FEASIBILITY ANALYSIS OF THE DRIVE TRAIN ELECTRIFICATION FOR A RESCUE BOAT

CLAUDIA ANDRUETTO
FEASIBILITY ANALYSIS
OF THE DRIVE TRAIN ELECTRIFICATION
FOR A RESCUE BOAT

CLAUDIA ANDRUETTO

Master Thesis at the School of Electrical Engineering & Computer Science

Supervisor: Luca Peretti
Examiner: Oskar Wallmark

Department of Electric Power & Energy Systems

August 2019
Abstract

Progressing constraints on greenhouse gas emissions lead to a sustainability trend, which greatly affects the transport sector. Nowadays, companies show increasing interest in developing sustainable solutions.

This thesis has been started thanks to a project given by Sjöräddningssällskapet, the most relevant association that performs sea rescue operations in Swedish waters. Sjöräddningssällskapet would like to explore the possibility of making their rescue boat fleet entirely carbon-free, hence more sustainable. What may provide a suitable solution is an electric drive train with hybrid energy storage, composed by a battery pack and a fuel cell stack. The research question is whether it would be feasible to combine fuel cell stacks and battery packs to provide power to a fast small boat.

From a sketch of a rescue boat, the drive train design for such boat is studied in its integrity, from the water jet pump to the battery and fuel cell systems. The required power has been calculated empirically, using data from online tests on water jet boats. Different tests have been considered, resulting in a mean power curve and a mean consumption curve allowing comparison between the hybrid electric drive train with an internal combustion engine drive train. Three profiles of speed, power and consumption have been assumed for the calculation of the required energy and hence rate the energy storage system. A design has been proposed in terms of fuel cell capacity and battery capacity. The propulsion unit, composed by the electric machine and water jet, has been studied, focusing on different electric drive technologies. Few conclusions on both the weight and sustainability requirements are discussed. A sustainability analysis is carried out in terms of CO₂ emissions, through a life cycle assessment accounting for the environmental impact of the system during the whole life cycle, from cradle to grave.

Keywords: electric boat, rescue sector, boating, drive train modelling, water jet, fuel cells, batteries, hybrid electric storage, sustainability, CO₂ emissions, life cycle assessment.
Abstrakt

Ökande begränsningar för utsläpp av växthusgaser leder till en hållbarhetsutveckling, vilket påverkar transportsektorn kraftigt. Nuförtiden visar företag ett ökande intresse för att utveckla hållbara lösningar.

Denna avhandling har startats tack vare ett projekt som ges av Sjöräddningssällskapet, den viktigaste föreningen som utför havsräddningsinsatser i svenska vatten. Sjöräddningssällskapet vill undersöka möjligheten att göra deras räddningsbåtflotta helt emissionfri, och därmed mer hållbar.

Det som kan ge en lämplig lösning är ett elektriskt drivsystem med hybrid energilagring, sammansatt av ett batteripaket och en bränslecell-stapel. Forskningsfrågan är om det skulle vara möjligt att kombinera bränslecellstaplar och batteripaket för att driva en snabb liten båt.

Tre profiler av hastighet, effekt och förbrukning har antagits för beräkning av den erforderliga energin och därmed för energilagringssystemet. En design har föreslagits vad gäller bränslecelskapacitet och batterikapacitet.
Framdrivningsehiten, sammansatt av den elektriska maskinen och vattenstralen, har studerats med fokus på olika elektriska drivtekniker. Några slutsatser om både den elektriska maskinen och den framdrivningsehiten diskuteras.
En hållbarhetsanalys utförs med avseende på koldioxidutsläpp genom en livscykelbedömning som redovisar systemets miljöpåverkan under hela livscyklens, från vägga till grav.

Nyckelord: elbåt, räddningssektor, båtar, drivsystemsmodellering, vattenstråle, bränsleceller, batterier, hybrid elektrisk lagring, hållbarhet, CO2 utsläpp, livscykelbedömning.
Acknowledgements

I would like to thank my supervisor, Professor Luca Peretti, for supporting me throughout the entire project and for giving me valuable advice. Furthermore, I would like to thank my examiner, Professor Oskar Wallmark, for accepting this thesis proposal. I have received technical and moral support from all my colleagues from the Division of Electric Power and Energy Systems, that assisted me every day. For this, I would like to express my gratitude.

I would also like to acknowledge Ariel Chiche, for helping me and giving essential contribution for the development of the project. I would also like to thank Professor Carina Lagergren, for allowing a collaboration between myself and the Division of Applied Electrochemistry.

In addition, my family and my friends were always there for me, with their wise counsel, supporting me through each and every problem and providing useful distractions. For this, I am extremely grateful.
# Table of Contents

Abstract \hspace{1cm} i  
Abstrakt \hspace{1cm} iii  
Acknowledgements \hspace{1cm} v  
Table of Contents \hspace{1cm} vii  
List of Abbreviations \hspace{1cm} xi  

## 1 Introduction

1.1 Background \hspace{1cm} 1  
1.1.1 History of electric boats \hspace{1cm} 1  
1.1.2 Boating in Sweden \hspace{1cm} 2  
1.1.3 Rescue sector \hspace{1cm} 3  
\hspace{1cm} 1.1.3.1 Rescue sector in Sweden \hspace{1cm} 3  
\hspace{1cm} 1.1.3.2 Sjöräddningssällskapet \hspace{1cm} 4  
1.2 Experience in maritime electrification \hspace{1cm} 4  
\hspace{1cm} 1.2.1 Tourist boats \hspace{1cm} 4  
\hspace{1cm} 1.2.1.1 ZEMShip project \hspace{1cm} 4  
\hspace{1cm} 1.2.1.2 Nemo H2 \hspace{1cm} 6  
\hspace{1cm} 1.2.1.3 Gold Green HYGEN \hspace{1cm} 6  
\hspace{1cm} 1.2.2 Leisure boats \hspace{1cm} 7  
\hspace{1cm} 1.2.2.1 Marti \hspace{1cm} 7  
\hspace{1cm} 1.2.2.2 Future Project Hydrogen \hspace{1cm} 7  
\hspace{1cm} 1.2.2.3 Hydroxy 3000 \hspace{1cm} 8  
\hspace{1cm} 1.2.2.4 eJET 450 \hspace{1cm} 8  
\hspace{1cm} 1.2.3 Conclusion \hspace{1cm} 9  
1.3 Outline \hspace{1cm} 10  

## 2 Case study

2.1 Rescue boat \hspace{1cm} 11
# Table of Contents

2.2 Smedjebacken station ................................................. 14  
2.2.1 Types of rescue mission ........................................ 15  
2.2.2 Poker run .......................................................... 15  
2.3 List of requirements ................................................. 16  
2.4 Sustainability ......................................................... 16  
2.4.1 Contribution to green house gases emissions .................. 17  
3 Boat Drive Train Modelling ............................................. 19  
3.1 Background ............................................................. 19  
3.1.1 Hull resistance ...................................................... 19  
3.1.1.1 Components of hull resistance ............................... 20  
3.1.2 Hybrid electric ship drive train ................................. 22  
3.1.2.1 Propulsive efficiency ........................................... 23  
3.1.2.2 Effective power ............................................... 23  
3.1.2.3 Performance curves ............................................ 24  
3.1.2.4 Estimation of round trip efficiency .......................... 26  
3.1.3 ICE drive train ...................................................... 26  
3.1.3.1 Propulsive efficiency ........................................... 27  
3.2 Methodology ............................................................ 27  
3.2.1 Online data gathering .............................................. 27  
3.2.2 Graphs and visual representation of data ....................... 28  
3.2.3 Mean power speed curve and mean consumption speed curve 29  
3.2.4 Comparative analysis with theoretical results .................. 29  
3.3 Results ................................................................. 29  
3.3.1 Online data gathering - Yamaha AR195 .......................... 30  
3.3.2 Graphs and visual representation of data - Yamaha AR195 30  
3.3.3 Mean power speed curve ......................................... 32  
3.3.4 Mean consumption curve ......................................... 33  
3.3.5 Comparative analysis with theoretical results .................. 33  
3.4 Conclusions ............................................................. 34  
4 Energy Storage ......................................................... 35  
4.1 Background ............................................................. 35  
4.1.1 Energy storage technologies ...................................... 35  
4.1.2 Fuel cells .............................................................. 36  
4.1.2.1 Fuel cell power system interconnection ....................... 37  
4.1.2.2 Fuel cell characterization ..................................... 37  
4.1.2.3 Application of fuel cells in vehicles .......................... 37  
4.1.2.4 PEMFC ............................................................ 38  
4.1.2.5 Hyundai Nexo .................................................... 39  
4.1.2.6 Fuel cell efficiency ............................................. 40  
4.1.3 Battery pack .......................................................... 40  
4.1.3.1 Secondary battery technologies ............................... 41  
4.1.3.2 Primary battery technologies .................................. 42  
4.1.4 Specifications of chosen technologies ........................... 42  
4.1.4.1 Battery systems ............................................... 42  
4.1.4.2 Fuel cell system ............................................... 43  
4.1.4.3 ICE ............................................................... 43  
4.1.4.4 Electric machine ............................................... 44  
4.2 Methodology ............................................................ 44
TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.2.1 Speed, power and consumption profiles</td>
<td>44</td>
</tr>
<tr>
<td>4.2.1.1 Typical mission</td>
<td>46</td>
</tr>
<tr>
<td>4.2.1.2 Mission I: missing person</td>
<td>48</td>
</tr>
<tr>
<td>4.2.1.3 Mission II: tow a boat</td>
<td>49</td>
</tr>
<tr>
<td>4.2.2 Analysis of different energy storage technologies</td>
<td>50</td>
</tr>
<tr>
<td>4.3 Results</td>
<td>50</td>
</tr>
<tr>
<td>4.3.1 Typical mission</td>
<td>50</td>
</tr>
<tr>
<td>4.3.1.1 Mission I: missing person</td>
<td>53</td>
</tr>
<tr>
<td>4.3.1.2 Mission II: tow a boat</td>
<td>55</td>
</tr>
<tr>
<td>4.3.2 Analysis of different energy storage technologies</td>
<td>56</td>
</tr>
<tr>
<td>4.4 Conclusion</td>
<td>56</td>
</tr>
<tr>
<td>4.4.1 Design proposition</td>
<td>57</td>
</tr>
<tr>
<td>5 Propulsion Unit</td>
<td>59</td>
</tr>
<tr>
<td>5.1 Background</td>
<td>59</td>
</tr>
<tr>
<td>5.1.1 Electric machine</td>
<td>59</td>
</tr>
<tr>
<td>5.1.1.1 DC motors</td>
<td>61</td>
</tr>
<tr>
<td>5.1.1.2 Induction motors</td>
<td>61</td>
</tr>
<tr>
<td>5.1.1.3 Synchronous motors - permanent magnets brushless motors</td>
<td>61</td>
</tr>
<tr>
<td>5.1.1.4 Switched reluctance motor</td>
<td>62</td>
</tr>
<tr>
<td>5.1.2 Evaluation of electric machine technologies for HEV</td>
<td>62</td>
</tr>
<tr>
<td>5.1.3 Rare earth elements</td>
<td>63</td>
</tr>
<tr>
<td>5.1.4 Water jet systems</td>
<td>65</td>
</tr>
<tr>
<td>5.1.4.1 Statistics</td>
<td>66</td>
</tr>
<tr>
<td>5.1.4.2 Water jet hydrodynamics</td>
<td>66</td>
</tr>
<tr>
<td>5.1.4.3 Assessment of wake parameter</td>
<td>67</td>
</tr>
<tr>
<td>5.2 Methodology</td>
<td>68</td>
</tr>
<tr>
<td>5.3 Results</td>
<td>69</td>
</tr>
<tr>
<td>5.3.1 Electric machine</td>
<td>69</td>
</tr>
<tr>
<td>5.3.1.1 Emrax</td>
<td>69</td>
</tr>
<tr>
<td>5.3.1.2 Bosch Mobility Solutions</td>
<td>70</td>
</tr>
<tr>
<td>5.3.1.3 Zytek</td>
<td>70</td>
</tr>
<tr>
<td>5.3.1.4 Lafert Group</td>
<td>71</td>
</tr>
<tr>
<td>5.3.2 Water jet</td>
<td>71</td>
</tr>
<tr>
<td>5.3.3 Fuel cell stack</td>
<td>73</td>
</tr>
<tr>
<td>6 CO₂ Emissions</td>
<td>75</td>
</tr>
<tr>
<td>6.1 Life cycle assessment</td>
<td>75</td>
</tr>
<tr>
<td>6.2 Methodology</td>
<td>76</td>
</tr>
<tr>
<td>6.3 Estimated fixed and variable emissions</td>
<td>77</td>
</tr>
<tr>
<td>6.3.1 ICE</td>
<td>77</td>
</tr>
<tr>
<td>6.3.1.1 Fixed emissions</td>
<td>77</td>
</tr>
<tr>
<td>6.3.1.2 Usage emissions</td>
<td>77</td>
</tr>
<tr>
<td>6.3.2 Battery pack</td>
<td>77</td>
</tr>
<tr>
<td>6.3.2.1 Fixed emissions</td>
<td>78</td>
</tr>
<tr>
<td>6.3.2.2 Impact of the electricity mix</td>
<td>78</td>
</tr>
<tr>
<td>6.3.2.3 Usage emissions</td>
<td>79</td>
</tr>
<tr>
<td>6.3.3 Fuel cell stack</td>
<td>79</td>
</tr>
<tr>
<td>6.3.3.1 Fixed emissions</td>
<td>80</td>
</tr>
<tr>
<td>6.3.3.2 Availability of hydrogen</td>
<td>80</td>
</tr>
</tbody>
</table>
# TABLE OF CONTENTS

6.3.3.3 Usage emissions ........................................ 81
6.3.4 Electric machine and inverter ................................ 82
6.3.5 Summary of values ........................................ 83
7 Conclusion .................................................. 83

## Conclusion

7.1 The project ............................................. 85
7.2 Boat drive train modelling ................................... 85
7.3 Energy storage ............................................ 86
7.4 Propulsion unit .......................................... 86
7.5 CO\textsubscript{2} emissions ................................ 87
7.6 Future work ............................................. 87
7.6.1 Control system .......................................... 87
7.6.2 Coupling of the propulsion system with the energy storage system ........................................ 88
7.6.3 On board equipment ..................................... 88

Bibliography ............................................... 89
# List of Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC</td>
<td>Alternating Current</td>
</tr>
<tr>
<td>AFC</td>
<td>Alkaline Fuel Cell</td>
</tr>
<tr>
<td>BEV</td>
<td>Battery Electric Vehicles</td>
</tr>
<tr>
<td>ca.</td>
<td>circa (approximately)</td>
</tr>
<tr>
<td>CCS</td>
<td>Carbon dioxide Capture and Storage</td>
</tr>
<tr>
<td>CMM</td>
<td>Coal mine Methane Mitigation</td>
</tr>
<tr>
<td>$\text{CO}_2$eq</td>
<td>$\text{CO}_2$ equivalent</td>
</tr>
<tr>
<td>DC</td>
<td>Direct Current</td>
</tr>
<tr>
<td>DMFC</td>
<td>Direct Methanol Fuel Cell</td>
</tr>
<tr>
<td>DT</td>
<td>Drive Train</td>
</tr>
<tr>
<td>e.g.</td>
<td>exempli gratia (for example)</td>
</tr>
<tr>
<td>EV</td>
<td>Electric Vehicles</td>
</tr>
<tr>
<td>GHG</td>
<td>Green House Gases</td>
</tr>
<tr>
<td>GPS</td>
<td>Global Positioning System</td>
</tr>
<tr>
<td>GWP</td>
<td>Global Warming Potential</td>
</tr>
<tr>
<td>HEV</td>
<td>Hybrid Electric Vehicles</td>
</tr>
<tr>
<td>ICE</td>
<td>Internal Combustion Engine</td>
</tr>
<tr>
<td>IM</td>
<td>Induction Motor</td>
</tr>
<tr>
<td>IMO</td>
<td>Internationa Maritime Organization</td>
</tr>
<tr>
<td>LCA</td>
<td>Life Cycle Assessment or Analysis</td>
</tr>
<tr>
<td>Li-ion</td>
<td>Lithium ion</td>
</tr>
<tr>
<td>LPH</td>
<td>Liters Per Hour</td>
</tr>
<tr>
<td>MCFC</td>
<td>Molten Carbonate Fuel Cell</td>
</tr>
<tr>
<td>NiCd</td>
<td>Nickel Cadmium</td>
</tr>
<tr>
<td>NiMH</td>
<td>Nickel Metal Hydride</td>
</tr>
<tr>
<td>PAFC</td>
<td>Phosphoric Acid Fuel Cell</td>
</tr>
<tr>
<td>PCFC</td>
<td>Photonic Ceramic Fuel Cell</td>
</tr>
<tr>
<td>PEM</td>
<td>Proton-Exchange Membrane</td>
</tr>
<tr>
<td>PEMFC</td>
<td>Proton-Exchange Membrane Fuel Cell</td>
</tr>
<tr>
<td>PGM</td>
<td>Platinum Group Metals</td>
</tr>
<tr>
<td>PMSynRM</td>
<td>Permanent Magnet assisted Synchronous Reluctance Motor</td>
</tr>
<tr>
<td>REE</td>
<td>Rare Earth Elements</td>
</tr>
<tr>
<td>RPM</td>
<td>Rotations Per Minute</td>
</tr>
<tr>
<td>SDGs</td>
<td>Sustainable Development Goals</td>
</tr>
<tr>
<td>SoC</td>
<td>State of Charge</td>
</tr>
<tr>
<td>SOFC</td>
<td>Solid Oxide Fuel Cell</td>
</tr>
<tr>
<td>SRM</td>
<td>Switched Reluctance Motor</td>
</tr>
<tr>
<td>SSRS</td>
<td>Swedish Sea Rescue Society</td>
</tr>
<tr>
<td>SynRM</td>
<td>Synchronous Reluctance Motor</td>
</tr>
<tr>
<td>UCTE</td>
<td>Union for the Co-ordination of Transmission of Electricity</td>
</tr>
<tr>
<td>UN</td>
<td>United Nations</td>
</tr>
<tr>
<td>ZAFC</td>
<td>Zinc Air Fuel Cell</td>
</tr>
</tbody>
</table>
Chapter 1

Introduction

In this introductory chapter, a background is given regarding electric crafts, boating in Sweden and the rescue sector. A literature review of the experience in marine electrification is presented. Finally, an outline for all the other chapters is provided.

1.1 Background

The background section for this chapter includes a brief introduction to electric crafts and their history, to boating in Sweden and to the rescue sector. A more detailed background regarding the different aspects of this thesis project is given in the next chapters.

1.1.1 History of electric boats

Moritz von Jacobi is to be considered the developer of the first electric boat, in May 1834. He was a Prussian inventor, that installed his model of electromotor powered by zinc batteries into a 28 feet paddle boat. In September 1838, the boat made his first trip on the Neva River in St. Petersburg, with 14 passengers on board [1].

With the development of lead-acid wet cell battery in 1859 by Gaston Planté, electric boats became more feasible and commercially viable in terms of weight. The Electrical Power Storage Company in England launched in 1882 its first boat called \textit{Electricity}, able to run up to 13 km/h, leading to the development of floating charging stations in 1888 and the deployment on six boats along the river Thames [1].

By the 1920s, with the development of commercial internal combustion engines, the electric boat concept became less and less popular. The industries that were still interested in its deployment were environmentally sensitive ones, as fishing and trolling, or zones as the Königssee Lake in Germany, which had banned the use of steam and motor boats from 1909. The other sector where electrical power remained in use is the military, which used electric engines in submarines [1].
CHAPTER 1. INTRODUCTION

Only in the latest decades electric boats became commercially available again. Duffy Electric Boat Company of California began the production of electric boats in the 70s, while in the 80s solar powered boats emerged [1]. The largest example is Turanor PlanetSolar, a 31 meters long and 15 meters wide catamaran that can accommodate 13 people, of which 6 crew members, and get 40 people on board [2].

As it can be seen from history, electric boats stopped being commercially viable with the introduction of the internal combustion engine, while now their popularity has started to rise again due to the environmental problems that the planet is facing. To keep climate change under control, it is essential to limit the use of fossil fuels. It is well known that renewable energy systems are promising solutions, but they are sporadic in nature and hence a support energy storage is needed [3]. Moreover, for every application that does not allow a connection to the grid, an energy storage is necessary anyway. With the massive increase of electrification in automotive, marine and many others, it is possible that batteries may not solve the problem of energy storage for all applications. This is why hydrogen is assumed to become a possible alternative energy carrier helping the transition towards the elimination of fossil fuels [2].

1.1.2 Boating in Sweden

Sweden is an ideal place for boating, and Swedes have always had interest in boats. One third of adult population goes boating at least once a season, and the boat-building industry is well developed. One of the reasons is that Sweden coastline counts for 2700 km, and including all the inlets and the islands, it extends to 8000 km (one fifth of the way around the world). Moreover, the country hosts the most extensive archipelago in the world, with more than 60000 islands, and over 8.5% of the country surface is covered by lakes and watercourses [4].

The number of adults per pleasure boat is around eight, making Sweden one of the countries with the most pleasure boats per capita, together with New Zealand, Finland and Norway. Table 1.1 shows some statistics regarding the type of boats owned by Swedes [1].

<table>
<thead>
<tr>
<th>Type of boats</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Canoes and kayaks</td>
<td>6.0</td>
</tr>
<tr>
<td>Dinghies and rowboats, with or without motor</td>
<td>18.0</td>
</tr>
<tr>
<td>Open boats with motors under 10 hp</td>
<td>18.4</td>
</tr>
<tr>
<td>Motor boats with motors of at least 10 hp without cabin</td>
<td>32.0</td>
</tr>
<tr>
<td>Sailboats and dinghies without sleeping accommodation</td>
<td>2.6</td>
</tr>
<tr>
<td>Sailboats with temporary sleeping accommodation</td>
<td>2.2</td>
</tr>
<tr>
<td>Motorboats with sleeping accommodation</td>
<td>13.6</td>
</tr>
<tr>
<td>Sailboats with sleeping accommodation</td>
<td>7.2</td>
</tr>
</tbody>
</table>

Table 1.1: Percentage of boats by type [1]
1.1.3 Rescue sector

Search And Rescue (SAR) Operations are defined as follows by the European Commission [5].

*In the EU context, operation of EU Member States to render assistance to any vessel or person in distress at sea regardless of the nationality or status of such a person or the circumstances in which that person is found in accordance with international law and respect for fundamental rights.*

SAR organizations are present in each Member State to rescue and assist people in distress, not only to comply to the European regulation, but also due to moral obligation [6].

1.1.3.1 Rescue sector in Sweden

Boating is considered a safe leisure activity in Sweden: over the past 20 years the number of deaths connected to boating has halved and in 2011 only 41 people have drowned in pleasure boat accidents. This is mainly due to the high usage of life jackets (80% of boat owners have life jackets always on board) and to the fast intervention of the sea rescue services [4].

In 2017 a total of 1208 sea rescue missions was carried out: 68% of them concerned recreational boats, 12% trade and passengers ships, under 10% cases of people in distress without a vessel (such as swimmers, skaters and fishermen). The most common reasons were motor failure, running aground and harsh weather conditions [7]. Figure 1.1 shows the numbers of rescues per month, where it can be seen that most of the rescues occur in the summer season, as expected [8].

![Figure 1.1: Number of rescues per month and year](image-url)
1.1.3.2  *Sjöräddningssällskapet*

*Sjöräddningssällskapet* is an association of around 2200 volunteer seamen founded in 1907. The association owns 71 rescue stations and more than 230 rescue boats along Swedish coasts and largest lakes. The result of having a volunteer based organisation is that the rescue boat is on its way within 15 minutes from when the alarm goes off [9]. *Sjöräddningssällskapet* is, by far, the most relevant SAR organization in Sweden, performing over 80% of the total rescues [8].

1.2  Experience in maritime electrification

In this section, a literature review regarding experience in maritime electrification and use of fuel cells has been carried out. The analysis has been divided into two different use cases, tourist boats and leisure boats.

1.2.1  Tourist boats

Tourist boats have the characteristic of being bigger and slower, and also more predictable. Usually, a route is assigned to a tourist boat, which will be mostly followed. Thanks to this predictability, the boat power curve can be clearly defined, often consisting in cycles. When dealing with cyclic power curves, it is convenient to use an hybrid storage system with fuel cells and batteries. Fuel cells are optimised to work at constant power, allowing the battery to recharge when the demand of the boat is higher that the power rate of the fuel cell, and to discharge when the demand of the boat is lower than the power rate of the fuel cell.

1.2.1.1  ZEMShip project

*FCS Alsterwasser* (Figure 1.2) is the first commercially used fuel cell driven passenger ship, equipped with a hydrogen fuelled PEMFC (Proton-Exchange Membrane Fuel Cell) system [10]. The passenger vessel has been developed in the ZEMShip (Zero Emission Ship) project and put into service on August 29th, 2008; it carries 100 passengers on the inner city lake of Hamburg without generating any local emissions [11].

![Figure 1.2: FCS Alsterwasser in operation](image-url)
1.2. EXPERIENCE IN MARITIME ELECTRIFICATION

The fuel cell propulsion system includes the items listed below, as shown in Figure 1.3.

- Hydrogen fuel tanks with a pressure of 350 bar, for a storage weight of 50 kg. The fuel allows the boat to run for two to three days [11].
- PEM fuel cell, with a peak power of 48 kW [11], model PM Basic A 50 maritime, total weight of fuel cell stack is of ca. 1000 kg (two single fuel cell systems of ca. 500 kg each) [12].
- Buffer and peak load shaving lead-gel battery, for an energy storage of ca. 200 kWh [12].
- Electric motor (AC motor) of 100 kW [12].

Using such a system, provided by Proton Motor, local emissions are zero and the only byproduct is pure water. The system is controlled by an energy management system, which controls the power flow from the fuel cell and from/to the battery. When the ship needs more power than the fuel cell can deliver, the surplus is taken from the battery (discharge state); when the ship needs less power, the surplus is given to the battery (recharge state) [11].

The ZEMShip project is a good reference example for a fuel cell powered ship, and it proves that the technology has already been used and tested. Moreover, a fire caused by the overheating of the batteries occurred, damaging the vessel but not the fuel cell system and hydrogen storage, proving the hydrogen safety concept [10]. It is though not a suitable example in terms of weight and length, since it is a heavier and bigger boat (25 m long and 72 tons heavy when fully loaded) running at lower speeds (maximum cruising speed of 15 km/h) [12].
1.2.1.2 Nemo H₂

Fuel Cell Boat BV is a consortium of five Dutch companies that share the interest in hydrogen and fuel cell technology. The main objective of the consortium has been to develop a fuel cell boat for canal cruises in Amsterdam [13].

Similarly to the ZEMShip project, Nemo H₂ is equipped with a hybrid power system with a 60-70 kW PEMFC and 30-50 kWh batteries. The 24 kg hydrogen storage is stored at 350 bar pressure [14]. It was baptized in Amsterdam in December 9th, 2009, with a capacity of 87 passengers, and its commercial operation stared in 2011. Fuel Cell Boat BV claimed that the hydrogen would have been produced by a land-side electrolysis system, using electricity from a North Sea wind farm [15]. It has been though reported that the vessel has not entered active service as of now due to the absence of a permanent hydrogen fuelling station [10].

As another example of slow speed passenger boat (driving at a maximum cruise speed of 16 km/h [16]), Nemo H₂ has a great potential in terms of renewable energy utilization. The important lesson learnt from Nemo H₂ is to study the hydrogen network of the area and plan in advance a permanent fuelling station or a different method of hydrogen provision.

1.2.1.3 Gold Green HYGEN

Gold Green HYGEN is the first fuel cell powered boat in Korea. It is powered by 2 fuel cells of 25 kW each and a Li-ion battery pack of 47 kWh [17]. The demonstration of the boat proved its reliability at around 7 knots of speed with a power output of 85 kW [18].

In Figure 1.4 the schematic of the fuel-cell-battery hybrid system of the boat is shown. A power greater than 90 kW can be delivered through the system to all the electricity-requiring components. The maximum hydrogen storage capacity is of 25 kg at 350 bar. The energy storage system is sufficient to power the boat for ca. 1 hour at the maximum power-consumption rate. The water jet propulsion system consumes a power of ca. 86 kW, propelling the boat to a speed of 7.5 knots. An additional 3 kW power is required for the auxiliary equipment [18].

![Figure 1.4: Schematic of the fuel-cell-battery hybrid system of Gold Green HYGEN](image)
1.2. EXPERIENCE IN MARITIME ELECTRIFICATION

1.2.2 Leisure boats

In leisure boats, it is possible to imagine a boat that runs entirely on fuel cell or on batteries, since the autonomy can be lower and the requirements less strict. The option of having both fuel cells and battery systems is developed, so far, only in larger boats. These allow the energy storage system to occupy more space and to weight more. This study aims at proving that such a system can also be installed in high speed small boats.

1.2.2.1 Marti

*Marti* is a Turkish fuel cell powered boat, developed by the Istanbul Technical University. The boat is powered by a 8 kW PEMFC with 20 kg of hydrogen stored at 200 bar. The storage allows the boat to run for 40 hours, with a maximum speed of 13 km/h [19].

The dimensions of the boat are similar to the ones of the boat taken into account in this project, since *Marti* is 8.13 m long and 3.22 m wide. It though has a catamaran hull, which makes a difference in the power profile [20].

The hydrogen for the vessel will come from an electrolyser-based fuelling station, able to produce 65 kg of hydrogen per day, supplied by Hydrogenics, a Canadian-based company. The station will be situated in the Golden Horn estuary and will be used also for refuelling forklifts, buses and other vehicles [19].

1.2.2.2 Future Project Hydrogen

Future Project Hydrogen was initiated by the collaboration of the Fronius International, Bitter GmbH and Frauscher, in the state of Upper Austria. The 4 kW fuel cell provides power thanks to a 0.7 kg hydrogen replaceable cartridge. No time has to be spent charging the batteries, and the boat has twice the range of conventional battery-powered boats (80 km on a full hydrogen tank) [21].

Fronius International provided the fuel cell technology, while Frauscher provided the test bed. The first boat is a Riviera 600, launched in April 2009. Bitter GmbH developed the refuelling stations, with Fronius system of using an array of PV panels to electrolyse water [22].

From Figure 1.5 it can be seen that the boat is smaller the other boats analysed so far in this Chapter. The Frauscher Riviera 600 model is a 6 m long and 2.2 m wide boat, being then much closer to the design studied in this thesis project [23]. The boat is not a speed boat, hence it is designed to go at lower speeds.
1.2.2.3 Hydroxy 3000

*Hydroxy 3000* is a catamaran powered by a 3 kW PEMFC, fuelled by hydrogen at 200 bar, in parallel with buffer batteries, which provide energy in case of a failure of the fuel cell system. In Figure 1.6, it can be seen how the different components are placed in the 1500 kg ship [24].

The catamaran is made for up to seven people, with a cruise speed of 11-12 km/h. When propelled at a speed of 8 km/h, the power need is of 1 kW and the autonomy is of around 12 h with full hydrogen tanks, not considering the batteries contribution. Five square meters of PV panels are enough to provide the necessary hydrogen (through an electrolysis process) to propel the ship during one typical boating season [24].

1.2.2.4 eJET 450

The eJET 450 is a high performance electric jet tender. It is a boat produced by Avon Marine, a UK tender and inflatable boat maker [25].

It is a 4.5 m long inflatable tender (Figure 1.7), that has a maximum speed of 30 knots. It is equipped with a Torqeedo DB 80 / 55 kW electric motor, that paired with a 32 kWh BMW i3 battery allows an autonomy of 1.5 hours at 30 knots and about 8 hours at 5 knots [26].
1.2 EXPERIENCE IN MARITIME ELECTRIFICATION

Figure 1.7: Avon Marine eJET 450 [26]

This boat is not ideal for the SAR application, since it is an inflatable boat and it is small. Torqeedo motor could be installed in a bigger boat, but it would guarantee even a smaller autonomy (about 35 minutes at full throttle) with the same BMW i3 battery [27].

1.2.3 Conclusion

Throughout the literature review, boats that differed in size, speed, autonomy and use have been analysed. These examples were not designed to be fast: it appears that so far there has been no development of a small fast boat powered by a combined system of fuel cells and battery.

Choi et al. state that the speed achieved by Gold Green HYGEN (7.5 knots) is only adequate for tourist boats, since the maximum speed of water jets is up to 50 knots, depending on purpose. For larger boats, the application of fuel cells is limited to low-speed water crafts [13]. This can also be seen in the boats FCS Alsterwasser and Nemo $H_2$, which achieve a maximum speed of 8 knots and 8.6 knots respectively [12] [16].

When looking at smaller boats, it can be seen that again the speed is limited to a maximum of around 7-8 knots. In these boats, the power need is much lower, ranging from 1 kW to 8 kW (Section 1.2.2).

The research question then becomes whether it would be feasible to imagine a boat that is powered by such an hybrid electric system, especially in terms of weight and CO$_2$ emissions. The main aim of the project is to design a boat that is sustainable, taking into account the requirements for a SAR boat set by Sjöräddningssällskapet as stated in Section 2.3.

The literature review proves that the technology exists and it is ready: it is a matter of rating the system and finding out the possible drawbacks of such a combination of technologies.
1.3 Outline

This thesis is divided into seven different chapters.

After this introductory chapter with a general background, the focus moves to the specific case study. The scope of the project, its specifications and its requirements are described in Chapter 2. The boat taken into consideration is analysed, together with the proposed hybrid electric drive train. Moreover, other possible solutions that contemplate the use of a pure battery driven boat or an internal combustion engine (ICE) boat are compared throughout the thesis project.

In Chapter 3, the methodology for the calculation of the power required by such drive train is explained, and the results are shown. The diesel consumption of a boat powered by an ICE is calculated, using the same methodology.

In Chapter 4, speed, power and energy consumption profiles are shown for different missions: these should predict the different operating conditions in which the boat will perform. From these, the rating of the battery and fuel cell is possible. The hybrid electric drive train is compared in terms of weight with other available storage options, including pure battery and ICE systems.

In Chapter 5, few possible and commercially available electric motors are shown as reference. A discussion on the differences among those is carried out, with reflections also on the global impact of the choice. Similarly a manufacturer for water jets is chosen. Few different water jets are proposed, that could be coupled with the presented electric engines. Some conclusions on the entire propulsive unit are drawn.

The sustainability aspect is analysed in Chapter 6, where a life cycle assessment is carried out for the different solutions (hybrid electric, pure electric or ICE systems).

Chapter 7 concludes the project, with a summary of the main choices made during the project. The main advantages and disadvantages of using the hybrid electric drive train are shown. A comment on the control system of such drive train is made, and finally hints for further studies are provided.
Chapter 2

Case study

In this chapter the case study is introduced. The design of the rescue boat is discussed and its use at Smedjebacken station is defined. Furthermore, a reflection on the sustainability scope of this project is carried out.

2.1 Rescue boat

The subject of study of this project is a rescue boat, equipped with an hybrid electric drive train.

The boat in question is rather small (5.5 m long, 2.5 m wide). From a design point of view, the boat has just been sketched in a drawing. The main features have been defined, but some details such as the shape of the hull, the material, and the dry weight are not known at this stage of the project.

This thesis should not focus on the design of the shape of the boat and of the hull, but it should instead focus on the definition and rating of a proper and suitable drive train.

In Figure 2.1 a sketch of the boat and its hull has been drawn. Note that this is only added as a reference, and no study on the shape of the hull nor the configuration of the boat has been carried out. The sketch has been done according to similar boat shapes and to the requirements given by Smedjebacken station, as listed in Section 2.3 [28]. The required items in a rescue boat are a light and a stretcher (spinal board), added in the figure as well. The light is obviously used for searching purposes and for navigating at night, while the stretcher is used to carry injured people. To facilitate the use of the stretcher, the bottom of the boat towards the stern is flat. This feature can also be useful when fitting special equipment, e.g. a pump to suck water out of a sinking boat [28].
The main components of the drive train are listed below, as can be seen in Figure 2.2. In Chapter 3, the system configuration and losses are explained with more detail.

- Water jet propulsion system
- Reduction gear
- Electric motor
- Inverters
- Battery pack
- Fuel cell stack
- Hydrogen storage tanks

A comparative analysis is also carried out considering as competitive technologies an ICE drive train layout and a battery-only drive train solution.
2.1. RESCUE BOAT

Figure 2.2: Hybrid electric ship drive train

The ICE system is composed by the items listed below, as can be seen in Figure 2.3. To facilitate the comparison, in Chapter 3, also the ICE configuration is analysed in more detail.

- Water jet propulsion system
- Reduction gear
- ICE
- Diesel fuel tank

Figure 2.3: ICE ship drive train
The pure battery system is composed by the items listed below, as can be seen in Figure 2.4.

- Water jet propulsion system
- Reduction gear
- Electric machine
- Inverter
- Battery pack

![Figure 2.4: Pure battery system ship drive train](image)

### 2.2 Smedjebacken station

The specific requirements are based on the potential usage of the boat in the station of Smedjebacken, on lake Barken, a long and narrow lake connected to lake Mälaren through other lakes and locks. This station serves also the adjacent lakes Runn and Siljjan, hence towing the boat with a trailer is a requirement. This lake has been chosen since the currently operating rescue boat is old (year 1988) and would need maintenance [28]. Figure 2.5 shows lake Barken in its entirety: it is ca. 24 km long, from the station, located in the northern spot, till the end of the lake [29].

![Figure 2.5: Smedjebacken municipality](image)
From the station to the end of the lake, it currently takes the rescuers 40 minutes at a full speed of 30 knots. The requirement for the new boat would be to undergo the same distance within the same time \[28\]. Some necessary assumptions on the speed profile are made in Section \[4.2.1\].

2.2.1 Types of rescue mission

There are two different kinds of rescue mission. The first kind is connected to the fire department. If a situation is life threatening, the person in danger calls the fire department that has the responsibility to hurry and perform a rescue. This is where \textit{Sjöräddningssällskapet} comes in, since its rescuers can be quicker due to the fact that they usually already have a boat on the lake. This kind of rescue has occurred on a yearly basis of 2 rescues per year (4 in total since the opening of the station, two years ago) \[28\].

The other kind of rescue is when the situation is characterized by a non life threatening situation, when a boat and its passengers have some problems and cannot get back on shore. This situation occurs more often (around 10 times a year) and the person involved contacts directly \textit{Sjöräddningssällskapet}. In this case, not as critical as the one mentioned above (for example if a boat is without fuel in the middle of the lake), the requirement of \textit{Sjöräddningssällskapet} is just to bring it to a safe place close to the shore. Given the narrow shape of the lake, the rescue boat will not have to tow the boat for a long distance. The boats that are present in the lake are 27-30 feet long. The biggest is ca. 42 feet long: the boat hence need not to be designed to carry heavy boats. The boats are mostly motor boats and there is hardly any sailing boat. There are though two heavier steam boats (around 55 tons), that the current boat (equipped with a 60 hp engine, ca. 50 kW) can park and manage around the lake \[28\].

2.2.2 Poker run

Every year for two to three days a race is hosted in the lake. During those days, where cigarette boats come from all over Sweden to chase poker cards and win the race, \textit{Sjöräddningssällskapet} needs to be present not for the participants but for the spectators of the race. Every year, five to six boats belonging to the spectators need to be assisted or rescued in some way. In occasion of this race, another boat has been usually borrowed from the station of Runn. This boat does not seem to be suitable for the shallow water and the narrow parts of Lake Barken, since it is not equipped with a water jet but with a standard outboard propeller.
2.3 List of requirements

Below there is a summary of the requirements, given by Smedjebacken Station 28.

- The maximum speed of the boat is ca. 30 knots.
- The storage system satisfies the power requirements described in Section 4.2.1.
- To avoid the propeller, which can be dangerous for people in the water, the use of a water jet is requested. Moreover, having no propeller means having less risk of breaking the engine when the water is full of debris.
- The boat is able to fit two people from Sjöräddningssällskapet and a doctor.
- The stern of the boat is flat, to fit a stretcher and special equipment.
- The boat is small and agile, able to easily run through shallow waters.
- The maximum power needs to be enough to tow a boat of 55 tons.
- The boat needs to be carried out with a trailer, in case operation in the adjacent lakes is needed.

2.4 Sustainability

The reason why Sjöräddningssällskapet started this project is introducing and spreading sustainability in the context of water transportation and in the rescue sector. Electrification is happening fast in the sector of mobility, but it is nowadays mainly focusing on cars and buses rather than other ways transportation, such as boats.

The main focus of electrification in mobility is on road transportation, but some change has also been seen in the water transportation. Different cases of hybrid cruise ships can be seen across Europe, including many cases regarding electrification of water public transportation (for example in Venice and Amsterdam). There are also some examples of electric outboard engines powered by batteries for small boats, but these usually have a very short autonomy, especially at higher speeds.

This thesis aims at designing a suitable energy storage that can provide power to a water jet propulsion system for a planing hull, that can reach speeds of 30 knots and still have a reasonable autonomy. Autonomy is of key importance since the boat will be used for rescuing purposes, where people’s lives are at stake.

One of the scopes of this thesis project is to carry out a comparative analysis of the $CO_2$ emissions between the selected solution, the ICE option and the full battery option (Chapter 6).
2.4.1 Contribution to green house gases emissions

The contribution to green house gases (GHG) emissions is measured in \( \text{CO}_2 \text{eq} \), carbon dioxide equivalent, a metric measure that allows to compare the effect of different GHG on the basis of the global warming potential. The emissions of all GHG are converted to the equivalent amount of \( \text{CO}_2 \), in this way there is a real comparison of the global warming potential \[30\].

Ships are responsible for roughly 3% of global \( \text{CO}_2 \) and GHG emissions in \( \text{CO}_2 \text{eq} \), emitting approximately 1 billion tonnes of \( \text{CO}_2 \) and GHGs per year, on average from 2007 to 2012. Ship emissions are expected to increase in both absolute terms and in shipping share of global \( \text{CO}_2 \) and GHG emissions. Smith et al. (2015) \[31\] estimate that ship \( \text{CO}_2 \) emissions will increase 50%–250% from 2012 to 2050, and the CE Delft (2017) \[32\] report projects that emissions will increase 20%–120% over the same period, assuming a scenario in which the global temperature rises less than 2°C \[33\].

The International Maritime Organization (IMO), a specialized agency of the United Nations (UN), is the global standard-setting authority for safety, security and environmental performance of international shipping, encouraging innovation and efficiency. As part of UN, IMO is working towards the Sustainable Development Goals (SDGs), since all aspects of the Organization’s work can be linked to all SDGs \[34\]. In April 2018, IMO adopted a strategy on reduction of GHG emissions from ships, aiming at reducing the total annual GHG emissions at least 50% by 2050 compared to 2008 \[35\].
Chapter 3

Boat Drive Train Modelling

The aim of this chapter is to study the model of the proposed drive train and its losses. After understanding the theory of the different components of the drive train, the resistance of the hull will be studied to calculate the power that the storage system needs to supply at different boat speeds.

It is of key importance to carry out an hydrodynamic analysis: the specifications of the boat and the hull design are very important factors for the determination of the required power. The mechanical power that needs to be delivered to the water jet can be calculated through this analysis: it is an essential information to choose a proper engine. Moreover, the electrical machine delivers power with an efficiency: to design a proper storage system, also the losses that occur in the machine need to be considered.

Throughout the chapter, a background is given on theory of ship drive train and its losses, hull resistance and water jet propulsion systems. The methodology for the calculation is explained, followed by the analysis of the results. A comparison between the results obtained with the theory is carried out, followed by a conclusion on the required power.

3.1 Background

In this background section, the hydrodynamic theory of hull resistance is introduced, followed by the description of the studied systems, their components and their efficiencies.

3.1.1 Hull resistance

A background on hull resistance is given, even though in this thesis work the effective power will be calculated using online test results, without the use of hull model experimentation since it would take too long and it would be out of the scope of the project.
The hull resistance of a ship is a force acting on the hull against the motion of the boat. The total hull resistance of a ship is function of many factors (ship speed, hull shape, water temperature, calm or wavy water...). The resistance curve is not linear, often is roughly proportional to the cube of the speed [36].

Two of the most important coefficients are the Froude number $F_n$ and the speed coefficient $C_v$, defined in Equation (3.1) and (3.2), where $V$ is the velocity of the ship, $g$ is the acceleration of gravity, $L$ is the length of the ship, $B_t$ is the transom beam (width of the ship at the stern) [36] [37].

$$F_n = \frac{V}{\sqrt{g}L}$$

(3.1)

$$C_v = \frac{V}{\sqrt{g}B_t}$$

(3.2)

The hydrodynamic evaluation can be explained as follows [37].

- At low speed, planing boats are displacement hulls: the volume of water displaced by the hull (which depends on the weight of the boat) produces a buoyancy force, which is the only component of the lift force.
- As speed increases, dynamic effects start producing positive contribution to lift, but still not enough to let the bow emerge from water. In the range of speed coefficient from 0.5 to 1.5, the boat is a high speed displacement hull.
- At high speeds, for speed coefficients above 1.5, the dynamic effects make the bow rise and the boat is a planing hull.

### 3.1.1.1 Components of hull resistance

Three different components of hull resistance can be identified, as shown in Figure 3.1: viscous resistance, wave making resistance and air resistance. Viscous resistance and air making resistance increases almost linearly with speed, while wave making resistance is the term responsible of the shape of the total resistance curve, with a hump and a hollow [36].

![Figure 3.1: Components of total hull resistance, adapted from Branco [38]](image)
The viscosity term can be divided into friction resistance and viscous pressure resistance, the first opposing the motion through a net force parallel to the body, the second acting tangential to the body. Viscous resistance varies according to the type of flow of water around the ship; the flow can be laminar or turbulent, which depends on the Reynolds number, as shown in Figure 3.2. One characteristic of turbulent flow is the formation of a "boundary layer", which is a layer of water along the hull moving in the direction of the ship.

![Figure 3.2: Transition from laminar to turbulent flow for a plate](image)

The other major component of the total hull resistance is wave making resistance. Creation of waves requires energy: an increase in power can be seen due to this energy loss and it can be represented as a form of resistance force. A moving ship produces both transverse and divergent waves. The first ones travel approximately at the same speed of the ship. The speed where the wavelength and the ship length are equal is called hull speed. This is the last efficient speed before a steep increase in resistance starts (hump, Figure 3.1).

![Figure 3.3: Wave patterns at different speeds](image)

Figure 3.3 shows the profile of different wave patterns at different speeds, which means at different wavelengths. These different patterns also explain the shape of the curve of total resistance.
The last of the major terms of resistance is air resistance, which typically corresponds to 5-10% of the total hull resistance [36].

### 3.1.2 Hybrid electric ship drive train

In Figure 3.4 the hybrid electric ship drive train is shown. The terms used have the following meaning [36].

- \( P_B \) - **Battery power**, power supplied by the battery to the system.
- \( P_{FC} \) - **Fuel cell power**, power supplied by the fuel cell to the system.
- \( P_S \) - **Storage power**, power delivered by the energy storage system (sum of the battery power with the fuel cell power) to the electric motor: \( P_S = P_B + P_{FC} \).
- \( P_{EM} \) - **Electro-mechanical power**, power output of the engine. The power of a rotating engine is given by the torque multiplied by the rotational speed. In this system, it is also equal to the storage power multiplied by the electric motor efficiency.
- \( P_D \) - **Delivered mechanical power**, power delivered to the water jet. In between the electric engine and the water jet, there are losses in the reduction gear and in the bearings.
- \( P_E \) - **Effective power**, power required to move the ship at a given speed, and can be calculated multiplying the resistance of the hull by the speed.

![Figure 3.4: Hybrid electric ship drive train](image)
3.1. BACKGROUND

3.1.2.1 Propulsive efficiency

The efficiencies of the stages from the storage power to the effective power are listed in Equations (3.3), (3.4) and (3.5), where $\eta_M$ is the efficiency of the electric motor \[40\], $\eta_G$ is the efficiency of the reduction gear \[36\] and $\eta_{WJ}$ is the efficiency of the water jet \[41\].

\[\eta_M = \frac{P_{EM}}{P_S} \approx 0.95 - 0.97\]  \hspace{1cm} (3.3)

\[\eta_G = \frac{P_D}{P_{EM}} \approx 0.95 - 0.99\]  \hspace{1cm} (3.4)

\[\eta_{WJ} = \frac{P_E}{P_D} \approx 0.4 - 0.7\]  \hspace{1cm} (3.5)

The propulsive efficiency $\eta$ is calculated simply by multiplying the different efficiencies, as can be seen in Equation (3.6) \[36\]. The propulsive efficiency, in this definition, does not include the storage efficiency.

\[\eta = \eta_M \cdot \eta_G \cdot \eta_{WJ} \approx 0.35 - 0.65\]  \hspace{1cm} (3.6)

From the estimated numbers of efficiencies \[36\] \[40\] \[41\], it can be seen how the water jet influences the most the overall efficiency. There are different types of engines, mainly categorized as follows: outboards, inboards, stern drives and water jets. The outboard is the most used since it has a higher efficiency, while the water jet solution has the lowest efficiency: it is though used for its advantage of having no propeller, as this is one of the requirements described in Section 2.3. This is the basis of the choice of the water jet as an engine, even though this brings efficiency issues.

As discussed in the next sections, the power that the online tests allow to calculate is the delivered power. Hence, for the scope of this thesis, the propulsive efficiency of the hybrid electric drive train $\eta_{DT,\text{electric}}$ is defined as in the product of the efficiency of the electric motor and the efficiency of the reduction gear, excluding the one of the water jet.

\[\eta_{DT,\text{electric}} = \eta_M \eta_G\]  \hspace{1cm} (3.7)

3.1.2.2 Effective power

The amount of power that is needed to propel the ship through the water at a certain speed needs to be calculated for the single ship, since it depends on the resistance of the hull \[56\].

Effective power $P_E$ is often derived from experimentation model data. A hull model is towed through water at different speeds, so that the force of resistance can be measured. Model resistance data is then scaled up to the real dimensions, and effective power can be derived from the resistance \[54\].
3.1.2.3 Performance curves

Accordingly, an engine will have different performance curves. At any rate, there are five standard performance curves, listed below [42].

- Maximum output power without reduction gear curve - Electro-mechanical power curve
- Maximum output power with reduction gear curve - Delivered mechanical power curve
- Propeller power curve
- Torque curve
- Specific fuel consumption curve

These different curves can be seen in Figure 3.5 for a diesel engine of 420 hp. The reduction gear is needed both for backing up the boat and allowing a good match between the torque characteristic to the optimum propeller, but it reduces the efficiency since it takes away around 3% of power [42].

![Graph showing performance curves](image-url)

Figure 3.5: Yanmar 6CX(M)-ETE performance curve, adapted from [Gerr] [12]
3.1. BACKGROUND

If the electro-mechanical power curve shows the maximum power the engine can deliver for each RPM, the propeller power curve shows the demand of the propeller for each RPM. The shape between the two curves is quite different, as can be seen in Figure 3.5 and Figure 3.6. The goal of the designer is to have a propeller curve that meet the engine curve at max RPM. This will be a compromise, since the two curves are quite different, but it is the only option and it has been proved to be the optimal solution [42]. Figure 3.6 also shows the ideal propeller power curve compared with propellers that do not have the right pitch or diameter. Choosing the right propeller allows the propeller power curve and the engine power curve to meet at max RPM.

![Figure 3.6: Propeller power curve variations, adapted from Gerr [42]]

Since the propeller curves for the tested boats are not available, Equation (3.8) can be used to plot the propeller power curve. Equation (3.8) comes from the estimation shown in Table 3.1 where \( k \) is a parameter that connects the engine power and RPM [42].

\[
P = k \times RPM^{2.5}
\]  

(3.8)

<table>
<thead>
<tr>
<th>RPM</th>
<th>Engine Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>90% of max</td>
<td>about 68% of max rated engine power</td>
</tr>
<tr>
<td>80% of max</td>
<td>about 48% of max rated engine power</td>
</tr>
<tr>
<td>70% of max</td>
<td>about 30% of max rated engine power</td>
</tr>
<tr>
<td>60% of max</td>
<td>about 22% of max rated engine power</td>
</tr>
<tr>
<td>50% of max</td>
<td>about 15% of max rated engine power</td>
</tr>
<tr>
<td>40% of max</td>
<td>about 11% of max rated engine power</td>
</tr>
</tbody>
</table>
3.1.2.4 Estimation of round trip efficiency

Later in this chapter, the power needed by the water jet engine at different speeds is estimated. Hence, it is not needed to consider the efficiency of the water jet when calculating the storage power, but only the electrical engine efficiency and the gear efficiency.

In this short section, the round trip efficiency for an electric machine coupled with a gear is assumed after some literature research. These numbers will be used in the calculations of the power and energy that the storage system needs to supply.

Scarce literature has been found regarding water jet propulsion systems in particular, but a lot of material can be found when looking at electric vehicles. The electrical engine itself is very efficient, as seen in Section 3.1.2.1, but when looking at a round trip efficiency these values change slightly. The inverter needs to be considered as well, accounting for an efficiency of 95%. According to Markowitz, the drive train round trip efficiency (including the motor, the reduction gear and the inverter) is ca. 85%. Markowitz analysis calculates the entire round trip efficiency of the vehicle (hence including also 90% efficiency of the battery and 95% efficiency of the charger), which adds up to a 73% efficiency, which is very close to the round trip efficiency reported by Tesla, of 75% [43].

For the analysis proposed in this thesis project, a round trip efficiency (of the combination motor, inverter and reduction gear) of 85% is then considered. This value is used later on to estimate the energy needed from the energy storage system.

3.1.3 ICE drive train

When looking at the existing water jet boat technology, the majority of them has a diesel engine. As described in Section 2.1, the ICE ship drive train is composed by a fuel tank (in most cases, a diesel tank), an internal combustion engine, a reduction gear and a water jet.

Figure 3.7 is a graphical representation of the ICE drive train, and it shows also the efficiencies of the components and the power transfer that occurs. The terms used in the figure have the following meaning.

- \( \dot{m}_{\text{diesel}} \) - Power connected to fuel mass flow, product of the fuel mass flow and the energy density of diesel fuel. The energy density is defined as energy content (in MJ or Wh) per liter of fuel, as discussed in Section 4.1.1.
- \( P_M \) - Mechanical power, power output of the engine. The power of a rotating engine is given by the torque multiplied by the rotational speed. In this system, it is also equal to the fuel mass flow multiplied by the energy density of diesel divided by the efficiency of the ICE.
- \( P_D \) - Delivered mechanical power, power delivered to the water jet. In between the ICE and the water jet, there are losses in the reduction gear and in the bearings.
- \( P_E \) - Effective power, power required to move the ship at a given speed, and can be calculated multiplying the resistance of the hull by the speed.
3.2. METHODOLOGY

Comparing Figure 3.7 with Figure 3.4, it can be seen that, given the same boat, the effective power $P_E$ is in common for both configurations, and considering the use of the same water jet, also the delivered mechanical power $P_D$ is identical. The reduction gear can vary depending on the engine, hence the mechanical power $P_M$ delivered by the ICE and the electro-mechanical power $P_{EM}$ delivered by the electric engine can vary slightly. The biggest difference is though the efficiency of the engine, as discussed in next section.

3.1.3.1 Propulsive efficiency

In the next sections, the efficiency of the drive train has been calculated using empirical data from online tests. In the online tests, the consumption in liters of diesel per hour is given per ship speed. With this data, the propulsive efficiency of the ICE drive train $\eta_{DT_{ICE}}$ can be calculated, as in Equation (3.9).

$$\eta_{DT_{ICE}} = \eta_G\eta_{ICE} = \frac{P_D}{m_{diesel}c_{diesel}} \quad (3.9)$$

The ICE drive train efficiency is expected to be in the order of 30%, which results to be much lower when compared with the expected efficiency of the hybrid electric configuration.

3.2 Methodology

After studying the theory of hydrodynamics of the hull, an analysis of different existing water jet boats has been carried out. It is important to choose boats that use water jets as engines in order to have relevant results. Using the data available online, it is possible to estimate how much power is needed to power the boat just by comparison.

3.2.1 Online data gathering

The first step has been finding a good source of water jet tests online. The best source found is BoatTest [44], where tests on different boats are stored. Using data from the same source makes the analysis easier since the same kind of data is available for all tests. Hence it has been decided to proceed only with BoatTest, trying to make the comparison as accurate as possible. The selected boat size that has been searched for is 16-20 ft, since the rescue boat design size is of 18 ft (5.5 m).
The following eight boats have been taken into consideration, since they have been tested recently and they are of similar size of the boat considered in this project.

- Yamaha AR195 (2019-) 20 ft
- Yamaha 190 FSH Sport (2019-) 20 ft
- Chaparral 203 Vortex VRX (2014-) 20 ft
- Yamaha SX195 (2019-) 19 ft
- Yamaha SX190 (2019-) 19 ft
- Yamaha AR190 (2019-) 19 ft
- Yamaha 190 FSH (2019-) 19 ft
- Scarab 195 Open ID (2017-) 19 ft

On the website, the test on each boat is available and it is possible to get access to the following relevant data [44].

- Length overall: length of the ship hull from bow to stern.
- Beam: width of the hull from port to starboard.
- Dry weight: weight without any fluid in the tanks [45].
- Tested weight: test including liquid in the tanks and people on board.
- Dead-rise transom angle: angle between the boat hull and a horizontal plane, on both sides from the center of the hull. The dead-rise is not usually constant on the length of the boat, the transom angle is measured at the stern of the boat [46].
- Test results: a table that relates the following quantities.
  - Rotational speed of the engine in rotations per minutes.
  - Speed of the boat in miles per hour, knots and kilometers per hour.
  - Fuel consumption in liters per hour.

### 3.2.2 Graphs and visual representation of data

From the gathered data, the relation between RPM and boat speed is shown. For the purpose of this paper, the relation between power and speed is needed. As explained in Section 3.1.2, there are different definitions of power. The methodology used for the delivered power calculation and the consumption profile is the following.

1. The relations RPM-speed and RPM-consumption are taken from the online data.
2. The maximum RPM and maximum power of the engine is found online.
3. The parameter $k$ is calculated, by setting in Equation (3.10) the maximum rated power and the maximum rated RPM of each engine.
   \[
   k = \frac{P_{\text{max}}}{(RPM_{\text{max}})^{2.5}}
   \]  

4. The propeller power curve is plotted according to Equation (3.8), showing the relation between RPM and power.
5. The relation between boat speed and power can be plotted in a graph, the power speed curve. The graph represents the relation for one boat, and it requires interpolation between the few calculated points. The interpolation is shown on the graph.
6. The relation between speed and consumption is plotted in a graph using the points taken from the data set and interpolating to obtain values for the entire speed range.
This procedure is repeated for each selected boat, obtaining then eight different power speed curves and consumption speed curves.

### 3.2.3 Mean power speed curve and mean consumption speed curve

A mean power curve is calculated averaging all the boat power curves, and a graph showing all the single results and the mean curve is plotted. A mean consumption speed curve is similarly calculated by averaging the eight different consumption curves, and plotted in a comparative graph.

### 3.2.4 Comparative analysis with theoretical results

The mean power curve obtained through the online tests can be compared with the theoretical shape of the resistance, knowing that the power requested by the ship is simply the non-linear resistance multiplied by the speed. Hence, the shape of the resistance curve and the power curve should be similar.

Another calculation that can be carried out is the hull speed, that can be calculated as shown in Equation (3.11). This is the last efficient speed before a steep increase in resistance starts, as explained in Section 3.1.1. The speed of the hump can be calculated as well, as shown in Equation (3.12).

\[
v_{\text{hull}} = \sqrt{L_{\text{hull}}} \tag{3.11}
\]

\[
v_{\text{hump}} = \sqrt{\frac{1.5L_{\text{ship}}}{g}2\pi} \tag{3.12}
\]

### 3.3 Results

In this section, the results obtained by comparing the different water jet tests found online are shown. Moreover, some calculations have been made according to the theory, to prove that the results are coherent with the theoretical calculations.
3.3.1 Online data gathering - Yamaha AR195

All the data and the results for Yamaha AR195 are listed in this section as example. Similar results are obtained for all considered boats. The specifications have been checked in terms of weight and size of the boat, as can be seen in Table 3.2.

Table 3.2: Specifications of Yamaha AR195 [47]

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length overall</td>
<td>5.92 m</td>
</tr>
<tr>
<td>Beam</td>
<td>2.49 m</td>
</tr>
<tr>
<td>Dry weight</td>
<td>1134 kg</td>
</tr>
<tr>
<td>Tested weight</td>
<td>1406 kg</td>
</tr>
<tr>
<td>Dead-rise transom</td>
<td>18°</td>
</tr>
</tbody>
</table>

3.3.2 Graphs and visual representation of data - Yamaha AR195

Following the methodology for the calculation of the delivered power and the consumption, the results are shown below.

1. Data from Boat Test [44]. In Table 3.3, the test result section shows the relation between RPM and speed (in knots) and between RPM and consumption (in LPH, liters per hour).

Table 3.3: Test results of Yamaha AR195 [47]

<table>
<thead>
<tr>
<th>RPM</th>
<th>knots</th>
<th>LPH</th>
</tr>
</thead>
<tbody>
<tr>
<td>1250</td>
<td>1.8</td>
<td>2.27</td>
</tr>
<tr>
<td>2000</td>
<td>4.8</td>
<td>4.16</td>
</tr>
<tr>
<td>2500</td>
<td>5.2</td>
<td>5.68</td>
</tr>
<tr>
<td>3000</td>
<td>5.7</td>
<td>7.57</td>
</tr>
<tr>
<td>3500</td>
<td>6.3</td>
<td>10.98</td>
</tr>
<tr>
<td>4000</td>
<td>7.2</td>
<td>14.38</td>
</tr>
<tr>
<td>4500</td>
<td>9.5</td>
<td>19.31</td>
</tr>
<tr>
<td>5000</td>
<td>12.7</td>
<td>25.74</td>
</tr>
<tr>
<td>5500</td>
<td>21.1</td>
<td>32.55</td>
</tr>
<tr>
<td>6000</td>
<td>27.3</td>
<td>40.13</td>
</tr>
<tr>
<td>6500</td>
<td>31.7</td>
<td>49.59</td>
</tr>
<tr>
<td>7000</td>
<td>36.1</td>
<td>62.84</td>
</tr>
<tr>
<td>7540</td>
<td>42</td>
<td>78.74</td>
</tr>
</tbody>
</table>

2. Maximum RPM is 7540 and maximum engine power is 184 kW [48].
3. Calculation of parameter \( k \).

\[
k = \frac{P_{\text{max}}}{(RPM_{\text{max}})^{2.5}} = \frac{184}{7540^{2.5}} = 3.727 \cdot 10^{-8}
\] (3.13)
3.3. RESULTS

4. Propeller curve, Figure 3.8

![Figure 3.8: Propeller power curve for Yamaha AR195](image1)

5. Power speed curve, Figure 3.9

![Figure 3.9: Power speed curve for Yamaha AR195](image2)

6. Consumption speed curve, Figure 3.10

![Figure 3.10: Consumption speed curve for Yamaha AR195](image3)
3.3.3 Mean power speed curve

The graph in Figure 3.11 shows the power curves obtained from the testing of the previously listed boats. The average curve is shown as well in the graph. It has been calculated only for the range of speed in which all the boats have available data (2000-7400 engine rotational speed in RPM, 4.2-35.5 boat speed in knots).

Figure 3.11: Summary of all tests and mean power curve

Figure 3.11 shows that the required power does not increase linearly, with different gradients in four intervals of speed. In the first interval, below 5 knots, the required power does not increase significantly, while in the second interval, between 5 to 10 knots, the gradient is higher and the curve goes up quickly. At ca. 10 knots the power stabilises until 20 knots, defining the third interval of speed. After 20 knots, the curve rises again significantly. This is due to the fact that at around 10 knots the boat starts planing, hence reducing the increase in resistance due to increase of speed.

These considerations can be useful when determining the different set speeds at which the boat will run (Section 4.2.1).
3.3.4 Mean consumption curve

The graph in Figure 3.12 shows the consumption in liters of diesel per hour from the testing of the considered boats. The average is calculated and shown in the graph. Similarly as the power speed curve, it has been calculated only for the range of speed in which all the boats have available data (2000-7400 engine rotational speed in RPM, 4.2-35.5 boat speed in knots).

![Mean consumption curve graph]

Figure 3.12: Summary of all tests and mean consumption curve

3.3.5 Comparative analysis with theoretical results

When comparing Figure 3.11 and Figure 3.1, the similarities are clear. For a hull of around 18 feet (5.5 m), the hull speed, calculated as in Equation (3.11), is approximately 5.7 knots. This number matches with the last efficient speed when looking at Figure 3.11. For the same hull, the hump speed, calculated as in Equation (3.12), is of about 7 knots, which corresponds to the end of the steep section, before the curve flattens.
3.4 Conclusions

To conclude the results of the power need and consumption in the water jet testing analysis, three different speeds have been taken into account: low speed, cruise speed and maximum speed. For these speeds, the corresponding value of power is taken from the mean power speed curve and the corresponding value for the consumption is taken from the mean consumption speed curve. The values for power, consumption and speed are shown in Table 3.4.

Table 3.4: Conclusions in terms of power need and consumption

<table>
<thead>
<tr>
<th>Speed</th>
<th>Power Need</th>
<th>Consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low speed</td>
<td>5 knots</td>
<td>13.27 kW</td>
</tr>
<tr>
<td>Cruise speed</td>
<td>15 knots</td>
<td>67.3 kW</td>
</tr>
<tr>
<td>Maximum speed</td>
<td>30 knots</td>
<td>114.4 kW</td>
</tr>
</tbody>
</table>

These values are used in the next chapters as reference values to simplify the analysis of the speed, power and consumption profiles, discussed in Section 4.2.1. Since no speed profile of the rescue missions is available, the three speeds have been chosen in accordance to the mean power speed curve.

The low speed of 5 knots has been chosen since it is close to the hull speed, hence it is still an efficient speed. Cruise speed of 15 knots is located already on the almost flat piece of the curve, when the boat is already planing. The maximum speed is instead fixed to 30 knots as requirement (Section 2.3).
Chapter 4

Energy Storage

In this chapter, the energy storage requirements are defined and a suitable energy storage system is designed.

Thanks to the help of the Division of Applied Electrochemistry, different options have been taken into consideration. The most interesting one appears to be an hybrid electric energy storage system that would include both a fuel cell stack and a battery pack. The combination of fuel cells, which work well on stationary power demand, and battery pack is expected to be the best solution in terms of weight and volume.

All these considerations are examined in this chapter. Moreover, the rating of the system is discussed and some results and conclusions are presented.

4.1 Background

In this section, a background on energy storage technologies, in particular on fuel cells and batteries, is given. Different technologies for both energy storage alternatives are explored, focusing on the ones that have been chosen for this thesis project.

4.1.1 Energy storage technologies

When comparing different energy storage technologies, a Ragone analysis is usually carried out. The Ragone plot in Figure 4.1 shows the different technologies in a graph, making the comparison possible in terms of both power and energy density.

The specific power or power density of an energy storage technology is defined as the power that the technology can supply to the system divided by the weight of its components. Similarly, the specific energy or energy density is defined as the energy that the technology is able to store divided by the weight of its components. In the Ragone plot, the specific power is represented on the x axis, while the specific energy is represented on the y axis.
CHAPTER 4. ENERGY STORAGE

Figure 4.1: Example of a ragone plot

In the example of Figure 4.1 another variable is shown, which is the characteristic time. This time is defined as the maximum period of time over which the system is able to deliver the maximum power.

Hence, to choose the right technology, the features that need to be defined are listed below.

- Maximum required power
- Required energy in one cycle or mission
- Characteristic time

Once these parameters are defined, the technology can be chosen. It is unlikely that any of the available technologies is able to satisfy all the requirements, without oversizing the system. In this thesis work, an hybrid system is chosen: the combination of different technologies is proven to be the best solution in terms of weight, which can satisfy the requirements above.

4.1.2 Fuel cells

Fuel cells are electrochemical cells that convert chemical energy into electricity. Both batteries and fuel cells produce electricity, but they make it in a different way. Batteries are closed systems, and produce electricity from the energy stored inside them. Fuel cells are open systems, and produce energy from fuel in an external fuel tank: they can produce electricity as long as fuel is supplied to the cell. They also have several advantages, which include clean byproducts and zero emissions. For these reasons they are being studied as powering system for this project.

Fuel cells have been on the market since 1960s, but have become feasible for few applications from 1990s. They are suitable for both stationary and non stationary applications, even though they still face as main challenge reducing cost and improving operating reliability.
4.1. BACKGROUND

4.1.2.1 Fuel cell power system interconnection

To be functional, a fuel cell needs a power system interconnection: the typical configuration is shown in Figure 4.2. A fuel processor and an oxidant supply provide the energy to the fuel cell stack (a connection of fuel cells). The energy generated by the fuel cell stack goes through a power conditioner that provides the needed power quality to the load and to an additional energy storage. The power between the energy storage and the power conditioner flows in both ways, so that the energy storage has the possibility to both be charged by the fuel cell or load and discharged by delivering power to the load [51].

![Figure 4.2: Block diagram of fuel cell power system interconnection, adapted from Gou et al. 51](image)

4.1.2.2 Fuel cell characterization

The characterization of fuel cells is mostly done according to the type of electrolyte used, with a significant variation in the required operating temperature. The most common fuel cell types are listed below [51].

- Proton exchange/polymer electrolyte membrane fuel cell (PEMFC)
- Direct methanol fuel cell (DMFC)
- Alkaline fuel cell (AFC)
- Phosphoric acid fuel cell (PAFC)
- Molten carbonate fuel cell (MCFC)
- Solid oxide fuel cell (SOFC)
- Zinc air fuel cell (ZAFC)
- Photonic ceramic fuel cell (PCFC)

4.1.2.3 Application of fuel cells in vehicles

As already discussed, fuel cells are systems that produce power with zero emissions and clean byproducts. Hence there is great interest in the automotive industry to use them due to air pollution and greenhouse gas problems. Moreover, fuel cells have higher efficiency than internal combustion engines (see Section 4.1.2.6) [51].

At present, proton exchange/polymer electrolyte membrane is the most promising technology for vehicle applications, thanks to the high power density, solid electrolyte, long stack life, low corrosion and low temperature (50°C-100°C, allowing fast start-up) [51].
4.1.2.4 PEMFC

As it can be seen in Figure 4.3, a fuel cell produces power through an electrochemical reaction between fuel and oxygen. In a PEMFC, the semipermeable barrier that allows the reaction is a polymer electrolyte that is permeable to protons but impermeable to electrons. To close the circuit, the electrons are allowed to travel around the membrane through wires, hence creating an electrical current [52].

Equation (4.1) and (4.2) take place respectively in the anode and in the cathode, while Equation (4.3) represents the overall reaction [52].

$$2H_2 \Rightarrow 4H^+ + 4e^- \quad (4.1)$$
$$4H^+ + O_2 + 4e^- \Rightarrow 2H_2O \quad (4.2)$$
$$2H_2 + O_2 \Rightarrow 2H_2O \quad (4.3)$$

From the equations, the reactions happening and the overall process seem easy, but the detailed functioning of a fuel cell, its losses and energy calculations are far more complex. There are though many models that try to simplify and make calculations easier. Most of these models derive from principles and incorporated with empirical correlations, allowing designers to reduce time and money spent on prototyping and testing by predicting the behaviour of the fuel cells [52].

$$\Delta \hat{g}_f = -nFE^0 \quad (4.4)$$

Equation (4.4) gives the electrical potential of a fuel cell, where $\Delta \hat{g}_f$ is the Gibbs free energy of reaction, $n$ is the number of electrons transported, $F$ is the Faraday constant and $E^0$ is the maximum theoretical voltage. This last value is affected by the gas pressure and concentration. From this value, the reversible open circuit voltage can be obtained, and it represents the maximum voltage a fuel cell can produce.
4.1. BACKGROUND

The actual voltage a fuel cell can produce will always be less than this value due to the reasons listed below [52].

- Activation over potential losses, $\eta_{act}$: part of the potential is lost because an increase of current output is needed when the cell is not at electrochemical equilibrium (exchange current density).
- Ohmic over potential losses, $\eta_{ohm}$: losses due to motion of charged particles.
- Mass transport over potential losses, $\eta_{mt}$: mass transport rate is regulated by concentration, which implies voltage loss when the mass transport is not at usual rate since it causes a reduction in reaction rate.

The actual cell voltage $V_{cell}$ can be modelled by subtracting the over potentials from the reversible fuel cell voltage $E$, as in Equation (4.5) [52].

$$ V_{cell} = E - \eta_{act} - \eta_{ohm} - \eta_{mt} $$ (4.5)

4.1.2.5 Hyundai Nexo

One of the latest examples of fuel cell vehicles is the Hyundai Nexo. From the technical specifications [54], the data shown in Table 4.1 can be retrieved.

Table 4.1: Specifications of Hyundai Nexo

<table>
<thead>
<tr>
<th>Powertrain</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor type</td>
<td>Permanent magnet motor</td>
<td></td>
</tr>
<tr>
<td>Maximum power</td>
<td>120 kW / 163 ps</td>
<td></td>
</tr>
<tr>
<td>Maximum torque</td>
<td>395 Nm</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Battery</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Total system output</td>
<td>135 kW</td>
<td></td>
</tr>
<tr>
<td>Power output - battery</td>
<td>40 kW</td>
<td></td>
</tr>
<tr>
<td>Power output - fuel cell stack</td>
<td>95 kW</td>
<td></td>
</tr>
<tr>
<td>Stack density</td>
<td>3.1 kW/L</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Performance</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum speed</td>
<td>179 km/h</td>
<td></td>
</tr>
<tr>
<td>$CO_2$ combined</td>
<td>0 g/km</td>
<td></td>
</tr>
<tr>
<td>Driving range</td>
<td>666 km - 756 km</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Capacities and weights</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall fuel tank capacity</td>
<td>156.6 L</td>
<td></td>
</tr>
<tr>
<td>Curb weight</td>
<td>1814-1873 kg</td>
<td></td>
</tr>
<tr>
<td>Gross vehicle weight</td>
<td>2340 kg</td>
<td></td>
</tr>
</tbody>
</table>

This example has been chosen to prove that PEMFCs systems combined with a battery pack can be used in applications with a power need of around 120 kW, which is the range that has been studied in this project.
4.1.2.6 Fuel cell efficiency

An important value when including a fuel cell system in an application is its efficiency. The fuel cell efficiency is defined as in Equation (4.6), where $E_{el}$ is the energy produced in electrical form and $E_{H_2, primary}$ is the energy content of the hydrogen consumed [55].

$$\eta_{FC} = \frac{E_{el}}{E_{H_2, primary}} \tag{4.6}$$

A fuel cell theoretical efficiency is 83%, assuming that all Gibbs free energy is converted to electrical energy and using hydrogen’s higher heating value as energy content of hydrogen. The actual efficiency is lower due to various losses [55].

The fuel cell efficiency of the main fuel cell types is shown in Table 4.2 [56].

Table 4.2: Fuel cell efficiency values [56]

<table>
<thead>
<tr>
<th>Fuel cell type</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alkaline</td>
<td>70%</td>
</tr>
<tr>
<td>Molten carbonate</td>
<td>60-80%</td>
</tr>
<tr>
<td>Phosphoric acid</td>
<td>40-80%</td>
</tr>
<tr>
<td>Solid oxide</td>
<td>60%</td>
</tr>
<tr>
<td>Proton exchange membrane</td>
<td>40-50%</td>
</tr>
</tbody>
</table>

4.1.3 Battery pack

When looking at the battery branch of the energy storage technology, two types can be defined: non rechargeable batteries or primary batteries, and rechargeable batteries or secondary batteries.

In this thesis, the interest lies mainly in secondary batteries since the sustainability requirement is to be rechargeable. Nevertheless, a comparison between the designed storage system with a storage composed of a primary battery exclusively is carried out in this chapter. This is mainly done because of the better performance of primary batteries when compared to secondary batteries: non rechargeable batteries have higher power and energy density, making the system less heavy.

Batteries are generally composed by a pack of several cells, which have specific characteristics as power density and energy density. The main characteristic of a cell stack is its initial capacity $C$, which is amount of energy that can be stored in the battery.

During the usage of a battery, another variable that is take into account is the State of Charge SoC, defined as the energy storage available divided by its initial energy storage [57].
The C-rate is another important variable when analysing the charge and discharge of a battery. When a battery is discharged with a rate of $1 C$, it takes one hour to empty the battery of its full capacity. Similarly, $1 C$ of charge means one hour to completely recharge the battery from empty. Faster charge happens at higher C-rates ($2 C$ means full charge/discharge in half an hour) while slower charge happens at lower C-rates ($0.5 C$ means full charge/discharge in two hours). Battery producers indicate the "rated" capacity at a C-rate of $1 C$, but the value of capacity is different whenever the C-rate is not unitary [58].

- When the C-rate is higher than $1 C$ (fast charge/discharge), the capacity of the battery is likely to be lower than the rated capacity, due mainly to internal losses.
- When the C-rate is lower than $1 C$ (slow charge/discharge), the capacity of the battery is likely to be higher than the rated capacity.

### 4.1.3.1 Secondary battery technologies

In this section an overview of the existing and proven secondary battery technology is given, with some advantages and limitations [59].

- Lead acid systems are the oldest rechargeable batteries. These are rugged and cheap, but have low specific energy and limited cycles in one lifetime. A disadvantage of the lead material is that it is toxic and cannot be dumped in landfills, making it harder to recycle.
- Nickel cadmium (NiCd) systems are mature and used for applications which require long service. Their chemistry allows ultra fast charging, but cadmium is a toxic metal and cannot be disposed in landfills.
- Nickel metal hydride (NiMH) systems are a replacement of the nickel cadmium, with only mild toxic metals. The technology provides higher specific energy, and it is also available in AA and AAA cells for consumers use.
- Lithium ion (Li-ion) systems are more expensive than other batteries, but they provide high cycle count and low maintenance. They need a protection circuit for safety and they are classified into different types, named after their active materials.

Amongst these technologies, Li-ion is chosen for secondary battery in the hybrid electric drive train, especially because of the high specific energy, long cycle and low maintenance. Figure 4.4 shows the flow of ions that move between cathode and anode. The cathode is a lithium metal oxide while the anode is porous carbon. The flow is from the cathode to the anode during discharge, with the anode undergoing oxidation (loss of electrons); it is from the anode to the cathode during charge, with the cathode undergoing reduction (gain of electrons) [60].

![Figure 4.4: Ion flow in a Li-ion battery](image)
4.1.3.2 Primary battery technologies

In this thesis project, a comparison between different storage options has been carried out. For this reason, the most common primary battery are listed in this section, with few advantages and disadvantages [61].

- Zinc carbon is the earliest and cheapest type of primary batteries. It is still used in few consumers applications.
- Alkaline technology is an improved version of zinc carbon, delivering more energy at higher currents, totally leak proof.
- Lithium iron disulfide (Li-FeS\textsubscript{2}) is a newer technology, compatible with AA and AAA formats, with higher capacity and lower internal resistance than alkaline technology. Li-FeS\textsubscript{2} batteries come though with higher price and some transportation issues due to the presence of lithium in the anode.
- Lithium thionyl chloride (LiSOCl\textsubscript{2}) is a rugged lithium metal battery, able to withstand high heat and strong vibrations, offering twice the specific energy of the best Li-ion rechargeable batteries.
- Lithium manganese dioxide (LiMnO\textsubscript{2}) is similar to LiSOCl\textsubscript{2} but with lower specific energy.

4.1.4 Specifications of chosen technologies

In the next sections, few specifications are listed for the different storage technologies. Also considerations on the weight of the ICE and the electric machines are made, since the weight of those is included in the analysis later in the chapter. The machine is not part of the energy storage system, but depending on the latter the former is either ICE or electric machine, hence it has been included in this section. The water jet weight has not been considered since it would be the same for all the systems, being irrelevant in the comparison.

4.1.4.1 Battery systems

For the primary battery the Li/\textsubscript{SO}_4\textsubscript{Cl}_2 technology has been chosen, for the secondary battery Li-ion technology. The characteristic time changes depending on the use of the boat, but it is of 10 to 60 minutes. When looking at the Ragone plot (Figure 4.1), it can be seen that the Li-ion and Li-polymer lie in the top right area of the graph, corresponding roughly with a characteristic time of 6 minutes. As already mentioned, not all the requirements are always met. This time is close enough to the value of characteristic time. Moreover, it has to be considered that the system will also include a fuel cell stack, which has a much higher characteristic time.
4.1. BACKGROUND

The specifications of such batteries are shown in Table 4.3 [57] [62]. These values have been used for the calculations of the weight and volumes of the different systems previously described.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Wh/kg</th>
<th>Wh/L</th>
<th>Efficiency [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Li/SO₂Cl₂ (primary battery)</td>
<td>600</td>
<td>1200</td>
<td>90</td>
</tr>
<tr>
<td>Li-ion (secondary battery)</td>
<td>217</td>
<td>337</td>
<td>85</td>
</tr>
</tbody>
</table>

4.1.4.2 Fuel cell system

The PEMFC efficiency of 40-50% found in Table 4.2 is an average value, that can be significantly improved by controlling the fuel and air flow rate. The design of a controller is key in increasing the efficiency [63]. With an hybrid system that includes both a battery and a fuel cell, it is possible to run the fuel cell at an almost constant power close to the nominal power, making its efficiency higher than the average value. The value of efficiency for fuel cells used in this project is of 60%, based on the results of projects such as the Japanese URASHIMA project, the French IDEFIX project and the German DEEPC project [62].

The specifications for the hydrogen storage system are shown in Table 4.4 [49].

<table>
<thead>
<tr>
<th>Storage technology</th>
<th>( \rho_{mH_2}[kgH_2/kg] )</th>
<th>( \rho_{nH_2}[kgH_2/m^3] )</th>
</tr>
</thead>
<tbody>
<tr>
<td>200 bar H₂</td>
<td>0.012</td>
<td>16</td>
</tr>
<tr>
<td>350 bar H₂</td>
<td>0.032</td>
<td>21</td>
</tr>
<tr>
<td>700 bar H₂</td>
<td>0.06</td>
<td>35</td>
</tr>
</tbody>
</table>

4.1.4.3 ICE

The weight of the ICE has been calculated using data from existing water jet diesel engines from Mercury and Volvo Penta. The weight of such engines is much different than the weight of an ICE that for example serves for road transport purposes, since it is specific for water applications.

In Table 4.5, the data from Mercury [64] and from Volvo Penta [65] [66] [67] has been retrieved. The average is shown in the last column. The table shows the main specifications of the five different inboard diesel engines, including the power to weight and the power to volume. These two values are respectively the maximum power divided by the weight and the maximum power divided by the volume. Hence, the weight of the ICE is calculated by multiplying the required power by the power to weight average value.

The ICE efficiency is calculated throughout the chapter, thanks to the mean consumption curve obtained in Section 3.3.4.
### Table 4.5: Diesel engine inboards specifications and average

<table>
<thead>
<tr>
<th></th>
<th>Mercruiser 4.5</th>
<th>D3-200</th>
<th>D3-220</th>
<th>D4-225</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Power</strong></td>
<td>200 hp</td>
<td>250 hp</td>
<td>200 hp</td>
<td>220 hp</td>
<td>225 hp</td>
</tr>
<tr>
<td><strong>Displacement</strong></td>
<td>4.5 L</td>
<td>4.5 L</td>
<td>2.4 L</td>
<td>2.4 L</td>
<td>3.4 L</td>
</tr>
<tr>
<td><strong>Volume</strong></td>
<td>0.29 m³</td>
<td>0.29 m³</td>
<td>0.56 m³</td>
<td>0.56 m³</td>
<td>0.54 m³</td>
</tr>
<tr>
<td><strong>Weight</strong></td>
<td>345 kg</td>
<td>343 kg</td>
<td>301 kg</td>
<td>301 kg</td>
<td>546 kg</td>
</tr>
<tr>
<td><strong>Power to weight</strong></td>
<td>0.43 kW/kg</td>
<td>0.54 kW/kg</td>
<td>0.49 kW/kg</td>
<td>0.54 kW/kg</td>
<td>0.30 kW/kg</td>
</tr>
<tr>
<td><strong>Power to volume</strong></td>
<td>0.51 kW/L</td>
<td>0.64 kW/L</td>
<td>0.26 kW/L</td>
<td>0.29 kW/L</td>
<td>0.31 kW/L</td>
</tr>
</tbody>
</table>

#### 4.1.4.4 Electric machine

The weight of the electric machine has been assumed looking at the most promising technologies on the market. Siemens and Emrax, two of the main electric machines companies, claim to have the best power to weight ratio, in the range from 5 to 10 kW per kg. For example, Emrax model 268 is ca. 20 kg heavy and it can produce a maximum power of 230 kW. For this motor, the value of the power to weight ratio is of 11.5.

The average value of 7 kW/kg has been chosen when calculating the weight of the electric machine. In any case, using these numbers, the weight of the electric machine does not have a great impact on the total weight of the system.

The efficiency of the electric machine has been tackled in Section 3.1.2.4 and 3.1.2.1. In Chapter 5, different machines technologies are listed. Few options of machines are presented and compared in terms of specifications.

### 4.2 Methodology

After calculating the power required for driving the boat at different speeds, the next step is to calculate the required energy for the water jet motor in different situation, to achieve the required speed. Knowing the required energy, the energy storage is chosen. In the next sections the rating methodology is explained in more detail.

#### 4.2.1 Speed, power and consumption profiles

An assumption of different speed curves has to be made: a speed profile is a curve that assumes, for one mission, different time steps in which the boat will run at different speeds. Different missions are defined to take into account different uses of the boat: these missions should predict the different operating conditions, to design a drive train suitable to all situations. The speed profile is then a curve of speed dependent on time. To simplify the analysis, only three speeds are allowed in the curve: low speed, cruise speed and maximum speed. Both a required power and consumption value are associated to each of these three speeds (see Section 6.3).
4.2. METHODOLOGY

From the speed profile, power curves can be obtained using the mean power speed curve (see Section 3.3.3). A power profile is a curve that takes into account the needed power (in the form of delivered power $P_D$) of the rescue boat during the time of one mission.

The area underneath the power curve represents the delivered energy $E_D$, and can be calculated as the integral of the power curve $P_D(t)$ with respect to time, as it can be seen in Equation (4.7), where $t_0$ and $t_M$ represent the start and the end time of the mission. The delivered energy is the same for both the ICE system and the hybrid electric system designed in this thesis work.

$$E_D = \int_{t_0}^{t_M} P_D(t)dt$$

(4.7)

To estimate the energy that the storage system needs to provide $E_S$, the efficiency of the electric motor $\eta_M$ and reduction gear $\eta_G$ need to be taken into account. For these, a round trip efficiency has been assumed (see Section 3.1.2.4).

$$E_S = \frac{E_D}{\eta_G \eta_M} = \frac{E_D}{0.85}$$

(4.8)

The next step is understanding how much of this energy is produced by the fuel cell $E_{FC}$ and how much is drawn from the battery $E_B$. The fuel cell is assumed to be working at constant power $P_{FC}$ for the entire timing of the mission; the battery will need to provide the remaining energy needed for the mission to be completed.

$$E_{FC} = \int_{t_0}^{t_M} P_{FC}dt = P_{FC}(t_M - t_0)$$

(4.9)

$$E_B = E_S - E_{FC}$$

(4.10)

To understand what will be the primary energy needed by the battery $E_{grid,primary}$, it is sufficient to multiply the energy that the battery need to provide $E_B$ by the efficiency of the battery $\eta_B$ (see Table 4.3). This value will be the energy drawn from the electric grid.

$$E_{grid,primary} = \frac{E_B}{\eta_B} = \frac{E_B}{0.85}$$

(4.11)

The primary energy needed in form of hydrogen $E_{H_2,primary}$ by the fuel cell stack is calculated using the efficiency of the fuel cell $\eta_{FC}$ (see Section 4.1.3.2). The specific energy in kWh per kg of hydrogen $\epsilon_{H_2}$ expresses the energy content of hydrogen and it is used to calculate the required mass of hydrogen $m_{H_2}$ [70].

$$\epsilon_{H_2} = 33.3 \frac{kWh}{kg}$$

(4.12)

$$E_{H_2,primary} = \frac{E_{FC}}{\eta_{FC}} = \frac{E_{FC}}{0.6}$$

(4.13)

$$m_{H_2} = E_{H_2,primary} \epsilon_{H_2}$$

(4.14)
From the same assumptions of speed, also consumption profiles can be made. These profiles take into account how many liters per hour an ICE consumes in terms of diesel fuel to drive at a fixed speed. The data that comes from the tests is given in liters per hour, and from these the primary energy consumed by the internal combustion engine can be derived.

The area underneath the consumption curve \( C(t) \) represents the liters consumed in the mission \( L_{\text{cons}} \). The energy density is the value that allows to transform the liters in an energy value. The energy density for conventional diesel fuel \( e_{\text{diesel}} \) is shown in Equation (4.16) \[71\].

\[
L_{\text{cons}} = \int_{t_0}^{t_M} C(t)\,dt \quad (4.15)
\]

\[
e_{\text{diesel}} = 35 \frac{MJ}{L} = 9.67 \frac{kWh}{L} \quad (4.16)
\]

Equation (4.17) is used to calculate the primary energy contained in the fuel \( E_{\text{diesel,primary}} \). In order to calculate the efficiency of the internal combustion engine drive train \( \eta_{\text{DIE}} \), Equation (4.18) needs to be used.

\[
E_{\text{diesel,primary}} = L_{\text{cons}} \cdot e_{\text{diesel}} \quad (4.17)
\]

\[
\eta_{\text{DIE}} = \frac{E_D}{E_{\text{diesel,primary}}} \quad (4.18)
\]

Three different missions have been assumed, a typical mission and two rescue missions, which derive from the two rescue types explained in Section 2.2.1.

### 4.2.1.1 Typical mission

For the optimisation tool, a typical mission needs to be considered. The typical mission is assumed as a tour of the lake, during which the boat will run at high speed and low speed at intervals of 10 minutes each. Assuming the goal of the mission is duty coast guarding, the boat will run at low speed to check a certain area, and then move at higher speed to another area. Since it takes 40 minutes at maximum speed for the boat to reach the end of the lake, it is assumed that it will take 80 minutes to do the entire round of the lake, considering that during the coast guarding low speed time the boat does not move too much from the area. Since the intervals are of 10 minutes, it will take 8 cycles to travel the distance. This means that the total timing of the mission is 160 minutes to go till the end of the lake and back, for a total of 80 minutes at maximum speed and 80 minutes at low speed.

This kind of cyclical mission is needed to optimize the system: the optimization tool used in this thesis work allows to calculate a minimum of weight of the system, that occurs at a specific value of fuel cell power \[62\].
4.2. METHODOLOGY

Table 4.6 summarizes the assumptions for this mission, while Figure 4.5 is a graphical reference. In this example, the characteristic time is of 10 minutes.

Table 4.6: Typical mission - assumptions

<table>
<thead>
<tr>
<th>Timing of mission</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Time at maximum power</td>
<td>80 min</td>
</tr>
<tr>
<td>Time at low speed power</td>
<td>80 min</td>
</tr>
<tr>
<td><strong>Total time</strong></td>
<td>160 min</td>
</tr>
</tbody>
</table>

Figure 4.5: Typical mission - speed, power and consumption profiles

Using the data from this mission, the optimisation code finds what is the value of fuel cell power that minimises the weight of the system. After finding this value for the fuel cell power, the battery is sized in capacity as the difference between the energy needed for the entire mission and the energy generated by the fuel cell. Then the C-rate is calculated, using Equation (4.19), where \( P_{\text{max}} \) is the maximum power required by the system, \( P_{\text{FC}} \) is the rated power of the fuel cell and \( C \) is the battery rated capacity. As seen in Section 4.1.3, the value of the C-rate needs to be close to one. If the C-rate is not one, the battery size has to be changed accordingly. With the fuel cell power and battery size, the other two rescue missions need to be checked in terms of energy requirements.

\[
C_{\text{rate}} = \frac{P_{\text{max}} - P_{\text{FC}}}{C} \quad (4.19)
\]
4.2.1.2 Mission I: missing person

The assumption for mission I is that Sjöräddningssällskapet receives a call from a boat located at the furthest point from the rescue station, asking for help since a person is missing. In this case, the rescue boat will have to rush till the end of the lake. This will take approximately 40 minutes. For these first 40 minutes, the boat will proceed at maximum speed, running the machine at maximum power. Once arrived at destination, it will need to search for the person. Since it is not easy to understand how long the boat will look for the missing person, it will be assumed that the time is 80 minutes. During this time, the boat will not proceed at full speed, but at low speed. After finding the person, the assumption made is that the boat will have to rush back to the station, hence using full power for 40 minutes.

Table 4.7 summarizes the assumptions for this mission, while Figure 4.6 is a graphical reference. It can be seen that the characteristic time in this mission is of 40 minutes.

Table 4.7: Mission I - assumptions

<table>
<thead>
<tr>
<th>Timing of mission</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Time at maximum power</td>
<td>80 min</td>
</tr>
<tr>
<td>Time at low speed power</td>
<td>80 min</td>
</tr>
<tr>
<td><strong>Total time</strong></td>
<td>160 min</td>
</tr>
</tbody>
</table>

Figure 4.6: Mission I - speed, power and consumption profiles
4.2. METHODOLOGY

4.2.1.3 Mission II: tow a boat

Another need of Sjöräddningssällskapet is to tow the boats that are present on the lake. Currently on Lake Backen there are mainly small boats, around 27-30 feet long. The biggest is around 42 feet long. There are two heavier steam boats (around 55 tons), that the current diesel engine of ca. 50 kW they can park and manage around the lake.

Since the lake is a long but narrow lake, the need to tow boats is for short distances. In the worst case, the boat to tow is located in at the furthest point from the rescue station. For the first 40 minutes, the boat will proceed at maximum speed running the engine at maximum power. Once arrived at location of the accident, it will need to get close to the boat, ensure the passengers are safe and tow the boat to the shore. For around 20 minutes, the boat will run at low speed, before actually towing the boat. The lake maximum width is of around 1 km. The assumption made is that the boat will take around 20 minutes to tow the boat to the shore, even if this assumption is very conservative. The power used will be maximum power. For other 20 minutes the boat will run at low speed to ensure the boat is not in danger anymore, then the boat will have to go back to the station, running at cruise speed. This will take the boat around one hour.

Table 4.8 summarizes the assumptions for this mission, while Figure 4.7 is a graphical reference. In this case, the characteristic time is of 40 minutes.

Table 4.8: Mission II - assumptions

<table>
<thead>
<tr>
<th>Timing of mission</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Time at maximum power</td>
<td>60 min</td>
</tr>
<tr>
<td>Time at cruise speed power</td>
<td>60 min</td>
</tr>
<tr>
<td>Time at low speed power</td>
<td>40 min</td>
</tr>
<tr>
<td><strong>Total time</strong></td>
<td>160 min</td>
</tr>
</tbody>
</table>

Figure 4.7: Mission II - speed, power and consumption profiles
4.2.2 Analysis of different energy storage technologies

To make a relevant comparison, the eight different systems listed below have been compared in terms of weight.

- Hybrid system: secondary battery and PEM fuel cell, H\textsubscript{2} stored at 200 bar.
- Hybrid system: secondary battery and PEM fuel cell, H\textsubscript{2} stored at 350 bar.
- Hybrid system: secondary battery and PEM fuel cell, H\textsubscript{2} stored at 700 bar.
- Hybrid system: secondary battery and PEM fuel cell, H\textsubscript{2} in liquid state.
- Hybrid system: secondary battery and metal hydride fuel cell.
- ICE system with diesel fuel.
- Secondary battery system.
- Primary battery system.

The first five allow a comparison amongst the different hybrid system options, while the others show different technological options available on the market. The specifications of these technologies are shown in Section 4.1.4.

4.3 Results

In this section, the results obtained with the described methodology are shown. The energy storage system behaviour is simulated in every mission. An analysis on different storage technologies is carried out, comparing them in terms of weight.

4.3.1 Typical mission

The first simulation concerns the typical mission, since with these values an optimization can be carried out.

The optimization code checks the weight of the system every 500 W of fuel cell size; the results are shown in Figure 4.8. The axis of the figure are fuel cell power as abscissa and the weight as ordinate. The graph shows three lines: the weight of the fuel cell stack, the weight of the battery pack and the weight of the full hybrid system.

The fuel cell stack weight increases linearly with the increase of fuel cell power. This curve only takes into account the fuel cell stack, not the hydrogen mass needed as fuel.

The battery pack weight instead decreases with the increase of fuel cell power. This is because the bigger the fuel cell is, the least energy the battery needs to deliver to the system, hence becoming smaller in terms of capacity. With the increase of fuel cell power, the capacity of the battery decreases, and since the weight increases linearly with the capacity, also the weight decreases. There is though a turning point, when the battery weight decrease is not as steep. To understand this behaviour, the cycles need to be analysed in more detail.
4.3. RESULTS

A cycle for the typical mission, as defined in Section 4.2.1.1, is composed by 10 minutes at maximum speed followed by 10 minutes at low speed. During the 10 minutes at maximum speed, the battery needs to supply a value of power that added to the nominal power of the fuel cell gives the maximum power. The code optimizes the system with the smallest battery, which in this time will discharge until the set point of state of charge (which has been set as 0.1, to prevent the battery to discharge completely). Then, in the next 10 minutes, the battery can be recharged by the extra power provided by the fuel cell, since the power needed at low speed is very small. When the turning point occurs, the battery in this second part of the cycle recharges completely in less than 10 minutes. It is not possible though to make the battery size smaller since the requirement is set by the first part of the cycle.

Figure 4.8: Weight optimization for the typical mission

The full hybrid system weight includes the weights listed below:

- The electric machine and the inverter. This weight is the same for every step of the optimization, since it does not depend on the optimization itself.
- The battery pack weight, represented in the graph.
- The fuel cell stack weight, which is also represented in the graph.
- The hydrogen weight, which depends solely on the size of the fuel cell. The weight is based on an optimisation that uses as hydrogen storage 700 bar tanks. The use of a different hydrogen storage system changes the weight of the system but does not change the position of the minimum on the curve.

The reason why there is a minimum in a curve is explained by the shape of the battery pack curve and by the increase in need of hydrogen storage. If before the turning point the increase in weight of hydrogen is compensated by the decrease in weight of the battery system, after the turning point the steepness of the battery curve is not large enough. This is the explanation of the presence of a clear minimum at a fuel cell nominal power of 75 kW. This value will be used from now on for the simulation of all the missions, in order to analyse the behaviour of the system and choose the battery size.
Table 4.9 shows the summary of the values calculated thanks to the formulas shown in Section 4.2.

Table 4.9: Summary of typical mission

<table>
<thead>
<tr>
<th>Hybrid electric system</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Delivered energy</td>
<td>$E_D = 170, \text{kWh}$</td>
</tr>
<tr>
<td>Storage energy</td>
<td>$E_S = 200, \text{kWh}$</td>
</tr>
</tbody>
</table>

| ICE system             |
|------------------------|---|
| Liters, diesel         | $L_{cons} = 58.5\, \text{L}$ |
| Primary energy, diesel | $E_{diesel,\text{primary}} = 568\, \text{kWh}$ |
| ICE efficiency         | $\eta_{ICE} = 30.0\%$ |

From the simulation, the optimal battery size is of around $11.6\, \text{kWh}$ ($C_{min} = 11.6\, \text{kWh}$). This value would be sufficient since the fuel cell can recharge the battery during the low speed intervals of the cycle. By doing so, the C-rate of the battery would though be 5.14. Since the C-rate with this design is too high, the battery size has been multiplied by 5.14 in order to have a C-rate of 1.

$$C = C_{rate} \cdot C_{min} = 59.5\, \text{kWh} \quad (4.20)$$

Having these changes, the system specifications are as shown in Table 4.10. With this design the results are shown in Figure 4.9. The fuel cell energy and mass of hydrogen have been calculated as described in Section 4.2. In the simulations for the other missions, these values are used. The fuel cell power is estimated to be constant during the entire mission to calculate the energy provided by the fuel cell and hence the mass of hydrogen. The other missions are simulated as a check, to see if these values satisfy all the conditions.
4.3. RESULTS

Table 4.10: Design proposition of the storage system

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel cell power</td>
<td>$P_{FC} = 75 \text{ kW}$</td>
</tr>
<tr>
<td>Fuel cell energy</td>
<td>$E_{FC} = 200 \text{ kWh}$</td>
</tr>
<tr>
<td>Primary energy of hydrogen</td>
<td>$E_{H_2, primary} = 333 \text{ kWh}$</td>
</tr>
<tr>
<td>Mass $H_2$</td>
<td>$m_{H_2} = 10.0 \text{ kg}$</td>
</tr>
<tr>
<td>Battery size</td>
<td>$C = 59.5 \text{ kWh}$</td>
</tr>
</tbody>
</table>

4.3.1.1 Mission I: missing person

Table 4.11 shows the summary of the results for mission I. A graphical representation of the power curve, the power delivered by the fuel cell and the battery state of charge is given in Figure 4.10.

Table 4.11: Summary of mission I

<table>
<thead>
<tr>
<th>Hybrid electric system</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Delivered energy</td>
<td>$E_D = 170 \text{ kWh}$</td>
</tr>
<tr>
<td>Storage energy</td>
<td>$E_S = 200 \text{ kWh}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ICE system</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Liters, diesel</td>
<td>$L_{cons} = 64.2 L$</td>
</tr>
<tr>
<td>Primary energy, diesel</td>
<td>$E_{diesel, primary} = 623 \text{ kWh}$</td>
</tr>
<tr>
<td>ICE efficiency</td>
<td>$\eta_{ICE} = 30.6%$</td>
</tr>
</tbody>
</table>

Figure 4.10: Results for mission I
One more graph is shown for this mission, Figure 4.11, which shows the consumption of hydrogen. There has to be a control system that does not allow the fuel cell to overcharge the battery: the control set point for the battery state of charge is at 0.95%. This graph is relevant only in this situation, since the battery reaches the set point for a period of time.

Figure 4.11: Results for H₂ consumption for mission I

When the battery reaches a state of charge of 0.95%, the control system should decrease the power delivered by the fuel cell in order to avoid overcharging. The control system is not one of the scopes of the project, and it would need to be studied in a better way. A very simple control has been here simulated: when the battery reaches the set point state of charge, the fuel cell is turned off. The battery then solely provides power to the system. When the control system checks again, the battery is not at the set point anymore. Then the fuel cell is turned on again, and the process repeats until the system demands again maximum power.

This control strategy is not ideal, since it would damage both the battery and the fuel cell. The battery should not be charged and discharged continuously, and the fuel cell should not be turned on and off. A more elaborate discussion on the control system can be found in Section 7.6.1.

This can be seen in Figure 4.11 as a change in gradient of the hydrogen consumption curve. In this case, the consumption of hydrogen is lower than 10 kg, because the fuel cell is not on the entire time of the mission.
4.3. RESULTS

4.3.1.2 Mission II: tow a boat

The summary of the results for mission II are shown in Table 4.12. In Figure 4.12 a graphical representation is shown, showing the power curve, the fuel cell power and the battery state of charge.

Table 4.12: Summary of mission II

<table>
<thead>
<tr>
<th></th>
<th>Hybrid electric system</th>
<th>ICE system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Delivered energy</td>
<td>$E_D = 191 \text{ kWh}$</td>
<td></td>
</tr>
<tr>
<td>Storage energy</td>
<td>$E_S = 225 \text{ kWh}$</td>
<td></td>
</tr>
<tr>
<td>Liters, diesel</td>
<td>$L_{cons} = 64.1 \text{ L}$</td>
<td></td>
</tr>
<tr>
<td>Primary energy, diesel</td>
<td>$E_{diesel, primary} = 568 \text{ kWh}$</td>
<td></td>
</tr>
<tr>
<td>ICE efficiency</td>
<td>$\eta_{ICE} = 30.0%$</td>
<td></td>
</tr>
</tbody>
</table>

Figure 4.12: Results for mission II
4.3.2 Analysis of different energy storage technologies

In Figure 4.13 the different design options are compared in terms of weight. The values of weight of the components have been calculated using the data shown in Section 4.2.

![Comparison between different energy storage technologies](image)

Figure 4.13: Comparison between different energy storage technologies

4.4 Conclusion

From Figure 4.13 it is clear that using a combination of fuel cell and battery technologies is convenient over using a pure battery system. It has to be considered that for the pure battery system the C-rate has not been calculated, hence it is not of unit value. To achieve a C-rate of one, the size of the battery should be different. This aspect has not been tackled since out of scope of the project.

From the figure it is also clear that ICE technology is still convenient in terms of weight, even though the hybrid system with liquid hydrogen storage weight is close to be competitive. In Chapter 6 a life cycle analysis of CO₂ emissions is carried out, focusing on the sustainability aspect.

Comparing the different hydrogen storage technologies and fuel cell technologies, it is apparent how the an hybrid system of PEMFC using liquid hydrogen would be ideal in terms of weight. This comes though with a higher cost and a higher difficulty in providing fuel (since liquid hydrogen is harder to produce than compressed hydrogen). The metal hydride technology weight is in between the hybrid system with 200 bar H₂ storage weight and the hybrid system with 350 bar H₂ storage weight. PEMFC technology is though more mature. In Section 6.3.3.2 a reflection on the availability of hydrogen as fuel is carried out.
4.4.1 Design proposition

The specifications of the final design proposition are shown in Table 4.13. Both the power of the fuel cell and the capacity of the battery are set in the rating of the system.

Table 4.13: Design proposition specifications

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel cell nominal power</td>
<td>75 kW</td>
</tr>
<tr>
<td>Battery size</td>
<td>59.5 kWh</td>
</tr>
<tr>
<td>C rate</td>
<td>1</td>
</tr>
</tbody>
</table>

The type of storage technology has not been chosen, but considering the use of a hybrid storage with hydrogen fuel cells and batteries, the required hydrogen storage is the same for all the technologies and it is of 10 kg. This mass of hydrogen is the required mass that the system needs if the fuel cell nominal power is of 75 kW, and assuming that the fuel cell runs for 160 minutes, the time of all the missions. The 10 kg of hydrogen are not the total weight of the hydrogen storage, because this depends on the hydrogen storage technology, and it can be seen in Figure 4.13.
Chapter 5

Propulsion Unit

In this chapter, a background on both electric machines and water jet systems is given. A methodology for the choice of the entire propulsion unit is presented, with some results of compatible electric machines and water jet systems. A conclusion on the implication of the choices is presented at the end of the chapter.

5.1 Background

Different technologies of electrical machines are presented in this section and the choice of a suitable technology is discussed, considering the requirements of the application. Section 5.1.3 includes rare earth elements and their issues, to show how the choice of materials and technologies influences not only the cost and the efficiency but also the planet and the economy in general. For the water jet, few hydrodynamics theoretical concepts are explained.

5.1.1 Electric machine

Electrical machines are suitable for wide ranges of power and rotational speed. These characteristics make them suitable for diverse applications in almost every industry [72]. Electric machines are essential in the generation, industry and transport sector, providing a cleaner energy usage alternative compared to non-electric actuators.
CHAPTER 5. PROPULSION UNIT

The goal of an electric machine is to convert electricity into mechanical power. When the electric machine is connected to a frequency converter, to control speed and torque, the combination of converter and machine is called electric drive. There are many different alternatives to electric drives: for transport applications, the main alternative is represented by combustion engines. The main advantages and disadvantages of electric drives with respect to combustion engines are listed below [73].

Advantages
- Simple electrical energy supply
- No pollution in the vicinity of the drive
- Limited no-load losses and high efficiency
- Torque can be adapted easily to the requirements of the load
- High starting torque and high power capabilities over the entire range
- Low acoustic noise and low vibration operation

Disadvantages
- Need of a direct connection to the grid or a form of electric energy storage
- Energy density of electric energy storage technologies is lower than the competitive combustion technologies

One more difference worth mentioning is the maturity of technology. ICE is a mature technology, and it is rare to encounter damages to the engine itself. The electric machine is also a mature technology itself, but when looking at the other components, especially the inverter and controller of speed and torque, the reliability is still not proven for all applications, especially automotive ones.

There are two types of motors: AC and DC machines. Within this division, there are different other subdivisions: the main ones are listed below [73].

AC motors
- Induction motor
  - Squirrel cage
  - Wound motor
- Synchronous motor
  - Reluctance
  - Switched reluctance
  - Permanent magnet
  - Brushless DC motor

DC motors
- Brush DC motor
  - Shunt wound
  - Series wound
  - Compound wound
  - Permanent magnet

The type of technology is generally chosen depending on the application, according to the specifications and uses. When looking at propulsion applications, the options that are mostly studied are listed below [74].

- DC motors
- Induction motors
- Synchronous motors
- Switched reluctance motor (SRM)
5.1. BACKGROUND

5.1.1.1 DC motors

The main advantages of choosing DC motors over other types are that the power circuit is simple and inexpensive and the control system is easy to set, with fast responses and wide speed ranges [73]. In propulsion applications, what makes DC motors a valid option is their torque-speed characteristic, which suits traction requirements [74].

Several disadvantages are though present as well. Maintenance is frequently required, due to the use of brushes for powering the rotor circuit. The commutation makes the motor bulky and heavy, having as a consequence a small power to weight ratio. Moreover, DC generation is in general less efficient than AC generation [73].

At low power ratings, when it is not convenient to use an AC drive (used generally for higher power according to the cost of the inverter), DC machines are still used, as in the HEV version of the PSA Peugeot Citroën model Berlingo, called Dynavolt [74].

5.1.1.2 Induction motors

Induction motor (IM) drive is a very mature technology, and is well suitable for electric propulsion due to their reliability, low maintenance, low cost and robustness. Despite being a widely used and mature solution, IM are not the first option due to high losses which bring low efficiency, mainly relevant at higher speeds [74].

To improve induction motor efficiency, different solutions have been proposed.

One of the improvements regards the control system. A suitable and optimized control of torque and speed can increase significantly the efficiency of the drive [75].

Another important change that can improve the energy efficiency regards the materials used for the construction of the motor. The windings inside the stator are usually made of copper, while the rotor bars are made of aluminium, which is easily melted directly inside the motor. This type of construction makes the best combination between a cheap and an efficient solution. A better solution in terms of efficiency, would be using copper in the rotor as well, but it would increase the cost since melting copper requires high temperatures [75].

Other improvements for efficiency are found in better cooling control (in certain temperature zones the efficiency is higher), bearing design, different materials and optimization of the magnetic design [76].

5.1.1.3 Synchronous motors - permanent magnets brushless motors

Permanent magnets brushless motors are widely adopted in propulsion systems. They have several advantages as high power density and high efficiency. At higher speeds, the efficiency may drop and the motor may suffer from demagnetization due to high temperatures or high magnetic field. Their main drawback is that they have a short constant power region, but this can be tackled by controlling the conduction angle of the power converter. This type of control is though not easy [74].
CHAPTER 5. PROPULSION UNIT

The most important characteristic that these machines have is the use of permanent magnets. This represents the reason of their higher efficiency: due to the presence of permanent magnets in the rotor, there is no need for a magnetization current hence there are no losses in the rotor. This brings higher efficiency also considering possibly lower temperatures in the rotor and lower cooling requirements [73][75].

But this key characteristic also represents their main problem, connected to the use of rare earth metals for the construction of the magnets. Section 5.1.3 gives a background on these materials, their usage and their issues.

5.1.1.4 Switched reluctance motor

Switched reluctance motors (SRM) have potential for propulsion applications. They have simple construction and control, fault tolerant operations and an outstanding torque-speed characteristics, making them suitable for an extremely wide power range.

There are several disadvantages as well, which are acoustic noise generation, torque ripple, electromagnetic interference noise generation.

5.1.2 Evaluation of electric machine technologies for HEV

In Figure 5.1, the torque-speed characteristic of electric traction is shown. All the previously mentioned electric engine technologies are adjustable to have a similar torque-speed characteristic, by changing the base speed and designing a suitable the control system. This type of control is achievable thanks to flux weakening strategies.

Figure 5.1: Electric traction torque-speed characteristic

In Zeraoulia et al. paper [74], an evaluation of different technologies is carried out, focusing on the application of hybrid electric vehicles (HEV). The technologies are compared in terms of power density, efficiency, simplicity of control and reliability.
The results of this evaluation are shown in Table 5.1, where the main characteristics of the HEV electric propulsion are graded from 1 to 5 points for each technology, where 5 points means the best [74].

<table>
<thead>
<tr>
<th></th>
<th>DC</th>
<th>IM</th>
<th>PMSM</th>
<th>SRM</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Power density</strong></td>
<td>2.5</td>
<td>3.5</td>
<td>5</td>
<td>3.5</td>
</tr>
<tr>
<td><strong>Efficiency</strong></td>
<td>2.5</td>
<td>3.5</td>
<td>5</td>
<td>3.5</td>
</tr>
<tr>
<td><strong>Simplicity of control</strong></td>
<td>5</td>
<td>5</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td><strong>Reliability</strong></td>
<td>3</td>
<td>5</td>
<td>4</td>
<td>5</td>
</tr>
</tbody>
</table>

From Table 5.1 it can be concluded that, for HEV but in general for the propulsion applications, DC machines are the least ideal. Moreover, one of the main characteristics that makes them unsuitable for the application is the presence of brushes for powering the system [73]. These wear because of mechanical friction and electrical erosion, but the main issue is the occurring of sparks at brush, which brings the risk of commutation failure [76].

From the table, the permanent magnet synchronous machine (PMSM) seems to be the best option especially when focusing on efficiency and power density, given the possibility of conduction angle control. But this has environmental and sustainability issues, as described in next section.

### 5.1.3 Rare earth elements

![Rare earth metals](image)

Rare earth elements (REE) are a group of metals listed in Table 5.2, difficult to find and extract [78]. These metals are key in the production of many products as electric motors, smartphones, military jet engines, batteries, satellites and so on. They are crucial since they have magnetic, heat-resistant and phosphorescent properties, which makes them unique and non-replaceable [77].
First fact that is worth mentioning is that rare earth elements are abundant on the Earth crust: thulium and lutetium are two of the least common rare earth metals, but they have an average abundance which is nearly 200 times greater than the one of gold. Though, they are expensive to extract and there are only few available places where they can be extracted. The biggest mineable rare earth deposit is in China, the country that controls 90% of the global production and supply of REE. The US has only one REE mine in California; other countries where REE mining is possible are Brazil, India, South Africa, Canada, Australia, Estonia and Malaysia. Europe is another possible resource of REE, even enough to secure its own supply, but so far there is no beneficiation and processing method that guarantees sustainable exploitation.

The fact that China has the near-monopoly of REE makes the country powerful: in 2010 China reduced its exports, pushing prices up of 10%. The situation has the potential to easily turn into a trade war between the US and China, since the former relies on the latter exports of REE for 80%.

Adding to the evident political issues, environmental impacts of REE mining are not well known. Waste products, including radioactive chemicals used in the refining process, are often dumped in water near processing facility (Figure 5.3 and Figure 5.4). The biggest mining facility of China is situated in Mongolia, near to Xinguang Village (city of Baotou). Residents of this village, which boil water before drinking it, complain of a white foam formation, which tastes bitter and proves the presence of tailings of crushed minerals in the water.
5.1. BACKGROUND

Figure 5.4: An official from Baotou confirmed in 2010 that companies working in the mine had dumped mildly radioactive tailings into local water supplies, farmland and the Yellow River. Source: Reuters [77]

5.1.4 Water jet systems

The water jet boat was invented in the 1950s by the New Zealander Hamilton [80]. He started experimenting with water jets and with their possible application in marine situations: using a water jet installed in the hull that could use the water surrounding the boat, he was able to achieve the speed of 11 miles per hour (around 18 km/h) [81]. In 1954, the first water jet to be sold, Quinnat (Figure 5.5) had a noisy and unreliable gear, but could propel boats up to 26 miles per hour (around 42 km/h) [82].

Figure 5.5: Quinnat, first HamiltonJet water jet [82]

The decade were jet powered boats spiked was the 70s, with many contributions including well-known companies (Glastron, Formula and Sea Ray) [83]. The typical applications were high performance runabouts, term that generally refers to a small powerboat of around 14-24 foot length (4 m to 8 m) [83].

The main problem came up in the 80s with the fuel shortage: since water jets were about 40% less efficient than conventional propellers, even though they were safer, more reliable and required less maintenance, their production slowed down [83].

During the 90s, improvements in design and materials made the efficiency approach to 90% of the one of propellers. Today’s four leading jet pump manufacturers are Mercury, American Turbine, Kodiak Marine and Hamilton Jet [80].

In 2018, Hamilton Jet released the HTX-30 jet, with new hydrodynamics and refined materials to ensure better performance, more durability and easier installation [81].
CHAPTER 5. PROPULSION UNIT

5.1.4.1 Statistics

When comparing water jets with other boats, the first number worth mentioning is the percentage of jet engines. Figure 5.6 shows that amongst recreational boats in the US, only 3.3% of boats have a jet engine [84]. Outboards are by far the most common, since they are the default choice for many applications. The main reasons why outboards are preferred are that they have an easily accessed position, which allows to lift the engine completely (allowing better storage in winter), and that they can be replaced quite easily. One of the major drawbacks is matching the power need, which might require several outboards, but this is not crucial in smaller boats where the power need is not very high [85].

Figure 5.6: The statistic depicts the share of different propulsion systems amongst recreational boats in the U.S. [84]

5.1.4.2 Water jet hydrodynamics

Water jet propulsion systems are characterized by an inlet, a propulsion unit and a nozzle, as shown in Figure 5.7. The thrust $T$ produced by the system can be calculated as in Equation (5.1) [41], where $\dot{m}$ is the mass flow, $V_{out}$ is the velocity at the outlet, $V_{in}$ is the velocity at the inlet, $\rho$ is the density of water and $A_{out}$ is the area of the nozzle outlet.

$$T = \dot{m}(V_{out} - V_{in}) = \rho A_{out} V_{out}(V_{out} - V_{in}) \quad (5.1)$$

Figure 5.7: Water jet typical structure [86]

In Figure 5.8 the jet efficiency and jet diameter are represented as function of the velocity ratio, defined as $\mu = V_{S}/V_{jet}$ where $V_{S}$ is the velocity of the system (ship). It can
be seen how jet diameter increases with the velocity ratio, while the maximum efficiency occur at $\mu \approx 0.75$. According to this, to achieve high efficiency, a diameter higher than 1.3 m will mean having an efficiency of above 0.6. However, the ship geometry makes limitation for the diameter, therefore the latter is selected based on this main restriction [41].

![Figure 5.8: Jet efficiency and jet diameter as a function of velocity ratio [41]](image)

### 5.1.4.3 Assessment of wake parameter

Since the water jet is located at the stern of the ship, the velocity of the water entering the engine is lower than the ship velocity due to the presence of a hull boundary layer flow. It is important to take this into account since it impacts the optimal functioning of the water jet pump [41].

The boundary layer thickness $\delta$ can be calculated by using Equation (5.2), where $L_x$ is the distance from bow and $Re_x$ is the Reynolds number; accordingly the wake factor $\omega$ can be calculated as it can be seen in Equation (5.6), where $U_m$ is the flow speed at the inlet and $U_\infty$ is the uniform flow velocity. Both $\delta$ and $\omega$ decrease in value as the ship velocity increases, as can be seen in Figure 5.8 [41].

\[
\delta = 0.27 * L_x * Re_x^{-1/6} \quad (5.2)
\]

\[
Re_x = \frac{U_\infty \cdot L_x}{\nu} \quad (5.3)
\]

\[
\frac{U}{U_\infty} = \left(\frac{y}{\delta}\right)^{1/n} \quad (5.4)
\]

\[
n = \log_{10} Re_x \quad (5.5)
\]

\[
\omega = \left(1 - \frac{U_m}{U_\infty}\right) \quad (5.6)
\]

Even though the two parameters are not constant, the value of the wake parameter can be set as 0.9 and considered a constant quantity [41].
5.2 Methodology

After estimating the power need of the boat and designing the energy storage, the electric machine has to be chosen as part of the power train. To choose a suitable machine, different options have been analysed in terms of technology, of peak power and continuous power, of weight and of rotational speed. These values need to match the power requirement of the water jet engine and the specifications of the energy storage system. Hence, after choosing a suitable electric machine, a matched water jet engine needs to be chosen.

As discussed in Section 5.1.2, the most suitable technology for propulsion applications involves the use of permanent magnets to improve efficiency. But as discussed in Section 5.1.3, the issue with REE needs to be tackled, and using a technology that requires use of such materials would go against the sustainability goal of this project.

Since these two aspects are contradictory, the methodology for choosing an electric motor follows two directions. The first is the one of the permanent magnet motors, since it is the most efficient solution and would reduce the energy consumption during the usage of the final product. The second instead explores a different technology, which uses internal permanent magnets that do not require the use of REE.

The requirements that the motor has to satisfy are listed below.

- The nominal power has to be of ca. 120 kW.
- The motor has to be able to deliver nominal power for long periods (> 1h).
- The motor has to have a high power to weight ratio to be as light as possible.

Similarly, for the water jet, the requirements are listed below.

- The nominal power has to be compatible with the power of the electric machine.
- The maximum power input of the water jet needs to be consistent with the maximum power of the electric machine.
- The motor has to be able to deliver nominal power for long periods (> 1h).
- The RPM of the water jet have to match the RPM of the electric machine, or the use of a gear box is needed. In specific, the power - RPM curve needs to lie on the cubic curve \( P = a \cdot RPM^3 \), where \( a \) is a parameter defined by the specification of the water jet engine [87].
5.3 Results

In this section, few models of electric machine and of water jet engine are listed with their specifications.

5.3.1 Electric machine

In this section, the PMSM listed below have been taken into account and compared in terms of specifications.

- Emrax 268
- Emrax 348
- eAxle
- Zytek 170 kW

Moreover, the Lafert Interior Permanent Magnet (IPM) electric motor design is shown, since it does not require the use of REE.

5.3.1.1 Emrax

Emrax is a company that produces axial flux synchronous permanent magnet motors and generators, which have high power density at low cost [88]. Emrax motors are used in a variety of applications, including the marine sector [89].

Their products are divided in two categories, standard electric motors and custom electric motors. Standard motors are developed in five sizes: diameter 188, 208, 228, 268 and 348 mm. They also develop customized electric motors to meet the customers’ requirements [89].

Exploring the five different sizes of the standard motors, the options that could suit the power demand are Emrax 268 and Emrax 348. They come in different options: high, medium or low voltage; air cooled, liquid cooled or combined cooled [90].

In Table 5.3, the characteristics of Emrax 268 and Emrax 348 are shown. When looking at the Emrax 268 specifications, the suitable option in terms of continuous motor power would be the medium voltage combined cooled motor, which provides 110 kW continuous power at 4000 RPM. This motor would have a peak power of 230 kW. In the case of Emrax 348, the suitable option would be the high voltage liquid cooled option, with a continuous power of 100 kW and a peak motor power of 190 kW.

In both cases, the continuous motor power is barely sufficient for the application, since the maximum speed of the boat requires a power of 114.4 kW (Section 3.4), and the boat must run at maximum speed for a longer period of time than the time frame allowed by the peak power. In order to have a suitable continuous motor power, Emrax 348 medium voltage, air cooled could be an option, resulting though in a much higher peak motor power of 290 kW, that cannot be supplied by the current energy storage system.
Table 5.3: Emrax 268 and Emrax 348 technical data table

<table>
<thead>
<tr>
<th>Type</th>
<th>Weight [kg]</th>
<th>Peak motor power [kW]</th>
<th>Continuous motor power [kW]</th>
<th>Voltage [V]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emrax 268</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Medium voltage, combined cooled</td>
<td>20</td>
<td>230</td>
<td>50-110</td>
<td>680</td>
</tr>
<tr>
<td>Low voltage, combined cooled</td>
<td>20</td>
<td>220</td>
<td>50-90</td>
<td>250</td>
</tr>
<tr>
<td>Emrax 348</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High voltage, liquid cooled</td>
<td>40</td>
<td>190</td>
<td>100</td>
<td>800</td>
</tr>
<tr>
<td>High voltage, combined cooled</td>
<td>40</td>
<td>190</td>
<td>100</td>
<td>800</td>
</tr>
<tr>
<td>Medium voltage, air cooled</td>
<td>39</td>
<td>290</td>
<td>140</td>
<td>800</td>
</tr>
</tbody>
</table>

5.3.1.2 Bosh Mobility Solutions

As part of the German group Bosch, Bosch Mobility Solutions develops connected solutions for mobility, for new in-vehicle experiences.

The product that has been analysed in this work is the eAxle, a compact, cost-attractive and efficient modular drive system for battery-electric and hybrid applications. This comes though with modular construction and flexible manufacturing, which does not allow an accurate analysis of the power, dimensions and weight. It has a scalable output power from 50 kW to 300 kW, making it suitable for a wider range of applications. The weight is of approximately 90 kg for a power output of 150 kW, with a maximum speed of 16000 RPM.

5.3.1.3 Zytek

Zytek is an automotive engineering consultancy company, which delivers comprehensive solutions considering the whole life cycle and context in which the product is used. The main business segments are chassis and safety, hybrid and electric vehicle systems, engine management and interior functions.

The most relevant machine produced by Zytek is the 170 kW permanent magnet synchronous machine. Table 5.4 shows the specifications of the chosen motor. The important values in this case are the continuous shaft power, which can vary from 75 kW to 125 kW depending on speed, and the peak power of 170 kW.

Table 5.4: Technical data - 170 kW permanent magnet synchronous machine by Zytek

- Nominal voltage: 350 V
- Peak power: 170 kW
- Continuous shaft power: 75 kW to 125 kW
- Motor mass: 75 kg

Zytek has developed an electric drive package that comprises the PMSM, the control electronics and the integrated gearbox, which is optional. This drive package is suitable for electric and hybrid vehicles, and needs to be supplemented with a vehicle controller and a high voltage battery.
5.3. RESULTS

5.3.1.4 Lafert Group

Lafert Group is an electric motors and drives company, focused on industrial automation, energy saving and wind power. The fundamental aim is to improve performance and energy efficiency, while reducing environmental impact. Since 2003, Lafert Group produces permanent magnet synchronous machines that meet the European efficiency levels of IE4 and IE5 [95].

Lafert Group experts know the issues connected with PMSM and the use of REE. Moreover, by developing PMSM there is the challenge of keeping customers' expectations while REE may be increased in cost in the near future. These are the reasons behind the introduction of an innovative and cost-effective Interior Permanent Magnet (IPM) electric motor, with the use of sensorless control, constructed without the use of REE while keeping IE4 efficiency standards [96].

The main issue with these motors is that they are designed for smaller applications. The maximum nominal power of the IPM motors developed by the company is 22 kW, and weighs 71 kg. Also the power to weight ratio is not ideal [97].

The solution with these kind of motors would be to install six motors (to be able to meet the power requirements) but this would mean having a total weight of 426 kg, only for the motors and not including the connections.

5.3.2 Water jet

The chosen water jet company is Castoldi, considered as an innovator of water jet systems, with a new design that brings a higher efficiency and good manoeuvrability [98]. The products of the company deliver high efficiency at a wide range of high speeds (25 to 60 knots) due to axial flow impellers with the best resistance to cavitation and low impeller shaft, lowering the hydrodynamic losses at high speed thanks to smoother water stream flow [99].

Castoldi products range from low to high power applications. The Turbodrive 224 D.D. is the smaller water jet currently produced by the company, the only model not equipped with an integrated gearbox. This means that the engine needs to be matched directly through the impeller. The engine that matched the desired RPM of the water jet runs at 110 mHP (metric horsepower), which means 81 kW, at 3200 RPM. Other engines can be used as long as their power - RPM curve lies on the same cubic curve [57]. The dry weight of this engine is of 51.5 kg [100].

The other model that could be interesting for this project is the Turbodrive 240 H.C., the smallest water jet available with the integrated gearbox. It is probably the lightest, most complete and efficient water jet of its class on the market [101]. It has an input power up to 309 kW in intermittent duty, and up to 258 kW in continuous duty. The dry weight of the engine is of 130 kg [102].
As it can be seen from Figure 5.9, the maximum power input can very depending on the boat (fast boats are planning boats, while slow boats are displacement boats). Looking at the figure, it seems that the Turbodrive 224 D.D would be the best solution in our case since it supports up to 184 kW in continuous duty. This value is enough for the boat to reach the maximum required speed [103].

![Figure 5.9: Maximum power input for different water jet models][103]

Also as it can be seen in Figure 5.10, the maximum suggested displacement of the turbo drive 224 D.D. in single installation is of 2300 kg. This requirement needs to be taken into account later on in the design of the energy storage [104].

![Figure 5.10: Maximum suggested displacement for different water jet models][104]
5.4 Conclusion

In Table 5.5 the analysed PMSM options for the electric machine have been summarised.

<table>
<thead>
<tr>
<th>Name</th>
<th>Technology</th>
<th>Continuous Power</th>
<th>Peak Power</th>
<th>Max RPM</th>
<th>Voltage</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emrax 268, medium voltage</td>
<td>Axial Flux Synchronous Permanent Magnet</td>
<td>110 kW</td>
<td>230 kW</td>
<td>4700 RPM</td>
<td>680 V&lt;sub&gt;DC&lt;/sub&gt;</td>
<td>20.3 kg</td>
</tr>
<tr>
<td>Emrax 348, high voltage</td>
<td>Axial Flux Synchronous Permanent Magnet</td>
<td>100 kW</td>
<td>190 kW</td>
<td>1800 RPM</td>
<td>800 V&lt;sub&gt;DC&lt;/sub&gt;</td>
<td>40 kg</td>
</tr>
<tr>
<td>Emrax 348, medium voltage</td>
<td>Axial Flux Synchronous Permanent Magnet</td>
<td>140 kW</td>
<td>290 kW</td>
<td>2800 RPM</td>
<td>800 V&lt;sub&gt;DC&lt;/sub&gt;</td>
<td>39 kg</td>
</tr>
<tr>
<td>eAxle</td>
<td>N.A.</td>
<td>N.A.</td>
<td>50-300 kW</td>
<td>16000 RPM</td>
<td>N.A.</td>
<td>ca. 90 kg</td>
</tr>
<tr>
<td>Zytek 170 kW</td>
<td>PMSM</td>
<td>125 kW</td>
<td>170 kW</td>
<td>12200 RPM</td>
<td>350 V</td>
<td>75 kg</td>
</tr>
</tbody>
</table>

As previously discussed, these motors are not ideal from the sustainability point of view since they use REE. The option of internal permanent magnet technology is very promising, but so far the available solutions have low power and do not meet the requirements for power to weight ratio.

The choice of the water jet engine has to be taken with respect to the choice of electric machine. The presented water jet systems are suitable for a wide range of electric machines, depending on the maximum power of the machine and the RPM of the machine, according to the requirements stated in Section 5.2.

Throughout the chapter, different options have been proposed. No final choice has been made in the project, and it is left to further studies because of other type of constraints (sometimes non-technical related) that could appear during the design of a new boat. A promising technology, proposed by Lafert Group, could be an option to avoid the use of rare earth metals, which would be the most sustainable option. For obvious weight reason, it is not suitable with the present power to weight ratio. For better performances in terms of power to weight ratio, a PMSM would be the best solution both in terms of weight and efficiency.

Since the weight requirements are important for this application, and since it would be not possible to install a heavy system such as the IPM machines proposed by Lafert Group in a small boat, one possible solution to avoid the use of REE would be to look beyond the commercially available options, and explore some custom options designed ad-hoc for the application case.
Chapter 6

CO₂ Emissions

In this chapter, the sustainability scope of the project is discussed. Since the project aims at building a sustainable solution for rescue in lakes, a life cycle assessment needs to be carried out. In this way, the estimation of the environmental impact of the boat over the entire life time is possible. Throughout the chapter, the methodology of such assessment is explained, an estimation of the values needed for the assessment is carried out and finally the results are presented, with the related conclusions.

6.1 Life cycle assessment

Life Cycle Assessment (LCA) is a tool for the analysis of the environmental impact of a product, during the whole life cycle (from cradle to grave) [105]. This tool is used to study the impact of different power plants, and can be used for the purpose of this thesis to compare the emissions of different drive trains. In the next sections, the LCA of the different parts of the drive train will be assessed, considering different literature sources.

The LCA of many renewable energy systems looks very different from the LCA of conventional power plants: this difference lies in the fact that the emissions of a conventional power plant are dominated by the fuel production and combustion, while the ones of a renewable system have zero (or close to zero) emissions during the energy conversion. The construction of a conventional power plant counts for only 10% or less when compared to the total emissions on the life cycle, while the one of a renewable energy system becomes dominant [105].
CHAPTER 6. CO\textsubscript{2} EMISSIONS

6.2 Methodology

The scope of this chapter is to compare the emissions of different drive train systems, hence three different cases are proposed for the methodology for the CO\textsubscript{2} emissions calculation, listed below.

- Case 1: use of ICE fuelled by diesel.
- Case 2: use of full battery electric system.
- Case 3: use of hybrid electric system with fuel cells and battery pack.

The methodology used for calculating the CO\textsubscript{2} emissions and hence performing the LCA is the following.

1. For every case, the fixed amount of emissions $\text{Fix}$ due to production and decommissioning is estimated. Different scenarios are considered in some of the cases, due to discrepancies in the data found in literature.
   - Case 1: the only item that needs production and decommissioning is the ICE.
   - Case 2: the items that need to be considered are the battery, the electric machine and the inverter.
   - Case 3: the items that need to be considered are the fuel cell, the battery, the electric machine and the inverter.

2. The emissions per mission $\text{Var}$ as defined in Section 4.2.1 are calculated in every case.
   - Case 1: the data regarding the CO\textsubscript{2} emissions is taken from the online tests review, which includes data of diesel consumption. From this data (consumption in liter per mission), it is straightforward to calculate the emissions per mission, knowing the emissions per liter of diesel consumed.
   - Case 2: the emissions of CO\textsubscript{2} are connected with charging the battery. The value comes from the Swedish electricity grid, and the emissions per kWh can be easily calculated: from those, the data of emission per mission can be calculated as well.
   - Case 3: the emissions will be coming from charging the battery (calculated using the same methodology as Case 2) and from producing hydrogen. The two sub-cases allow to analyse the difference between the current production of hydrogen (which is mainly using fossil fuels) and the production by electrolysis.

3. Knowing both the total fixed amount of emissions (decommissioning and production) and the emissions per mission, a graph can be plotted to compare the different cases. The graph will show on the x axis the number of cycles, which in this case correspond to the typical mission, and on the y axis the tonCO\textsubscript{2eq} emitted.

4. From the graph, it can be easily seen where the different curves of emissions meet in terms of number of cycles, and some conclusions can be drawn.

Not much data is available for the water jet engine, hence it has been decided to leave it out of the analysis. It also has been considered that the water jet is common to all the cases, and would not affect the result of the comparison.
6.3 Estimated fixed and variable emissions

In the following sections, fixed and variable emissions are estimated for every case according to the methodology. Some consideration on the electricity mix influence and the availability of hydrogen as a fuel are also included.

6.3.1 ICE

When considering the diesel engine, it is difficult to find data regarding manufacturing and decommissioning, since the biggest part of the emissions occurs during the usage. For the emissions during the usage of the ICE, two different aspects need to be considered: the well-to-tank emissions, that depend on the origin of the fuel, and the tank-to-wheel emissions, that depend on the fuel itself.

6.3.1.1 Fixed emissions

In Liu et al. analysis, manufacturing of a 213 kW engine produces 4.844 tonCO$_2$ [106]. This would mean, for a 120 kW engine, an equivalent of 2.729 tonCO$_2$. Similar values are found in Kawamoto et al. analysis, where an hybrid vehicle with a 77 kW diesel engine is taken into consideration. In this case, manufacturing of the diesel engine only produces 1.539 tonCO$_2$, which would mean an equivalent of 2.398 tonCO$_2$ for a 120 kW engine. According to Kawamoto et al., decommissioning of diesel engines accounts for only around 5% of the emissions of the manufacturing stage [107]. For the scope of this thesis, the value considered is of 2.5 tonCO$_2$, considering the emissions of a 120 kW diesel engine manufacturing and decommissioning stages.

\[
Fix_{ICE} = 2500 \text{kgCO}_2\text{eq} \tag{6.1}
\]

6.3.1.2 Usage emissions

According to Gode et al. the well-to-tank emissions of diesel fuel are of 0.33 kgCO$_2$eq/L of diesel in Sweden [108]. The tank-to-wheel emissions instead are of 2.68 kgCO$_2$/L of diesel [109]. Summing the two emissions, the value of emissions per liter of diesel can be obtained.

\[
Var_{ICE} = 3.01 \frac{\text{kgCO}_2\text{eq}}{L} \tag{6.2}
\]

6.3.2 Battery pack

When considering the battery pack, it is very important to understand the impact of the battery production, considering that the impact of recharging the battery from the Swedish electrical grid are very low [110]. When comparing the total emissions with the one of an ICE drive train, the difference between the two is that the ICE has a lower production and manufacturing costs, but a high consumption per liter of diesel consumed (hence a higher consumption per mission), while an electrical drive train has much higher emissions in production and manufacturing (considering that it includes an electric motor, a battery and an inverter).
6.3.2.1 Fixed emissions

Looking at different studies on life cycle energy consumption and greenhouse gases emissions from lithium-ion batteries for light-duty vehicles, the first noticeable characteristic is how the results differ one another, as it can be seen in Table 6.1. The explanations for such discrepancies can be summarized as it follows [110].

- The reports are more or less transparent: most articles are non-transparent, with gaps of information.
- The design of the battery might differ, and the material data modelling is not coherent amongst all the articles.
- The analysis might not be done on the same level of depth.
- The electricity mix influences greatly the data (Section 6.3.2.2).

Table 6.1: Studies on electric vehicle battery production emissions

<table>
<thead>
<tr>
<th>Source</th>
<th>kgCO$_{2eq}$/kWh battery</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Message</td>
<td>56</td>
<td>Considers a 30 kWh battery constructed in the EU</td>
</tr>
<tr>
<td>Hao et al.</td>
<td>96-127</td>
<td>Uses China’s electricity mix</td>
</tr>
<tr>
<td>Romare and Dahllof</td>
<td>150-200</td>
<td>Assumes 50-60% of electricity mix based on fossil fuels</td>
</tr>
<tr>
<td>Wiedmann</td>
<td>106</td>
<td>Studies powertrains in Australia</td>
</tr>
<tr>
<td>Dunn et al.</td>
<td>30-50</td>
<td>Uses bottom-up approach, with US electricity mix</td>
</tr>
<tr>
<td>Ellingsen et al.</td>
<td>157</td>
<td>Concludes that with these emissions, for a BEV it may require up to 70000 km to make up the manufacturing emissions</td>
</tr>
<tr>
<td>Kim et al.</td>
<td>140</td>
<td>Concludes that total manufacturing of BEV creates 39% more GHGs than a ICE car</td>
</tr>
<tr>
<td>Peters et al.</td>
<td>110 (average)</td>
<td>Reports the difference based on methodology and chemistry</td>
</tr>
<tr>
<td>Nealer et al.</td>
<td>73</td>
<td>Bases the calculations in US</td>
</tr>
<tr>
<td>Majeau-Bettez et al.</td>
<td>200-250</td>
<td>Combines bottom up with top down approach</td>
</tr>
</tbody>
</table>

According to Table 6.1, the mean value for the emissions is of around 120 kgCO$_{2eq}$ per kWh of battery production.

6.3.2.2 Impact of the electricity mix

The electricity mix of the country of production affects greatly the results of the life cycle analysis, since 45-60% of the emissions come from the manufacturing stage (mainly electricity production). This would lead to conclude that, when assuming manufacturing in Sweden, the emissions could be lower than the standards. [Romare and Dahllof] come to the conclusion that for battery grade material production a most likely value of 60-70 kgCO$_{2eq}$/kWh can be assumed, while for manufacturing a value of 70-110 kgCO$_{2eq}$/kWh [Romare and Dahllof] also consider the raw material mining and refining, 18-50 kgCO$_{2eq}$/kWh and the recycling, 15 kgCO$_{2eq}$/kWh [110]. All these calculations come to a mean value of ca. 200 kgCO$_{2eq}$/kWh.

\[
Fix_{BAT, pessimistic} = 200 \times \frac{kgCO_{2eq}}{kWh}
\] (6.3)
6.3. ESTIMATED FIXED AND VARIABLE EMISSIONS

Romare and Dahllöf assume 50 to 60% of electricity mix based on fossil fuel, meaning that the emissions would be reduced of a half by assuming production in Sweden since the electricity mix of the latter is 94% low carbon emissions [120]. Assuming that the manufacturing is done in Sweden and that the electricity mix is almost 100% low carbon emissions, a value of 100 kgCO$_{2eq}$/kWh can be assumed for production and recycling [120]. This has also been confirmed to be a suitable value by some players in the industry, whom also state that in the future it is expected that the battery production emissions could potentially decrease to 20 kgCO$_{2eq}$/kWh, when improving recycling at maximum and using recycled material as input [121].

\[
Fix_{BAT,\text{current}} = 100 \frac{kgCO_{2eq}}{kWh} \quad (6.4) \\
Fix_{BAT,\text{optimistic}} = 20 \frac{kgCO_{2eq}}{kWh} \quad (6.5)
\]

In this analysis, only values from Equation (6.4) and (6.5) are used, since the project is based in Sweden and since the pessimistic value refers to a global manufacturing with a poor renewable electricity mix.

6.3.2.3 Usage emissions

Assuming that the battery will be recharged in Sweden, the usage emissions of the battery are measured in kgCO$_{2eq}$/kWh of charging. The value of emissions reflects the value of the electrical grid of Sweden, which is of ca. 40 gCO$_{2eq}$/kWh. This value does not vary based on the scenario, since in Sweden it is almost constant over time.

\[
Var_{BAT} = 0.04 \frac{kgCO_{2eq}}{kWh_c} \quad (6.6)
\]

6.3.3 Fuel cell stack

When looking into fuel cells, few LCA studies evaluating their environmental advantages can be found in literature. This section will be divided into the estimation of the emissions during the production and decommissioning of the fuel cell, and the estimation of the emissions due to the production of the fuel (hydrogen).
6.3.3.1 Fixed emissions

Pehnt investigated the PEMFC production and decommissioning, concluding that the environmental impact should not be neglected. Pehnt considered different scenarios \[105\], as can be seen in Table 6.2.

<table>
<thead>
<tr>
<th>Context</th>
<th>Electricity for production</th>
<th>Recycling of Platinum Group Metals</th>
<th>kgCO\textsubscript{2eq}/kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Context 1</td>
<td>German mix</td>
<td>No recycling of PGM</td>
<td>61</td>
</tr>
<tr>
<td>Context 2</td>
<td>Hydropower</td>
<td>No recycling of PGM</td>
<td>41</td>
</tr>
<tr>
<td>Context 3</td>
<td>German mix</td>
<td>75% of PGM recycling</td>
<td>43</td>
</tr>
<tr>
<td>Context 4</td>
<td>Hydropower</td>
<td>75% of PGM recycling</td>
<td>22</td>
</tr>
</tbody>
</table>

For the scope of this analysis, hydropower has been taken into account as source of electricity for production, considering that the electricity mix of Sweden is 94\% low carbon emissions \[120\]. Hence, the considered value for current scenario of emissions of the fuel cell stack production and decommissioning is of 41 kgCO\textsubscript{2eq}/kW, where recycling is not considered as an option. For the optimistic scenario, a value of 22 kgCO\textsubscript{2eq}/kW is taken, with 75\% recycling of platinum group metals \[105\].

\[
Fix_{FC,\text{current}} = 41 \frac{\text{kgCO}_2}{\text{kW}} \tag{6.7}
\]

\[
Fix_{FC,\text{optimistic}} = 22 \frac{\text{kgCO}_2}{\text{kW}} \tag{6.8}
\]

6.3.3.2 Availability of hydrogen

Nowadays, fuel cell applications are also restricted in terms of availability of hydrogen as a fuel. Currently, Sweco is proposing different implementation plans at national and European level. One of the projects includes the installation of hydrogen fuelling stations in Stockholm and Gothenburg \[122\].

Wallmark et al. report, developed for the Region Östergötland, gives arguments for possible production, distribution and use of hydrogen in 2030, with an outlook to 2050. The analysis of the potential for hydrogen production is based on previous experience of the authors, whom have worked in the field of hydrogen and fuel cells, and is based on a literature review of available production methods and their maturity \[123\].

The main drivers for hydrogen production for transport are the increasing production potential, the possibility to increase the proportion of EV without local emissions introducing hydrogen as storage instead of batteries, and the flexibility that hydrogen production may offer as storage. The main argument is the life cycle cost of production and distribution of hydrogen, which is high compared to current alternatives. This difference in cost will be likely less in 2030, but it is hard to specify the size of the market especially when the battery market sees rapidly falling prices \[123\].
6.3.3.3 Usage emissions

The main technologies used for producing hydrogen are steam methane reforming, partial oxidation of oil and coal gasification, which account for about 96% of the global production, as shown in Figure 6.1 [124].

In Figure 6.2 a comparison of the emissions in kgCO$_2$eq per H$_2$ production between electrolytic and non-electrolytic technologies is shown. The red line shows the variation of the values depending on different sources. The values for coal gasification appear to be of ca. 11 kgCO$_2$eq, as the values of steam natural gas reforming. The only value shown for oil refers to steam reforming of vegetable oil, which seems to have lower emissions of around 5 kgCO$_2$eq/kgH$_2$.
CHAPTER 6. CO₂ EMISSIONS

Office of Air and Radiation report on hydrogen production provides a value of 8.62 kgCO₂eq/kgH₂ for the production of hydrogen globally.

For this analysis, a current value of 9 kgCO₂eq/kgH₂ will be considered.

\[
Var_{FC, current} = \frac{11 \text{ kgCO}_2\text{eq}}{\text{kgH}_2} \quad (6.9)
\]

For an optimistic scenario, electrolysis is assumed as only method of fuel production. From Figure 6.2, a value for the electricity mix of Sweden can be assumed, considering that the share of renewable energy systems summed with the share of nuclear power reaches 94% of the electricity consumption in Sweden [120]. The values for wind, solar thermal, solar PV, nuclear and hydro are all around 2-4 kgCO₂eq/kgH₂. The value taken into account in this thesis project will therefore be of 3 kgCO₂eq/kgH₂.

\[
Var_{FC, optimistic} = \frac{3 \text{ kgCO}_2\text{eq}}{\text{kgH}_2} \quad (6.10)
\]

6.3.4 Electric machine and inverter

In Orlova et al. article, three motor types have been taken into account: synchronous reluctance motor (SynRM), permanent magnet assisted synchronous reluctance motor (PM-SynRM) and induction motor (IM). In the analysis, motors with rated power of 10 kW and weight of around 70 kg have been considered. The results of the analysis is a value of around 442, 490 and 550 kgCO₂eq respectively for SynRM, PMSynRM and IM, considering production, distribution and decommissioning [127]. According to Kawamoto et al., the production of an electric machine of 100 kW is of 1070 kgCO₂eq, not considering decommissioning. The value considered for this analysis will be of 1350 kgCO₂eq, considering a motor of 120 kW and taking into account decommissioning emissions of around 5% of production emissions [107].

An additional emission factor that needs to be taken into account is the inverter, which accounts for around 650 kgCO₂eq [107].
6.3.5 Summary of values

In Table 6.3, the list of all the values considered for the different cases and scenario is shown.

Table 6.3: Summary of values used for the CO\textsubscript{2} assessment

<table>
<thead>
<tr>
<th>Case 1 - ICE</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixed emissions, ICE</td>
<td>2500 kgCO\textsubscript{2eq}</td>
<td></td>
</tr>
<tr>
<td>Usage emissions, diesel fuel</td>
<td>3.01 kgCO\textsubscript{2eq}/L</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Case 2 - Full battery system</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixed emissions, battery, \textit{current}</td>
<td>100 kgCO\textsubscript{2eq}/kWh battery</td>
<td></td>
</tr>
<tr>
<td>Fixed emissions, battery, \textit{optimistic}</td>
<td>20 kgCO\textsubscript{2eq}/kWh battery</td>
<td></td>
</tr>
<tr>
<td>Fixed emissions, electric machine</td>
<td>1350 kgCO\textsubscript{2eq}</td>
<td></td>
</tr>
<tr>
<td>Fixed emissions, inverter</td>
<td>650 kgCO\textsubscript{2eq}</td>
<td></td>
</tr>
<tr>
<td>Usage emissions, electric grid</td>
<td>0.04 kgCO\textsubscript{2eq}/kWh</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Case 3 - Hybrid fuel cell and battery system</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixed emissions, battery, \textit{current}</td>
<td>100 kgCO\textsubscript{2eq}/kWh battery</td>
<td></td>
</tr>
<tr>
<td>Fixed emissions, battery, \textit{optimistic}</td>
<td>20 kgCO\textsubscript{2eq}/kWh battery</td>
<td></td>
</tr>
<tr>
<td>Fixed emissions, fuel cell, \textit{current}</td>
<td>41 kgCO\textsubscript{2eq}/kW fuel cell stack</td>
<td></td>
</tr>
<tr>
<td>Fixed emissions, fuel cell, \textit{optimistic}</td>
<td>22 kgCO\textsubscript{2eq}/kW fuel cell stack</td>
<td></td>
</tr>
<tr>
<td>Fixed emissions, electric machine</td>
<td>1350 kgCO\textsubscript{2eq}</td>
<td></td>
</tr>
<tr>
<td>Fixed emissions, inverter</td>
<td>650 kgCO\textsubscript{2eq}</td>
<td></td>
</tr>
<tr>
<td>Usage emissions, electric grid</td>
<td>0.04 kgCO\textsubscript{2eq}/kWh</td>
<td></td>
</tr>
<tr>
<td>Usage emissions, hydrogen, \textit{current}</td>
<td>11 kgCO\textsubscript{2eq}/kgH\textsubscript{2}</td>
<td></td>
</tr>
<tr>
<td>Usage emissions, hydrogen, \textit{optimistic}</td>
<td>3 kgCO\textsubscript{2eq}/kgH\textsubscript{2}</td>
<td></td>
</tr>
</tbody>
</table>

6.4 Conclusion

Figure 6.3 shows how the different systems compare with each other in terms of tonCO\textsubscript{2eq} emitted per cycle, which in this case represents one typical mission as defined in Section 4.3.1.

In the figure, the blue line represents the pure battery CO\textsubscript{2eq} emissions using current values, while the blue dotted line reference values are the optimistic ones. The ICE CO\textsubscript{2eq} emissions are represented with the black line, and for these there is no current or optimistic scenario. The purple line represents the hybrid electric system CO\textsubscript{2eq} emissions using current values, the purple dotted line using optimistic values.

In the figure, it is clear how the ICE fixed cost in terms of emissions is very low compared with all the other systems. The highest fixed cost is the one of the pure battery system in the current scenario. In the optimistic scenario, a very low value of fixed CO\textsubscript{2eq} emissions is used for the battery production and decommissioning. In this case, the emissions would be very low over the entire lifetime of the boat, since the variable CO\textsubscript{2eq} emissions of the pure battery system are the emissions coming from the usage of the Swedish electrical grid, which are amongst the lowest in the planet.
An interesting analysis that can be carried out looking at the figure regards the intersection points. For example, comparing the ICE line with the hybrid current line, it can be seen that for the first ca. 130 cycles the ICE system remains an advantage when comparing the total CO$_{2eq}$ emissions. Once surpassed the 130 cycles, since the variable ICE emissions are substantially higher than the hybrid variable ones, the latter becomes convenient in sustainability terms. When looking instead at the hybrid optimistic value, it can be seen that the intersection happens in the first few cycles, becoming immediately convenient.

Similarly, a comparison between the ICE system and the pure battery systems can be pointed out, concluding that only after ca. 160 cycles the current pure battery system becomes more sustainable. With optimistic values, the change happens in the first 40 cycles.

Comparing the hybrid current and optimistic lines, it can be seen that the difference in gradient is quite significant. This is because of the different technologies of production of hydrogen.

In conclusion, the issue that affects the most from the sustainability point of view is the impact of the battery production and decommissioning, which is incredibly high when compared with the ICE system fixed value. The other issue is the production of hydrogen, that can affect greatly the variable emissions of the hybrid electric system. The battery production and decommissioning problem would be solvable only using a different technology or encouraging a more sustainable production and an environmental awareness during decommissioning. It is important to consider also the place of production and the general cost of such batteries. The hydrogen production issue is instead something that can be tackled from a governmental point of view, encouraging the production using renewable energies in loco or providing a reliable hydrogen supply. Since this change, according to Wallmark et al. [123], should be included soon in the government plans, it is more plausible that would happen first.
Chapter 7

Conclusion

In this conclusive chapter, few salient points are extracted from each chapter, summarizing the project. Moreover, some hints for future work and studies are presented.

7.1 The project

*Sjöräddningssällskapet*, the most relevant SAR association that performs in Swedish waters, has started this project of designing an electric rescue boat for the station of Smedjebacken, with as main goal introducing sustainability in the rescue sector.

From the literature review the most important finding is that no existing fast boat powered by a combination of fuel cell and battery has been yet developed. The technology exists and it is ready; it is a matter of rating the system and finding out the possible drawbacks.

The research question becomes whether it would be feasible to combine fuel cell stacks and battery packs to provide power to a small boat, especially in terms of weight and CO$_2$ emissions. Hence, a comparative analysis is carried out, considering as competitive technologies an ICE drive train layout and a battery only drive train solution.

7.2 Boat drive train modelling

To calculate the required power for an application, a study on different online tests has been carried out. The chosen boats are powered by a water jet diesel engine. The specifications of the boat and the engine mounted are known, but the propeller power curve is not available, hence it has been estimated theoretically. The tests show the relation engine RPM-boat speed, that combined with the propeller power curve gives the required power-boat speed. Also the relation consumption-boat speed is taken from the tests. A theoretical calculation has also been carried out, and it matches with the empirically retrieved data.
7.3 Energy storage

For the design of the energy storage system, different options have been taken into account. These are five hybrid fuel cell and battery systems (which differ in technology or in hydrogen storage means), two pure battery systems and the ICE system. To compare them in terms of energy consumption, three missions have been assumed in theory, with their speed profiles. From the speed profiles, both power and consumption profiles have been obtained.

For all these systems, the storage energy that is required to complete the mission has been calculated. For the hybrid electric system, the power of the fuel cell and the rating of the battery have been chosen thanks to an optimization code, which minimises the weight. The results are that the hybrid electric system is convenient in terms of weight over a pure battery system. ICE technology is still the lightest, even though the hybrid electric system with PEMFC and liquid hydrogen storage is close to be competitive.

A design has been proposed in terms of fuel cell power and battery capacity. The type of storage technology has not been chosen, but considering the use of PEMFC the mass of hydrogen needed has been calculated.

7.4 Propulsion unit

The propulsion unit has to be chosen to comply the requirements of the application. Since the torque-speed characteristic of electric traction can be provided by DC machines, IM, PMSM or SRM, these are compared in terms of power density, efficiency, simplicity of control, reliability and sustainability. DC machines are not reliable because of the brushes used for powering the system. PMSM seem to be the best option especially for their high power to weight ratio, but they present environmental and sustainability issues due to the rare earth elements that can be found in the magnets. A reflection on their extraction concludes that these elements make PMSM not a suitable option from the sustainable and economical point of view.

The type of water jet has been chosen within Castoldi company engines. Few options are presented in terms of power and maximum displacement, and are suitable for a wide range of electrical machines, depending on their maximum power and RPM.

No final choice is proposed for neither the electrical machine or the water jet engine, since both the weight requirements and the sustainability goals have to be met in this project. One possible solution would be to look beyond the commercially available options and explore some custom options designed ad-hoc for the application case.
7.5 CO₂ emissions

A sustainability analysis has been carried out in terms of CO₂ emissions. The methodology is a life cycle assessment aimed at analysing the environmental impact of the product during the whole life cycle, from cradle to grave. Three drive trains are compared in terms of emissions: a diesel ICE drive train, a full battery electric drive train and the hybrid electric drive train analysed in this project. The calculation of the emissions is divided into fixed emissions coming from each of the components of the drive trains, which occur only once and include production and decommissioning, and usage or variable emissions, which occur per cycle (or mission). The conclusions of this analysis are that, with the current battery production technology, the fixed emissions make the full battery system not competitive in terms of emissions: the battery only system would become convenient in terms of emissions after ca. 160 cycles. The hybrid electric system is a bit more competitive since it becomes convenient in terms of emissions after ca. 110 cycles. These number consider the current production of hydrogen, which is mainly based on fossil fuels, and can be considerably improved with production of hydrogen via electrolysis.

7.6 Future work

This thesis project aims at being a reference for further works in this field, proposing a rating methodology and a technology that is proven to be suitable for high speed small boat applications. In the next sections, few other subjects are introduced for further studies.

7.6.1 Control system

The control system is one of the most important component of a drive train. Especially in this case, where a mean of control is needed both in the energy storage system and in the electric drive. In fact, the electric machine needs to be controlled in terms of torque and speed, and the energy storage system needs another type of control, that involves both the fuel cell stack and the battery pack. The fuel cell is optimized to work at constant power, and it suffers when turned on and off frequently. Similarly, the battery pack should not switch from giving power to receiving power too often. For example, if the battery is completely charged because the boat is running at low speed, the fuel cell instead of switching off should adapt its power to the application power, and the battery should be disconnected from the system until the required power from the system goes above the fuel cell power again. Another option could be, when the battery is charged and the required power is lower than the fuel cell power, to turn off the fuel cell until the battery state of charge reaches a certain set point.

These different options have not yet been explored, and a simple control is assumed in all the missions, which turns on and off the fuel cell to maintain the same battery state of charge.
7.6.2 Coupling of the propulsion system with the energy storage system

The power output of the energy storage system needs to be enough for the electric machine. So far, the energy storage system has been modelled looking at the consumption of the water jet tests available online. The output power of the energy storage system is enough to bring the boat at the speed requested by the profiles, but does not consider that the chosen electric machine maximum power might be higher. These considerations should be also taken into account when designing the storage system.

7.6.3 On board equipment

The electric power supply needs not only to ensure boat speed through the propulsion system but also the operation of all on board equipment and services. The energy availability should derive from the expected consumption of such equipment and services: there must be a power provision sufficient for full load operations \cite{128}. Full load operations are defined as a condition where the ship is moving at full speed with all the equipment and services turned on, at maximum power. This is the highest required power that the system undergoes.

Based on the full load power, in cruise ships both an incremental coefficient for possible increase of loads and a safety margin are applied. In such large ships, by controlling the generation side, it is possible to keep frequency and voltage constant even at varying loads \cite{128}. These ships have many required systems for safety and comfort, while the designed boat would need less equipment. The mandatory or recommended (especially for rescue boats) electric equipment and services are listed below \cite{129}.

- Navigation lights
- Maritime radio, transmitting-receiving system
- Satellite telephone
- Global Positioning System (GPS)
- Radar

Most of these systems are also available with a separate battery, that needs to be charged independently. They could be though easily included in the count for the total load. These would increase the total required power, that would make the required storage energy larger.
Bibliography


BIBLIOGRAPHY


Statista. (2013, jun) What type of propulsion does your boat have?

[86] Chegg Study. A jet ski (figure 3-a) propels itself through the use of a pump. [Online]. Available: https://d2vcm617u1fs.cloudfront.net/media%2F1fd%2F1fdca860-4feb-4312-a377-07757db5a5a6%2Fphp3Q7pVi.png 


[128] ABB SACE, “Generalities on naval systems and installations on board,” ABB s.r.l., 24123 Bergamo - Italy, Technical Application Papers No 12, 2015. [Online]. Available: https://library.e.abb.com/public/25475ee5b1f648cfb22f1cd259968d4718DC007111G0202.pdf?x-sign=3r7iRNAcNkUJAoDwwXh+9kDpOhlBEg4XGA/7fgFY2cVUp7GqmnZlOGGt4/7iC/
