix 9), we can calculate the needed Amp and divide it by the rated current of the Cell Pack V2

$$I = \frac{5000}{780/1000}$$

This formula equals an Amp of 6410 A needed for the UC's system. Dividing the 6410 A by the Amps per module, which are 100 A, tells us the system would need 64 modules of VP Cell Pack V2's.

Cost of the UC's

The Cost of a system that has 64\* Cell Pack V2's is unknown as this information is not provided by AEP. Looking at paragraph 2.4.2 and the cost table Table 15 we can deduct that the TCC of Ultra Capacitors is 229 €/kW. (Inage , 2009). For a 5000 kW Ultra Capacitor system this would come down to a TCC of

$$TCC \text{ of UC} = € 229 * 5000 \text{ kW} = € 1.145.000$$

This TCC will be used for the CAPEX of the UC system.

Dimensions

The Cell Pack V2 comes in series of 6-modules per pack. With 48 cells per module. The 6-modules pack has a size of 1122 x 758 x 537 mm, as depicted in picture [xxv2pack]. When 64 modules are needed, the volume of 1 serie of modules need to be multiplied by 64. This equals a total volume of 459,648 cm<sup>3</sup> or 0.46 cm<sup>3</sup> \* 64 = +/- 30m<sup>3</sup>

### **Hourly CAPEX**

Knowing the CAPEX of the SOFC, Battery system and UC's it is possible to calculate the hourly cost of the CF CAPEX. This hourly rate will, as the BAU hourly CAPEX, be based on the CIRIA parameters. These can be found in Appendix 6. Table 24 below, shows the total CAPEX of the CF system.

| Technology                    | €          |
|-------------------------------|------------|
| <b>Solid Oxide Fuel Cells</b> | 4,685,126  |
| <b>Battery storage</b>        | 6,006,000  |
| <b>Ultra-Capacitors</b>       | 1,145,000  |
|                               |            |
| <b>Total</b>                  | 11,836,126 |

Table 24 Sum of CAPEX of all CF technology

This brings the total CAPEX for the CF scenario to € 11,836,126. This is based on a SOFC where the ‘alt design’, as described in the SOFC CAPEX paragraph, is used as a reference. To calculate the hourly rate, the total CAPEX will be divided by 18 years, 33 weeks and 168 hours. Gives the following solution in the table below. The hourly CAPEX is calculated to be €118,60 for the SOFC

| Time          | €          |
|---------------|------------|
| <b>Total</b>  | 11836126.0 |
| <b>Annual</b> | 657562.6   |
| <b>Weekly</b> | 19926.1    |
| <b>Hourly</b> | 118.6      |

Table 25 hourly total CAPEX

### 2.6.4.2 OPEX

Determining the OPEX of the Clean Future solution for the HAM 318 is a near to impossible mission. The system as described above; with SOFC, Batteries and UC’s, has never been made before. It is hard to say what the expenditures during operation are going to be. First of all the SOFC system on this large scale has never been produced, nor tested on a large scale with ammonia. Therefore it is impossible to tell what the lifetime of the SOFC hybrid system is going to be or what other parts will need to be replaced at which points in the lifecycle.

To come to an estimation of the cost concerning the operation of the Clean Future solution, use has been made of the so called 3-point scenario estimations. In this scenario estimation the BAU-solution will form a base for the OPEX in the CF scenario. The 3 different scenarios are split up in an ‘Optimistic’, ‘Neutral’ and ‘Pessimistic’ scenario. Each coupled to a certain percentage level. The percentage levels being used are 75%, 100%, and 200% of the BAU OPEX output, which have the data derived from the CIRIA cost standard model for dredging vessel.

Below a table is published with the different scenario’s, the corresponding costs and the hourly costs based on the scenario estimations.

| Name              | Optimistic | Neutral | Pessimistic |
|-------------------|------------|---------|-------------|
| %                 | 75%        | 100%    | 200%        |
| <b>BAU weekly</b> | 915325     | 915325  | 915325      |
| <b>CF weekly</b>  | 686493.75  | 915325  | 1830650     |
| <b>CF hourly</b>  | 4086.3     | 5448.4  | 10896.7     |

Table 26 3-point scenario cost

In the Neutral scenario a rate of 100% relative to the BAU OPEX has been taken into account. Therefore the CF OPEX will not differ from the BAU OPEX. The CF hourly OPEX will remain €5448,4.

In the Optimistic scenario a rate of 75% relative to the BAU has been taken into account. In this scenario it is expected that the CF OPEX is expected to turn out lower than the BAU OPEX. This could be the case is the maintenance cost might turn out lower. The SOFC stack system does not have any moving parts. Moving parts in general are more vulnerable to wear and tear. If the SOFC turns out to have relatively less wear and tear than a conventional combustion engine, it could be that maintenance cost and the cost of other parts turn out lower. Calculating the hourly cost of the CF, based on the parameter operational profile, it gives us a hourly cost of €4086,3.

The Pessimistic scenario has a rate of 200% relative to the BAU OPEX. In this scenario it is expected that the CF OPEX will turn out twice as high as the BAU OPEX. The reasoning behind this rate comes from the novelty of the SOFC stack system technology. It is plausible that the components of the SOFC system turn out more expensive than components of conventional combustion engines. Another thing to take into account is that it is unclear how often parts have to be replaced as there are no available life-cycle analyses. Because of the possibilities of decreased lifetime and increased component cost the rate is set on 200%, resulting in a CF hourly of €10896,7.

### 2.6.4.3 Ammonia

In this paragraph the hourly cost of Ammonia in the CF scenario will be calculated and determined. With this price a comparison to the HFO hourly fuel price can be done. For the calculation of the Ammonia fuel price the following steps will be taken. The price of a tonne of Ammonia will be used, as described in the Ammonia chapter. This will be multiplied by the hourly fuel consumption that was determined in the Cinti research chapter. The price of Ammonia that was determined in the Ammonia chapter was set on \$400,-. (Wittrig, 2018). This is the expected future price through electrolysis, under the condition that the future technologies would have a increased efficiency. The fuel flow rate was determined to be 8.7687 tonne per hour. This will give the following equation:

$$\text{Hourly fuel cost Ammonia} = \text{Price of Ammonia} * \text{Fuel consumption rate}$$

This will give us

$$\$400, - * 8.7687 \text{ tonne per hour} = \$3507.5 \text{ per hour}$$

Converting this to € with the €/ \$ rate as used in chapter (bau something) gives us an hourly price of  
 $\$3507,50 * 0.89 = €3121,70 \text{ hourly fuel cost}$

## 2.6.5 Analysis of BAU vs CF

| Hourly          | Business As Usual | Clean Future |
|-----------------|-------------------|--------------|
| <b>Capex</b>    | €60.40            | €118.60      |
| <b>Opex</b>     | €5,448.40         | €4,086.30    |
|                 |                   | €5,448.40    |
|                 |                   | €10,896.70   |
| <b>Fuel</b>     | €1,370.60         | €3,121.70    |
| <b>Total</b>    | €6,879.40         | €7,326.60    |
|                 |                   | €8,688.70    |
|                 |                   | €14,037.00   |
| <b>Autonomy</b> | 820.46 hours      | 149.66 hours |

Table 27 Overview of CAPEX, OPEX and fuel costs for BAU and CF scenario. For the CF scenario there are 3 different values as the outcome of the 3-point scenario. The autonomy is expressed in operational hours.

Table 27 shows the summary of all the calculated hourly cost and autonomy for the ‘Business as Usual’ and the ‘Clean Future’ scenarios.

## CAPEX

Looking at the CAPEX of both technologies it can be concluded that the CF scenario turns out roughly twice as expensive as the BAU situation. This outcome is still at a hypothetical point for both the BAU as the CF scenarios. For the CAPEX of the BAU situation it needs to be taken into account that the outcome is a linear extrapolation of the price indication that was given by Wärtsilä. The actual price of a new 12V46C system might turn out to be higher.

Same holds for the CF scenario, that is also still hypothetical at this point. Especially the cost of the SOFC stack system will most likely have a higher outcome. The cost estimation is based on the Scatagliani research, which is focussed on the manufacturing costs rather than the consumer price. Next to that is the price of both the Battery Storage system as well as the Ultra-Capacitors. Both are based on literature review and might differ from the actual spot market price as well as the future price of the technologies. It can be expected that prices drop when technologies improve, supply improve or the Total Capital Cost decreases.

## OPEX

The OPEX for both BAU and CF are based on the CIRIA cost standard model. A market-based tool to calculate the cost of operation of Dredging vessels based on their capacity. It is safe to say that the OPEX for the BAU scenario is fairly accurate. For the OPEX of the CF scenario this is different. A 3-point scenario method was used to determine the OPEX in the future. This was set for 75%, 100% and 200% of the present OPEX. The 75% level could occur when it turns out that the maintenance and operation of a SOFC system are lower than present. The SOFC system does not have any moving parts, it operates statically. When less parts move, wear and tear is generally lower. Parts will have to be replaced less often. Realistically seen, it is likely that the OPEX turns out higher. New technologies, especially when at a lower technical development level, tend to have higher cost. Next to that is a SOFC cell more vulnerable to cycling, which could result in a shorter lifetime than has been taken into account.

## Fuel and Autonomy

Looking at the fuel costs and the autonomy of both technologies, significant differences can be concluded. The hourly fuel cost of Ammonia turn out to be 3 times as high. Next to that a few things need to be kept in mind about this cost. First of all, the Ammonia has the same price as HFO, this is an expected price and not a certain price. This price level, for carbon free Ammonia, can be reached under the condition that technology improvements occur. Next to that, the efficiency of the SOFC cell needs to be taken into account. The SOFC stack system needs more Ammonia to meet the required power demands. Therefore the costs will turn out higher. The autonomy of the HAM 318 will also be affected in case of a shift to Zero-Emission. The autonomy will, under the conditions of the research, drop with 80%. From 820 hours to 150 hours. The parameters for the operational profile of a TSHD, that have been used from the CIRIA cost standard model, states that an operational week exists from 168 hours. This means, that in a CF scenario, the HAM 318 will not be able to operate for a full week straight. This is a serious drawback for the succession of the CF scenario.

Figure 58 gives a visual comparison of the 4 situations. CF + being the optimistic scenario, CF +/- and CF - the neutral and pessimistic scenario respectively.

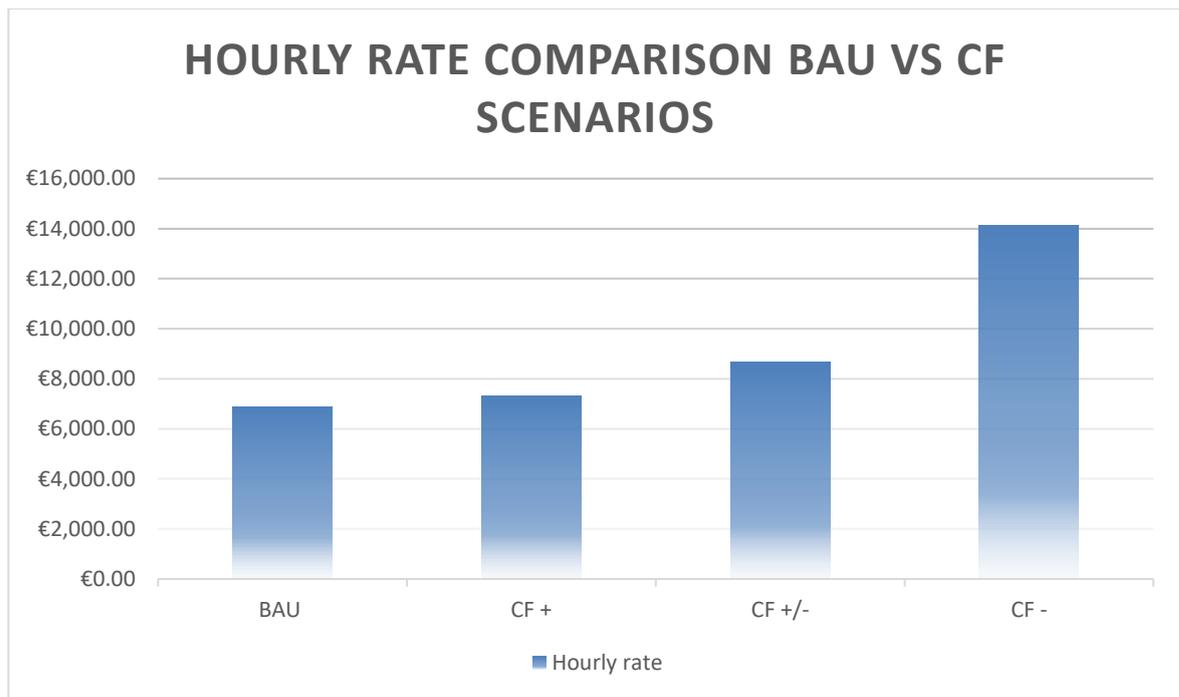


Figure 58 Hourly rate comparison BAU vs CF

## CO<sub>2</sub> reductions

Changing to a Zero-Emission solution for the HAM 318 is an interesting development in different ways. Besides the reduction of CO<sub>2</sub> emissions there are other benefits to this, for example the benefit in different future project tenders. In this paragraph the calculations on CO<sub>2</sub> are briefly walked through. To calculate the CO<sub>2</sub> reductions, basically we only need to know how much carbon is emitted in the present state, as the new technologies reduce the carbon emission from 100% to 0%. This can only be assumed when the production of Ammonia will be through green solutions for electrolysis of hydrogen and the Haber-Bosch process for Ammonia.

For the Carbon reduction calculation of the measured dataset a couple of things are needed. The total timeframe of the dataset, the consumed fuel per hour and the specific CO<sub>2</sub> content of HFO.

The total timeframe of the dataset is 113,5 hours. The start date of the dataset is 22-10-2018 at 23:25:00 till 27-10-2018 at 16:55:00. The consumed HFO per hour was calculated in the BAU fuel chapter and is 3,420 metric tonne per hour. The last unknown is the specific CO<sub>2</sub> content of HFO. The specific CO<sub>2</sub> content of HFO is expressed in KG<sub>CO<sub>2</sub></sub>/KG<sub>fuel</sub> and amount 3,11 kg of CO<sub>2</sub> per kg of fuel. (Toolbox, 2019)

With these parameters the following calculation can be set up.

$$\text{Total CO}_2 \text{ reduction} = (\text{hours dataset} * \text{hourly fuel consumption}) * \text{Specific CO}_2$$

Results in

$$(113,5 \text{ hours} * 3,420 \text{ metric tonne}) * 3,11 = 1207,21 \text{ tonne CO}_2 \text{ reduction}$$

A total reduction of 1207,1 tonne of CO<sub>2</sub> can be achieved. To put this in perspective, the spot price of CO<sub>2</sub> European Emission Allowances is at the time of writing €24,32 per tonne of CO<sub>2</sub> (Markets insider, 2019). This equals an amount of 1207,1 tonne \* €24,32 = €29,356.70 over a period of just under 5 days of operation. This equals an hourly Carbon Emission rate of €29,356.70 / 113,50 hours = € 258,65

### FV Calculation

To give an idea on the investment of the CF-scenario the Future Value of the total investment cost need to be made. The financial number, as presented in this research, are based on price that are at present or in some cases a bit older. The use of cost estimates from articles date from several years back, depending on which article. When the investment for a new system is being made, the prices might be higher due to inflation.

For the calculation of the Future Value of the investment, a few things are needed. These are the total investment cost at present, the forecasted inflation rate and the year when the investment is being made. The total investment cost of the CF scenario were calculated based on the CAPEX of the SOFC stack system, Battery Storage System and the Ultra-Capacitors. This accumulated to €11,836,126.00,-. The inflation rate is set on 2%. This percentage has been deducted OECD data website. The forecasted inflation rate of all OECD-countries is expected to be 2.6%. But as Van Oord is a Dutch company, the forecasted inflation rate of The Netherlands will be used, this is 2% till 2020. (OECD , 2019). There is no data or forecasts available for after 2020. The year of investment is set on 2030, this should meet the goals of both IMO and Van Oord, to produce Carbon-Free ships as of that year. Therefore the n-year is 11 years.

The following formula will be used to calculate the Future Value of the investment.

$$\text{Future Value of Investment} = \text{Present Value} * (1 + \text{Inflation Rate})^{N\text{-years}}$$

This results in a Future Value of

$$\text{Future Value} = €11,836,126 * (1.02)^{11} = €14,716,735,-$$

The Future Value of the investment results in €14,716,735,- if the investment is made in 2030 and the forecasted inflation rate is somewhat accurate and extrapolatable for the future after 2020.

## Discussion

To evaluate all the factors that are now known around the potential implementation of a Zero-Emission technology in the HAM 318, we can conclude that the technology is still far from reality. Some indications reveal the lack of possibility of a present implementation. These indicators are mainly the Autonomy, Price, Power Capabilities of SOFC and Ammonia storage. The Ammonia storage is limited due to its capacity. Further research should make clear if more Ammonia could be stored on board. This storage capacity also directly influences the Autonomy of the HAM 318. As less energy can be stored, Autonomy will decrease. This in combination with the efficiency of the SOFC stack system caused a serious drop in Autonomy. Further research needs to be done to find out if a higher efficiency can be reached as well as a higher power output of the SOFC. Lastly the price of the system is fairly high. There are some uncertainties considering the price indication of the system. As mentioned earlier, the OPEX of the CF scenario is unclear and the CAPEX cost are based on manufacturing cost models rather than consumer prices. For now it seems that the implementation of an SOFC system is far away, but an educated guess can tell us that there can be possibilities concerning the improvements of the new system.

In this chapter the research will be discussed this will be done for each topic; Power demand analyses, Solid Oxide Fuel Cell technology, Energy storage system, retrofit and the numbers. The limitations and research suggestions will be highlighted.

### Power Demand Analyses.

The length of the measured data, timewise, is not very extensive. It describes 10 cycles, covering 135 hours of operation on the Bilbao Project by the HAM 318. A longer period of time would make the analysis more accurate. In this case it is most likely that a correction on the analysed data would not be needed. It is expected that the analysed results will come closer to the expected/guidelines of the company.

Unfortunately it was not possible to acquire and analyse the data over longer periods of time. This is because of the limited access to the data. Full access to the database was not granted, neither was it possible to convert the exact data points into CSV files. In the analyses, use has been made of NC-file copies of the data. By not having all the exact data points it is hard to be accurate. Therefore formulas in SimPlot were needed to calculate the averages of certain timesteps and stages of the dredging cycles. This is done in hourly timesteps and gave an somewhat accurate overall average. By being able to access the exact datapoints and run analysis over longer periods of time, a more accurate Power Demand Analysis could have been made.

### Selection of the installed SOFC capacity.

The determination of an installed SOFC stack system of 17099 kW was based on the average power demand of the HAM 318 in different stages. This is chosen under the assumption that a SOFC stack system will not fluctuate in supplied load and that an Energy Storage System can back-up the power fluctuations. In reality it is not sure, neither has there been calculations made, if the SOFC stack system and ESS can physically or technically meet these fluctuations. It is needed to do further research into the actual technology and its capabilities to meet the Power demands and fluctuations as described in this thesis.

This brings us to the limitations of the Solid-Oxide Fuel Cell technology. As described in the thesis, the SOFC technology is a rather new but promising technology. Use of the SOFC has already been made and is extending, this use is based on hydrocarbon fuels. The use of Ammonia as a fuel in SOFC's is rather new. The Cinit research, by my knowledge, is the only research that proved the succession and feasibility of Ammonia as a direct fuel in SOFC's. This means that the development of the technology is rather on laboratory level than it is a proven technology in the commercial world. To know if the SOFC technology is hypothetically or factually feasible on a Power Demand level as described for the HAM 318, more research needs to be done. It needs to be mentioned that there are uncertainties in the application of SOFC's in the Maritime Industry. It is not clear how a SOFC system handles itself when there is motion, due to swell, neither is it clear if the humid and salty conditions at sea affect the SOFC's

The technical feasibility of a hybrid system, with Battery Storage and Ultra-Capacitors, is in line with the necessary research on the SOFC stack system. Researching and knowing the actual technical possibilities of the described hybrid system can be a gamechanger in the quest for a zero-emission technology for Van Oord or the Maritime Industry in general. When the technical feasibility is known, it is possible to rethink the optimal set of SOFC and ESS technology. Technical difficulties lie mainly in the lack of loadstep capabilities of the SOFC stack system and the rate of (dis)charging of the Battery storage system. Further research should determine the technical feasibility of the zero-emission solution.

#### The Numbers

In this chapter it is attempted to give an insight on the costs of a SOFC and ESS hybrid system. This is done by drawing 2 scenarios, a 'Business As Usual' and 'Clean Future' scenario. Both have their limitations as well as their assumptions.

In the BAU situation a few assumption are made. The CAPEX of a conventional combustion engine was based on prices that are provided by Wartsila. These prices are based on a certain power output and the price that is determined is based on an extrapolation of these prices. Which can have inaccuracy concerning the actual price when an investment is made. Therefore it needs to be kept in mind that the actual price can deviate from the described price.

For the OPEX it needs to be taken into account that the prices are based on the cost standards, based on hopper volume, set by CIRIA. This can limit the actual OPEX of the HAM 318 for Van Oord. The cost standards are mainly used because of 2 reasons. Firstly, OPEX can heavily fluctuate from one project to another. The OPEX in dredging can be affected by the dredged material, weather conditions and other location depended factors. Therefore the use of a cost standard is clearer. Secondly, the OPEX of the CF scenario is rather hard to estimate, therefore a cost standard with a 3-point scenario is assumed.

The CAPEX of the SOFC and ESS have different limitations. The most important limitation lies in the assumption of the SOFC cost. To determine the cost of the SOFC, a manufacturing cost model is used. The problem lies in the 'manufacturing cost' part. As a SOFC stack system with the power capacity described in this thesis, has never been made before, it is hard to get an accurate price determination. The consumer price of the SOFC stack system is unknown. It is needed to determine the actual price of the SOFC set in further research. If the actual consumer price is known, it is most likely that the total price of the CF-scenario will significantly increase, making SOFC less feasible.

The CAPEX of the ESS system differs from the limitations with the SOFC stack system. For the determination of the ESS CAPEX, prices from literature have been used. These prices entail the Total Capital Cost and can differ for tailor made systems. As years go by, technologies and its cost improve. Therefore it needs to be taken into account that the prices mentioned in this research could fall in the future.

Lastly the autonomy of the Zero-Emission solution is not waterproof. The autonomy that has been calculated is purely based on the performance of the SOFC stack system as tested in the Cinti research. The fuel consumption could differ if the stack system would be expanded. It is unclear whether relative consumption would drop or increase. If that is the case, the autonomy would have to be re-calculated.

# Conclusion

To conclude this evaluation study and thesis, a brief summary of what has been done in the research will be given. This is followed up by a summary of the results and an explanation on future work that needs to be done.

The research was split up into different segments. Firstly, a literature review was conducted. In this literature review background information and motivation for the thesis was presented. In this literature review, evidence was found for the potential of Ammonia and SOFC's as a Zero-Emission solution. This was followed up by demarcation of a reference ship and reference project to analyze the power demand behavior of a potentially refitted ship of the Van Oord fleet. This needed to be done to determine the optimal set of SOFC rated power on board of the reference ship, HAM 318. The chapter following up these analyses, researched the possibilities for an onboard Energy Storage System. After the SOFC's and ESS were determined, a possible retrofit was presented. The final chapter of the thesis entailed the cost estimation of the possible new technologies in retrospect to a 'Business As Usual' situation.

It was found that the Power demand of the HAM 318 fluctuates heavily and in short amounts of time. Therefore a hybrid solution was needed. It has been calculated and determined that an amount of 17099 kW of SOFC power would be needed on board of the HAM 318. This needs to be complemented with Energy Storage Systems, in the of Battery Storage and Ultra-Capacitors. In a system where 17099 kW of SOFC form the baseload power generation on board, there is expected to be needed 11.000 kWh of Battery Storage and 5.000 kW of Ultra-Capacitors, to meet the HAM 318's power demands. The decision on an Energy Storage System, existing from Batteries and Ultra-Capacitors, was based on the characteristics of the technologies. This being the energy storage capacity over longer periods of time and favorable €/kWh price for Li-ion batteries. For the Ultra-Capacitors this was based on its capabilities to quickly charge and discharge high power levels and its favorable €/kW price. The prices for Li-ion and UC's being 546 €/kWh and 229 €/kW respectively. Lastly the carbon dioxide reduction is prosperous. Switching to this Zero-Emission technology will cause the carbon emission to drop with 3,42 metric tons per hour. This equals an hourly amount of €258,65 with a present day carbon price. With this evaluation it can be stated that a Zero-Emission solution, where the fuel is ammonia and the electricity generation and storage is done with SOFC's, Batteries and Ultra-Capacitors, is still a capital intensive investment. Both in an initial as well as a future investment.

The results from this research are based on certain assumptions, that have been addressed in the research as well as in the discussion. Further research needs to be done to determine the exact numbers. Especially interesting would be research in the technical feasibility of the SOFC and ESS system. A system, as described in this research, has never physically been made or tested. The outcome of further research could affect the results of this thesis. Next to the technical feasibility, further research needs to be done to determine the exact number of the OPEX of the Zero-Emission solution. If the exact OPEX can be determined a more accurate cost estimation of the Zero-Emission solution can be calculated. This, most likely, can change the outcome of this thesis.

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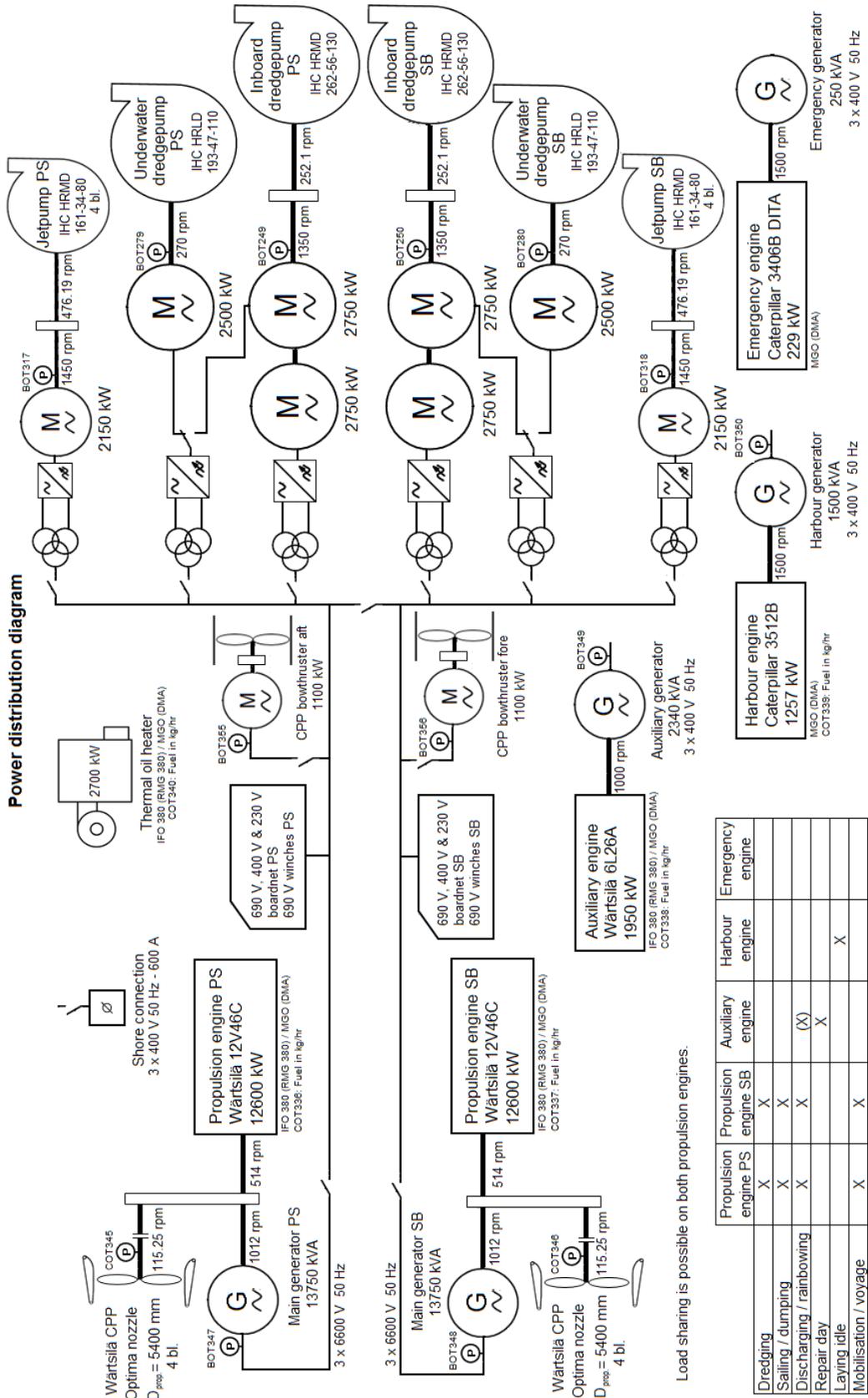
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# Appendix A

|  | Unit          |  | DUMP         |  | Rainbow/DUMP |  | PUMP         |
|--|---------------|--|--------------|--|--------------|--|--------------|
| Final load                                   | %             |  | 65           |  | 65           |  | 65           |
| Hopper load                                  | t             |  | 58244        |  | 58244        |  | 58244        |
| Hopper load                                  | TDS           |  | 36289        |  | 36289        |  | 36289        |
| sounded/measured hopper load                 | m3            |  | 22824        |  | 22824        |  | 22824        |
| <b>Hopper load pumped/dumped</b>             | <b>m3</b>     |  | <b>22824</b> |  | <b>22824</b> |  | <b>22324</b> |
| Number of pipes dredging                     | no            |  | 2            |  | 2            |  | 2            |
| Loading production                           | <b>m3/min</b> |  | <b>88</b>    |  | <b>88</b>    |  | <b>88</b>    |
| Dredging (incl turning)                      | min           |  | 259          |  | 259          |  | 253          |
| Sailing full                                 | min           |  | 40           |  | 40           |  | 41           |
| Manoeuvring                                  | min           |  | 20           |  | 20           |  |              |
| Connecting/disconnecting                     | min           |  |              |  |              |  | 15           |
| Pumping                                      | min           |  |              |  | 85           |  | 120          |
| Dumping                                      | min           |  | 10           |  | 5            |  |              |
| Sailing Empty                                | min           |  | 38           |  | 38           |  | 40           |
| <b>Total cycle</b>                           | <b>min</b>    |  | <b>367</b>   |  | <b>447</b>   |  | <b>469</b>   |
| <b>Total cycle</b>                           | <b>oh</b>     |  | <b>6.1</b>   |  | <b>7.5</b>   |  | <b>7.8</b>   |
| Service hours                                | hrs/wk        |  | 168          |  | 168          |  | 168          |
| <b>Operational hours</b>                     | <b>hrs/wk</b> |  | <b>136.4</b> |  | <b>136.4</b> |  | <b>136.4</b> |
| Efficiency                                   | %             |  | 81.2         |  | 81.2         |  | 81.2         |
| Trips per week                               | no            |  | 22.3         |  | 18.3         |  | 17.4         |
| <b>Hopper production</b>                     | <b>m3/oh</b>  |  | <b>3729</b>  |  | <b>3062</b>  |  | <b>2854</b>  |
| Hopper production                            | m3/wk         |  | 508634       |  | 417655       |  | 389228       |
| Fuel type                                    | l/hr          |  | <b>HFO</b>   |  | <b>HFO</b>   |  | <b>HFO</b>   |
| <b>Fuel consumption per operational hour</b> | <b>l/hr</b>   |  | 3653         |  | 3760         |  | 3549         |
| Total fuel consumption per week              | l/wk          |  | 506705       |  | 521124       |  | 498363       |

### HAM 318

#### Power distribution diagram



Load sharing is possible on both propulsion engines.

|                          | Propulsion engine PS | Propulsion engine SB | Auxiliary engine | Harbour engine | Emergency engine |
|--------------------------|----------------------|----------------------|------------------|----------------|------------------|
| Dredging                 | X                    | X                    |                  |                |                  |
| Sailing / dumping        | X                    | X                    |                  |                |                  |
| Discharging / rainbowing | X                    | X                    | (X)              |                |                  |
| Repair day               |                      |                      | X                | X              |                  |
| Laying idle              |                      |                      |                  |                |                  |
| Mobilisation / voyage    | X                    | X                    |                  |                |                  |

Appendix 2 Power Distribution of the HAM 318, (Paauw J., The HAM 318 power diagram, 2019)

|   |   |   |  |
|---|---|---|--|
|  <b>ROTOR b.v.</b><br>postbus 45,<br>7150 AA eibergen-nl | <h1>Certificate</h1>                      | №. : 200008-096<br>date : 2000.08.10              | <b>Squirrel-cage<br/>         Electric motors</b><br> |
|   |   | Certificate of Compliance (A) EN 10204.2.2 [1995] |  |
| our order ... : 0.20766<br>invoice №. : 574433<br>invoice date : 2000.08.10   | your order : 3015766<br>customer : 131424 | C O P Y - 1                                       |  |

Bakker Sliedrecht El.Ind. B.V.

Postbus 25

3360 AA SLIEDRECHT

|  |  |  |            |
|--|--|--|------------|
| motor type . . . . .   | 5RN90S04                               | moment of inertia J [kgm <sup>2</sup> ]: | 0,00000    |
| mounting . . . . .   | IM3011                                 | mass . . . . . [kg]:                     | 14         |
| output . . . . . [kW]:   | 1,10                                   | frequency . . . . . [Hz]:                | 50         |
| duty . . . . .   | S1-100%                                | starting torque d.o.l. [%]:              | 180        |
| speed . . . . [min-1]:   | C-CW 1405                              | no load current . . . [A]:               | 3,91 /2,26 |
| voltage . . . . [Vac]:   | D /Y 230/ 400                          | starting current d.o.l. [%]:             | 403        |
| nominal current [A]:   | 4,85 /2,80                             | temp.rise surface . . [K]:               | 32         |
| power factor cos.phi.:   | 0,81                                   | temp.rise windings . . [K]:              | 78         |
| efficiency . . . . [%]:  | 70,3                                   |  |            |
| insulation class . . .   | F                                      |  |            |
| protection class . . .   | IP 55 and tropicalized                 |  |            |
| marine classification:   | Acc. IEC 92.301 1980 RS 3014/AW/10 50° | amb.temp.                                | 50 °C      |
| high voltage dielectric test between phases and earth during 1 min. [Vac]: | 2000                                   |  |            |
| overload test during 15 seconds overload torque . . . . . [%FLT]:          | 160                                    |  |            |
| insulation resistance cold . . . . . [M.ohm]:                              | >200                                   | or as specified otherwise.               |            |
| vibration severity according IEC 34-14 dd. 11-1996 (half key) . . . . .    | class "N" or as specified below.       |  |            |
| bearings DE/NDE . . .  | 6205 2Z C3 / 6205 2Z C3                |  |            |
| motor serial numbers :   | 0080386 0080387 0080388 0080389        |  |            |



We herewith declare that the motor(s) covered by this certificate has/have been manufactured in accordance with the current standards and applicable regulations.  
 The type test results as stated on this certificate are also applicable to this/these motor(s) as these are measured on an identical machine.

**Appendix 4 Stage times and cycles for each stage of the dredging cycle**

Timetable of stage and cycle

Stage 1 sailing empty

| Cycle          | Day | start time | end time | time in min | part of a hour |
|----------------|-----|------------|----------|-------------|----------------|
| 1              | 22  | 23:25:00   | 23:55:00 | 00:30:00    | 0.50           |
| 2              | 23  | 07:30:00   | 07:50:00 | 00:20:00    | 0.33           |
| 3              | 23  | 16:10:00   | 16:40:00 | 00:30:00    | 0.50           |
| 4              | 24  | 01:11:00   | 01:37:00 | 00:26:00    | 0.43           |
| 5              | 24  | 09:30:00   | 10:05:00 | 00:35:00    | 0.58           |
| 6              | 24  | 17:35:00   | 18:00:00 | 00:25:00    | 0.42           |
| 7              | 25  | 02:30:00   | 03:25:00 | 00:55:00    | 0.92           |
| 8              | 25  | 10:40:00   | 11:15:00 | 00:35:00    | 0.58           |
| 9              | 25  | 17:40:00   | 18:00:00 | 00:20:00    | 0.33           |
| 10             | 26  | 00:30:00   | 00:55:00 | 00:25:00    | 0.42           |
| AVG Cycle time |     |            |          |             | 0.50           |

Stage 2 trailing

| cycle          | day | start time | end time | time in min | part of a hour |
|----------------|-----|------------|----------|-------------|----------------|
| 1              | 23  | 00:00:00   | 05:00:00 | 05:00:00    | 5              |
| 2              | 23  | 08:00:00   | 13:00:00 | 05:00:00    | 5              |
| 3              | 23  | 17:00:00   | 22:00:00 | 05:00:00    | 5              |
| 4              | 24  | 02:00:00   | 06:00:00 | 04:00:00    | 4              |
| 5              | 24  | 10:30:00   | 15:00:00 | 04:30:00    | 4.5            |
| 6              | 24  | 18:15:00   | 23:15:00 | 05:00:00    | 5              |
| 7              | 25  | 04:00:00   | 08:00:00 | 04:00:00    | 4              |
| 8              | 25  | 12:00:00   | 15:00:00 | 03:00:00    | 3              |
| 9              | 25  | 18:00:00   | 21:00:00 | 03:00:00    | 3              |
| 10             | 27  | 11:00:00   | 14:00:00 | 03:00:00    | 3              |
| AVG Cycle time |     |            |          |             | 4.15           |

## Stage 3 sailing full

| cycle | day | start time | end time  | time in min | part of a hour |
|-------|-----|------------|-----------|-------------|----------------|
| 1     | 23  | 05:25:00   | 05:50:00  | 00:25:00    | 0.42           |
| 2     | 23  | 13:20:00   | 14:10:00  | 00:50:00    | 0.83           |
| 3     | 23  | 22:25:00   | 22:55:00  | 00:30:00    | 0.50           |
| 4     | 24  | 06:20:00   | 07:10:00  | 00:50:00    | 0.83           |
| 5     | 24  | 15:10:00   | 15:45:00  | 00:35:00    | 0.58           |
| 6     | 24  | 23:45:00   | 00:15:00  | #####       | 0.50           |
| 7     | 25  | 08:00:00   | 08:30:00  | 00:30:00    | 0.50           |
| 8     | 25  | 15:10:00   | 15:40:00  | 00:30:00    | 0.50           |
| 9     | 25  | 21:58:00   | 22:26:00  | 00:28:00    | 0.47           |
| 10    | 27  | 06:50:00   | 07:30:00  | 00:40:00    | 0.67           |
|       |     |            | AVG Cycle |             |                |
|       |     |            | time      |             | 0.58           |

## Stage 4 dumping

| cycle | day | start time | end time  | time in min | part of a hour |
|-------|-----|------------|-----------|-------------|----------------|
| 1     | 23  | 06:30:00   | 07:05:00  | 00:35:00    | 0.58           |
| 2     | 23  |            |           |             |                |
| 3     | 24  | 00:50:00   | 01:02:00  | 00:12:00    | 0.20           |
| 4     | 24  | 09:05:00   | 09:22:00  | 00:17:00    | 0.28           |
| 5     | 24  | 17:17:00   | 17:26:00  | 00:09:00    | 0.15           |
| 6     | 25  | 02:05:00   | 02:20:00  | 00:15:00    | 0.25           |
| 7     | 25  | 10:15:00   | 10:30:00  | 00:15:00    | 0.25           |
| 8     | 26  |            |           |             |                |
| 9     | 26  | 00:10:00   | 00:20:00  | 00:10:00    | 0.17           |
| 10    | 27  | 09:15:00   | 09:20:00  | 00:05:00    | 0.08           |
|       |     |            | AVG Cycle |             |                |
|       |     |            | time      |             | 0.25           |

## Stage 5 shore discharge

| cycle | day | start time | end time  | time in min | part of a hour |
|-------|-----|------------|-----------|-------------|----------------|
| 1     | 23  | 06:30      | 07:05     | 00:35       | 0.58           |
| 2     | 23  | 14:35      | 16:00     | 01:25       | 1.42           |
| 3     | 23  | 23:10      | 00:25     | 01:15       | 1.25           |
| 4     | 24  | 07:20      | 08:45     | 01:25       | 1.42           |
| 5     | 24  | 15:55      | 17:10     | 01:15       | 1.25           |
| 6     | 25  | 00:41      | 02:00     | 01:19       | 1.32           |
| 7     | 25  | 09:00      | 10:10     | 01:10       | 1.16           |
| 8     | 25  | 15:50      | 17:20     | 01:30       | 1.50           |
| 9     | 27  | 07:30      | 09:00     | 01:30       | 1.50           |
| 10    | 27  | 15:30      | 16:55     | 01:25       | 1.42           |
|       |     |            | AVG Cycle |             |                |
|       |     |            | time      |             | 1.28           |

| Technology       | Energy Efficiency | Energy Density | Power Range | Power Density | Lifetime | Cycle Life | Self Discharge | Total Capt Cost | Fixed O&M | Storage |
|------------------|-------------------|----------------|-------------|---------------|----------|------------|----------------|-----------------|-----------|---------|
| Li-ion           | Green             | Yellow         | Yellow      | Yellow        | Pink     | Yellow     | Green          | Yellow          | Yellow    | Green   |
| VRFB             | Green             | Green          | Yellow      | Yellow        | Yellow   | Green      | Green          | Yellow          | Yellow    | Green   |
| Ultracapacitors  | Green             | Pink           | Yellow      | Green         | Green    | Green      | Yellow         | Green           | Yellow    | Yellow  |
| Flywheel (steel) | Green             | Pink           | Yellow      | Green         | Green    | Green      | Pink           | Green           | Yellow    | Pink    |
| Flywheel (comp)  | Green             | Pink           | Yellow      | Green         | Green    | Green      | Pink           | Green           | Yellow    | Pink    |

Appendix 5 positive/negative scheme ESS technologies

Appendix 6 CIRIA cost standard table for TSHD based on hopper volume

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| Hopper Volume | Displacement at dredging mark | Lightweight (W) | Power dredge pumps during suction (Pt) <sup>a</sup> b | Power jet pumps on draghead (Jt) | Free sailing propulsion power (S) | Value (V) <sup>d</sup> | Costs per week (D+i) | Cost per week (M+R) | M+R per Week |
|---------------|-------------------------------|-----------------|---|----------------------------------|-----------------------------------|------------------------|----------------------|---------------------|--------------|
| m3            | tonnes                        | t               | kW  | kW                               | kW                                | €                      | €                    | €                   | % of V       |
| 972           | 2160                          | 685.8           | 378   | 237.6                            | 1026                              | 114480                 | 33428.16             | 23670.36            | 0.223344     |
| 1404          | 3240                          | 1020.6          | 648   | 324                              | 1674                              | 165240                 | 48250.08             | 32948.64            | 0.215352     |
| 1944          | 4320                          | 1360.8          | 950.4   | 388.8                            | 2376                              | 213840                 | 62441.28             | 41832.72            | 0.211248     |
| 2592          | 5616                          | 1771.2          | 1080  | 712.8                            | 2700                              | 261360                 | 76317.00             | 46035.12            | 0.190188     |
| 2916          | 6264                          | 1944            | 1350  | 712.8                            | 3834                              | 293760                 | 85777.92             | 48753.36            | 0.17928      |
| 3780          | 8208                          | 2592            | 1674  | 820.8                            | 4320                              | 362880                 | 105960.96            | 54554.04            | 0.162324     |
| 5076          | 10692                         | 3294            | 2106  | 864                              | 5508                              | 441720                 | 128982.24            | 61170.12            | 0.14958      |
| 6696          | 14040                         | 4239            | 2592  | 918                              | 6966                              | 541080                 | 157995.36            | 69507.72            | 0.13878      |
| 8316          | 17280                         | 5162.4          | 2808  | 1080                             | 7938                              | 627480                 | 183224.16            | 76757.76            | 0.132084     |
| 9828          | 20520                         | 6085.8          | 3780  | 1728                             | 10152                             | 741960                 | 216652.32            | 86364.36            | 0.125712     |
| 11880         | 24840                         | 7376.4          | 4665.6  | 1728                             | 11664                             | 868320                 | 253549.44            | 96968.88            | 0.120636     |
| 13500         | 28080                         | 8218.8          | 5616  | 1728                             | 14040                             | 969840                 | 283193.28            | 105487.92           | 0.117504     |
| 14580         | 31320                         | 9379.8          | 5616  | 1944                             | 14040                             | 1055160                | 308106.72            | 112647.24           | 0.115344     |
| 19440         | 43200                         | 13068           | 7214.4  | 2160                             | 18036                             | 1382400                | 403660.8             | 140108.4            | 0.109512     |
| 20520         | 45360                         | 14850           | 7560  | 2160                             | 18900                             | 1522800                | 444657.6             | 151890.12           | 0.107676     |
| 24300         | 51840                         | 17226           | 7776  | 3240                             | 19440                             | 1695600                | 495115.2             | 166391.28           | 0.105948     |
| 25920         | 64800                         | 19710           | 10368   | 4320                             | 25920                             | 1987200                | 580262.4             | 190860.84           | 0.10368      |
| 37800         | 89640                         | 24235.2         | 10368   | 4320                             | 25920                             | 2289600                | 668563.2             | 216237.6            | 0.101952     |
| 48600         | 113400                        | 29160           | 14040   | 4860                             | 41040                             | 2818800                | 823089.6             | 260646.12           | 0.0999       |

| System Power/kWe | Systems/year | Stack cost base design \$/kWe-1 | Stack cost alternative design \$/kWe-1 | Cost increase /% |
|------------------|--------------|---------------------------------|--|------------------|
| 1                | 100          | 5387                            | 5463                                   | 1.4              |
| 1                | 1000         | 1196                            | 1252                                   | 4.7              |
| 1                | 10000        | 451                             | 485                                    | 7.4              |
| 1                | 50000        | 322                             | 347                                    | 7.7              |
| 10               | 100          | 1039                            | 1096                                   | 5.4              |
| 10               | 1000         | 342                             | 376                                    | 9.7              |
| 10               | 10000        | 197                             | 221                                    | 12.3             |
| 10               | 50000        | 178                             | 202                                    | 13.1             |
| 50               | 100          | 478                             | 514                                    | 7.7              |
| 50               | 1000         | 215                             | 240                                    | 11.5             |
| 50               | 10000        | 176                             | 200                                    | 13.2             |
| 50               | 50000        | 170                             | 193                                    | 13.5             |
| 100              | 100          | 339                             | 372                                    | 9.8              |
| 100              | 1000         | 194                             | 219                                    | 12.4             |
| 100              | 10000        | 171                             | 194                                    | 13.5             |
| 100              | 50000        | 168                             | 191                                    | 13.7             |
| 250              | 100          | 249                             | 274                                    | 10               |
| 250              | 1000         | 181                             | 204                                    | 13               |
| 250              | 10000        | 167                             | 190                                    | 13.7             |
| 250              | 50000        | 166                             | 189                                    | 13.9             |

Appendix 7 SOFC manufacturing costs depending on production level, annually

| Parameter             | Symbol   | Value   | Units   | Comments                       |
|-----------------------|----------|---------|---------|--------------------------------|
| Operation hours       | Ths      | varies  | hours   | 8h base shift (2-3 shifts/day) |
| Annual operating days | Tdy      | 240     | days    | 52 wks*5d/week - 20 holidays   |
| Avg. inflation rate   | J        | 0.023   |         | US average for 10 years        |
| Avg mortgage rate     | Jm       | 0.051   |         | Trading Economics              |
| Discount rate         | Jd       | 0.1     |         |                                |
| Energy inflation rate | Je       | 0.056   |         | US average for last 3 years    |
| Income tax            | li       | 0       |         | No net income                  |
| Property tax          | lp       | 0.01035 |         | US average                     |
| Assessed value        | lav      | 0.4     |         |                                |
| Salvage tax           | ls       | 0.5     |         |                                |
| EOL salvage value     | Keol     | 0.02    |         | Assume 2% of end-of-life value |
| Tool lifetime         | Tt       | 15      | Years   | typical value in practice      |
| Energy tax credits    | ITC      | 0       | Dollars |                                |
| Energy cost           | Ce       | 0.1     | \$/kWhe | Typical US value               |
| Floor Space cost      | Cfs      | 1.291   | \$ m2   | US average for factory         |
| Building depreciation | Jbr      | 0.031   |         | US department of Commerce      |
| Building recovery     | Tbr      | 31      | years   | US department of Commerce      |
| Hourly labour cost    | C-labour | 30      | \$/hr   | Hourly wage per worker         |

Appendix 8 Parameters of Scataglini's manufacturing cost model



## Typical Characteristics

Type VP with 48 cells for example

| Symbol        | Parameter                       | Description                                     | Value        | Unit  |
|---------------|---------------------------------|---|--------------|-------|
|               | Capacity                        |   |              |       |
| $C_r$         | Rated capacity                  |   | 62,5         | F     |
|               | Tolerance                       |   | +20/-0       | F     |
|               | Voltage                         |   |              |       |
| $V_r$         | Rated voltage                   |   | 130          | VDC   |
| $V_{max}$     | Max. operating voltage          |   | 137          | VDC   |
| $V_{ins}$     | Isolation voltage               | Max. voltage at base isolation                  | 1800         | VDC   |
|               | Internal resistance             |   |              |       |
| ESR, DC       | Equivalent series resistance DC | @ 25°C (Initial...Life time)                    | 9...28       | VDC   |
| ESR, AC       | Equivalent series resistance AC | @ 25°C and 1 kHz (Initial)                      | 11           | mΩ    |
|               | Environment                     |   |              |       |
| $T_o$         | Operating temperature range     |   | -20 till +65 | °C    |
| $T_{storage}$ | Storage temperature range       |   | -40 till +65 | °C    |
|               | Protection degree               |   | IP00         |       |
|               | Energy                          |   |              |       |
| $E_{max}$     | Energy density                  | @ $V_r$   | 4,4          | Wh/kg |
| $E_{use}$     | Usable energy                   | Between $V_r$ and $\frac{1}{2} V_r$             | 110          | Wh    |
|               | Current                         |   |              |       |
| $I_r$         | Rated current                   | Continuous                                      | 100          | A rms |
|               | Peak current                    | < 1 s   | 2000         | A     |
|               |                                 | < 5 s   | 750          | A     |
| $I_{leak}$    | Leakage current                 | After 72 hour @ 25°C and $V_r$ (only the cells) | 5,2          | mA    |
|               | Lifetime                        |   |              |       |
|               | Projected cycle life            | Between $V_r$ and $\frac{1}{2} V_r$ @ 25°C      | 1.000.000    |       |
|               | Projected DC life               | @ $V_r$ and 25°                                 | 10           | a     |
|               |                                 | @ $V_r$ and 65°                                 | 1500         | h     |
|               | Mechanical data                 |   |              |       |
|               | Weight                          |   | 33           | Kg    |
|               | Width                           |   | 600          | mm    |
|               | Depth                           |   | 436          | mm    |
|               | Height                          |   | 167          | mm    |

Appendix 9 AEP Characteristics of Ultra-Capacitors

## SUMMARY OF FUEL CELL TECHNOLOGIES

| Technology  | Relative cost | Module Power levels (kW) | Lifetime  | Tolerance for cycling | Fuel                            | Maturity   | Size   | Sensitivity to fuel impurities | Emissions   | Safety Aspects  | Efficiency                                      |
|---|---------------|--------------------------|-----------|-----------------------|---------------------------------|--|--------|--------------------------------|---|---|---|
| <b>Alkaline fuel cell (AFC)</b>                   | Low           | Up to 500 kW             | Moderate  | Good                  | High purity hydrogen            | High, experience from several applications including one ship        | Small  | High                           | No  | Hydrogen  | 50-60 % (electrical)                            |
| <b>Phosphoric acid fuel cell (PAFC)</b>           | Moderate      | 100-400 kW               | Excellent | Moderate              | LNG, Methanol, Diesel, Hydrogen | High, extensive experience from several applications                 | Large  | Medium                         | CO <sub>2</sub> and low levels of NO <sub>x</sub> if carbon fuel is used. | High temperature (up to 200 C), Hydrogen and CO in reforming unit             | 40 % (electrical) and 80 % (with heat recovery) |
| <b>Molten carbonate fuel cell (MCFC)</b>          | High          | Up to 500 kW             | Good      | Low                   | LNG, Methanol, Diesel, Hydrogen | High, extensive experience from several applications including ships | Large  | Low                            | CO <sub>2</sub> and low levels of NO <sub>x</sub> if carbon fuel is used. | High temperature (600-700 C), Hydrogen and CO in cell from internal reforming | 50 % (electrical) and 85 % (with heat recovery) |
| <b>Solid oxide fuel cell (SOFC)</b>               | High          | 20-60 kW                 | Moderate  | Low                   | LNG, Methanol, Diesel, Hydrogen | Moderate, experience from several applications including ships       | Medium | Low                            | CO <sub>2</sub> and low levels of NO <sub>x</sub> if carbon fuel is used. | High temperature (600-700 C), Hydrogen and CO in cell from internal reforming | 60 % (electrical) and 85 % (with heat recovery) |
| <b>Proton Exchange Membrane fuel cell (PEMFC)</b> | Low           | Up to 120 kW             | Moderate  | Good                  | Hydrogen                        | High, extensive experience from several applications including ships | Small  | Medium                         | No  | Hydrogen  | 50-60 % (electrical)                            |
| <b>High Temperature PEM fuel cell (HT-PEMFC)</b>  | Moderate      | Up to 30 kW              | Unknown   | Good                  | LNG, Methanol, Diesel, Hydrogen | Low, experience some applications including ships                    | Small  | Low                            | CO <sub>2</sub> and low levels of NO <sub>x</sub> if carbon fuel is used. | High temperature (up to 200 C), Hydrogen and CO in reforming unit             | 50-60 % (electrical)                            |
| <b>Direct methanol fuel cell (DMFC)</b>           | Moderate      | Up to 5 kW               | Moderate  | Good                  | Methanol                        | Under development  | Small  | Low                            | CO <sub>2</sub>   | Methanol  | 20 % (electrical)                               |