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Practical Application Limits of Fuel Cells and Batteries for Zero Emission Vessels

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Practical Application Limits of Fuel Cells and Batteries for Zero Emission Vessels

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Abstract

Batteries and hydrogen fuel cells provide zero emission power at the point of use. They are studied as an alternative powerplant for maritime vessels by considering 14 case studies of various ship sizes and routes varying from small passenger vessels to the largest cargo ships.

The method used was to compare the mass and volume of the required zero emission solution to the available mass and volume on an existing vessel considering its current engine and fuel storage systems.

The results show that it is practically feasible to consider these zero emission technologies for most vessels in the world's fleet. Hydrogen fuel cells proved to be the most capable while battery systems showed an advantage for high power, short duration missions. The results provide a guide to ship designers to determine the most suitable types of zero emission powerplants to fit a ship based on its size and energy requirements.

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- Red and White Fleet, especially Joe Burgard
- Staci Dorsey
- MAC Program

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I thank John for bringing his dedication, professionalism, curiosity, and critical thinking to this project. For jumping in with both feet and having some fun in the process. And especially for his current and future service to our country.

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CONTENTS

FIGURES

TABLES

EXECUTIVE SUMMARY

As the demand for fossil fuels continues to increase in our ever industrializing world, these nonrenewable resources will begin to deplete and prices will rise. At the same time, burning fossil fuels produces greenhouse gases (GHGs) and pollutes the air in our atmosphere. Pollution on the level seen in large cities like New York and Shanghai pose a threat to the air we breathe and changes the climate across the world. One major consumer of fossil fuels is the marine industry. Whether it is a fishing vessel off the coast of Alaska or a container ship that steams from Los Angeles to Singapore, the whole industry is dependent upon fuels like diesel and heavy fuel oil. This reliance will not decrease if nothing is done to create a reliable, cleaner source of energy.

Among the various clean sources of energy, fuel cells and batteries stand out as possible solutions. Fuel cells powered by either liquid hydrogen (LH_2) or compressed hydrogen gas, and batteries are currently commercially available and are scalable to high powers. This study seeks to determine the limits of scaling today's commercially available technology to maritime vessels considering 14 case studies of various ship sizes and routes. Vessels varied from small fishing vessels and passenger boats on limited routes to the largest cargo ships in the world travelling across the oceans.

The method used was to take the specifications of different commercially available fuel cell, hydrogen storage systems, and battery systems and analyze the trends to predict the mass and volume of possible replacements of internal combustion engines (ICEs). Then, limits on how big the overall systems can be were set based the currently available engine and fuel volume and mass on the studied vessel. The results were examined individually and as a whole to look for commonalities and trends.

The results showed that all but one of the fourteen vessel case studies can be practically powered by a zero emission fuel cell or battery power plant. The fuel cells proved to be the most versatile and the LH_2 fueled fuel cell more so than the 5000 psi. Batteries provided interesting results. They were only possible on the smaller ships and could only provide enough energy to travel one trip. On top of that, in one case they were shown to be more effective than hydrogen fuel cells on vessels that have short voyages but require a relatively high amount power.

The limiting factor in all cases was not power generation or energy storage of the technology itself but rather available volume. The results of all case studies were compiled to provide a guide to ship designers to determine early the most suitable types of zero emission powerplants to fit a ship based on its available volume or displacement and the energy requirements of its routes.

Ultimately, this was a high level study that uses several approximations, and requires further research to make concrete claims. However, the results show that it is practically feasible to consider zero emission technologies for most types of vessels in the world's fleet.

NOMENCLATURE

B	Beam
Cb	Block coefficient
E_A	Activation Energy
FC	Fuel Cell
GHG	Greenhouse Gas
HFO	Heavy Fuel Oil
ICE	Internal combustion engine
IFO	Intermediate Fuel Oil
IMO	International Maritime Organization
LF	Load Factor
LH_2	Liquid Hydrogen
LHV	Lower Heating Value
LOA	Length Overall
MARAD	[U.S.] Maritime Administration
MCR	Maximum Continuous Rating
MDO	Marine Diesel Oil
MT	Metric ton (1,000 kg)
NOAA	[U.S.] National Oceanic and Atmospheric Administration
PE	Potential Energy
PEMFC	Proton Exchange Membrane Fuel Cell
Pt	Platinum
R&D	Research and development
SOA	Speed of Advance
T	Draft
TEU	20 foot equivalent unit

1. INTRODUCTION AND BACKGROUND

1.1. Background of the Present Problem

Air emissions including greenhouse gases (GHGs) and criteria pollutants are affecting environments around the world, from smoggy skies in Beijing to the melting of the polar ice caps. Large portions of these GHGs, such as carbon dioxide (CO_2), come from burning different types of fuel in cars, ships, planes, and power plants. The massive containerships that steam across the oceans burn tons of fuel per day. However, ships are vital to global trade, provide jobs and transportation, and support offshore industries such as fishing.

Figure 1.1 illustrates the potential increase in maritime-related carbon dioxide emissions if nothing is done over the next few decades. As the need to eliminate GHG emissions increases, the maritime industry will face pressure to reduce their carbon footprint. Recently, the automotive, aerospace, and energy production industries have begun implementing ways of producing clean, zero emission energy; the maritime industry lags behind in that development. One possible solution for the maritime industry is to consider zero emission technology such as hydrogen fuel cells and batteries. As fossil fuels become scarcer and more expensive the urgency of finding a solution continues to increase.

1.2. Objective

The objective of this study is to determine the best role for batteries and fuel cells in realizing a wide range of zero emission marine vessels. The driving questions behind this objective are:

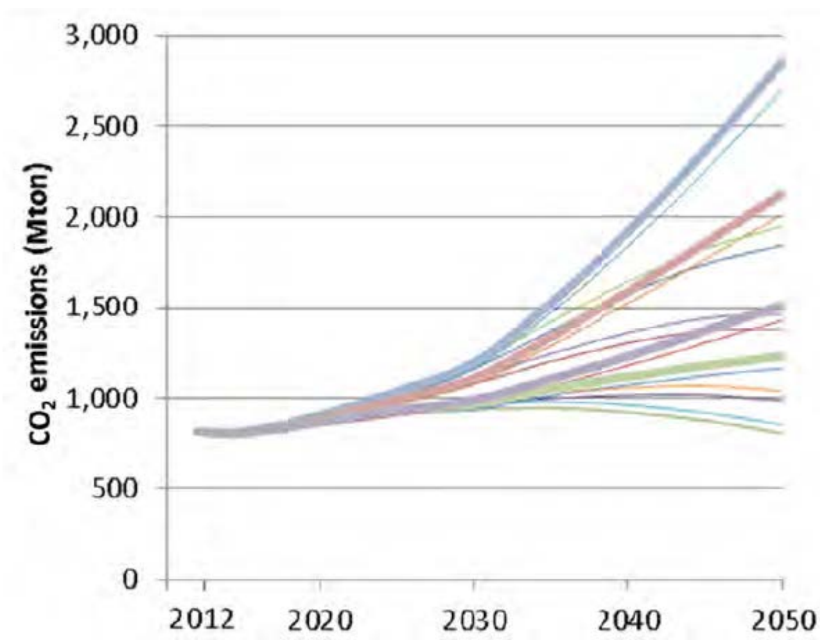

Figure 1.1 Predicted maritime CO_2 Emissions over the next three and a half decades: The top lines illustrate what could happen if nothing is done to reduce emissions; the bottom lines illustrate result of a 60% efficiency improvement and use of non-fossil fuels. [1]

[1] Figure 14 from "Third IMO GHG Study 2014 – Final Report," International Maritime Organization.

- Which marine vessels can battery-only systems power and which ones require hydrogen fuel cells using today's commercially-available technology?
- Is there a limit to the power and energy demand hydrogen fuel cells can support with today's commercially-available technology?
- In the aim to reduce the emission of (GHG) by marine vessels, what is the best role for batteries and hydrogen fuel cells in the propulsion plants of marine vessels?

This study will attempt to answer those questions to the fullest extent possible.

1.3. Method Overview

Determining definitive generalizable limits for zero emission technology on maritime vessels is an impractical goal. It would require generating vessel plans for the entire design space of the tens of thousands permutations of vessel types and missions encountered in the world today and evaluating the feasibility of each.

The intent of this study is not to provide definitive limits, but rather to provide a rough guide to the areas in the design space which appear to have higher or lower potential for zero emission technology adoption. With this information, areas that appear favorable can be examined in more detail for near-term deployment efforts, while areas that appear impractical with today's technology can help define development goals for future deployments.

With this more modest goal in mind, rather than examining all possible vessel combinations today, we can drastically reduce the work required by carefully selecting just a few types in use today as representatives of the larger design space. Furthermore, rather than conducting a full design of each of these vessels, we select a specific vessel in service today and perform a simple comparison of power and energy requirements based on overall mass and volume specifications.

The results provide vessel designers with an easy-to-use method to quickly estimate suitability of zero emission battery and hydrogen fuel cell power systems for a wide variety of marine vessels.

1.3.1. Battery and Fuel Cell Information

Determining the application of batteries and fuel cells begins with understanding how both batteries and fuel cells operate. The process of calculating the approximate mass and volume fuel cell and battery power plants on marine vessels requires compiling data on fuel cell and battery systems that are commercially available today. It is important that the calculated power plants accurately represent commercially available technology to illustrate the practical potential of these clean energy systems today.

Specifications needed for battery systems are the dimensions, volume, energy storage capacity, and mass. Not all of those pieces of information were available from every source, so using other specifications such as energy density and specific energy it is simple to calculate the mass and volume. Ultimately, the information captured for each battery system includes manufacturer, model, distinguishing features, energy storage, volume, mass, specific energy, energy density, and whether or not it was a system or module.

After the battery data were found, hydrogen fuel cell data were compiled in the same manner. However, fuel cells require an energy storage system, i.e. hydrogen fuel tank, so the calculations require both the fuel cell system and storage specifications. Similar to batteries, the specifications compiled for all fuel cells were as follows: manufacturer, model, power output, volume, mass, specific power, power density, and outfit type (system or module).

As a point of clarification, for both the batteries and the fuel cells the mass and volume is significantly greater for systems rather than the single module itself (specific energy/power and power/energy density values were much smaller). Therefore, it is important to note whether the specifications were of the system or module model. Data on fuel cell and battery systems are summarized in section 2.1.4 and 2.2.4.

1.3.2. Vessel Case Studies

We selected 14 vessels covering a range of sizes and routes to use as case studies. In each case study several characteristics are used including vessel name, vessel type, Length Overall (LOA), Draft (T), Beam (B), main engine power, max speed, IMO number, a sample voyage length, total voyage time, average voyage speed (SOA – speed of advance), and energy required for voyage. Using various sources of vessel data, the different case studies were compiled. Vessel physical characteristics were used to estimate a maximum mass and volume limit for the powerplant and fuel. No vessel re-design was considered; all case studies used existing layouts.

From there one of the zero emission powertrains was sized to meet one voyage or “trip” using energy storage characteristics of the battery system. The mass and volume of this system was compared to the available mass and volume limit calculated for the vessel. If the zero emission system fit within these limits, the number of trips was incremented by 1 and the process repeated until it no longer fit within the limits.

1.3.3. Engine Specifications

The limits are one of the most important parts of this study and setting an accurate limit for each vessel is essential to the validity of the data produced by the study. Therefore, to determine the limits on the mass and volume of the battery and fuel cell power plants, the mass and volume of the conventional power plants are needed. Similar to the fuel cell and battery data, the specifications of each engine are manufacturer, model, rated power output, volume, mass, power to weight ratio, and fuel consumption. From there charts of Power vs. Mass, Power vs. Volume, and Fuel Consumption vs. Power were used to develop trend lines that could then be used to find mass, volume, and fuel consumption of all vessels’ engines based on their power output even when specific engine data were not available.

1.3.4. Units

Many of the sources consulted for battery specification, fuel cell specifications, and vessel case studies provided information in different units. In order to universalize all the units for ease of calculations and conceptualization all units are in SI: Kilograms (kg) and metric tons (MT) for mass, kilowatts (kW) and megawatts (MW) for power, kilowatt-hours (kWh) and megawatt-hours (MWh) for energy, meters (m) and millimeters (mm) for length, and cubic meters (m^3) for volume.

2. FUEL CELLS, HYDROGEN, AND BATTERIES

This chapter gives brief background of each technology and includes the data used to determine the size and weights of these zero emission powerplant options.

2.1. Fuel Cells

2.1.1. Why fuel cells?

Fuel cells are means of producing zero emission power and can have a major impact in the transportation world. Already, some automotive manufactures have developed fuel cell powered cars and buses; however, the marine industry is also a potential application for fuel cells. Throughout history, ships have used almost all types of energy available, from raw human power with oars during the early days of maritime exploration, to wind in the age of sail, to fossil fuels after the industrial revolution exploited the steam engine. Today, fossil fuels are becoming more and more expensive while becoming scarcer across the globe. They also produce excessive amounts of pollution, causing the skylines to fill with smog, thus endangering the prosperity of not only the animal species that inhabit the Earth, but humans as well. In order to replace fossil fuels, alternative power sources must replace the vastly prevalent use of internal combustion engines (ICEs) that rely on fossil fuels for energy. One technology that challenges ICEs is hydrogen powered fuel cells – a clean source of power that utilizes gas or liquid hydrogen to produce electrical energy capable of powering homes, cars, and maritime vessels.

2.1.2. What is a fuel cell and how does it work?

This section and the following section, 2.1.3, are an adaptation of Chapter 1 of *Fuel Cell Systems Explained* by James Larminie and Andrew Dicks[2] and Chapter 3 of a *Feasibility of the SF-BREEZE: a Zero-Emission, Hydrogen Fuel Cell, High-Speed Passenger Ferry* by Joseph Pratt and Leonard Klebanoff.[3] On a basic level, a fuel cell is an electrochemical environment that combines gases to produce electrical energy. There are several types of fuel cells, but all rely on the same fundamental process to produce electrical energy. To understand how a fuel cell works, first look at the process of electrolysis:

Equation 2.1:

$$2H_2O\ (l)\ \rightarrow\ O_2\ (g)\ +\ 2H_2\ (g)$$

In this reaction a current supplies the activation energy (E_A) while running through water with a dissolved electrolyte in it to produce gaseous oxygen and hydrogen. This is illustrated below on the left side of Figure 2.1.

Looking at the physical set up of the reaction, a current carrying wire connects two electrodes made from Platinum (Pt), which are partially submerged in a dilute electrolyte. Pt is a catalyst for this reaction and lowers the activation energy. What is created is a circuit between the two electrodes. If the process is reversed the result is the reaction that takes place in fuel cells:

---

[2] Larminie, James, and Andrew Dicks. Fuel Cell Systems Explained. Sest Sussex, England: John Wiley & Sons, Ltd, 2000.

[3] J. W. Pratt and L. E. Klebanoff, “Feasibility of the SF-BREEZE: a Zero-Emission, Hydrogen Fuel Cell, High-Speed Passenger Ferry,” Sandia National Laboratories report SAND2016-9719, available at: maritime.sandia.gov.

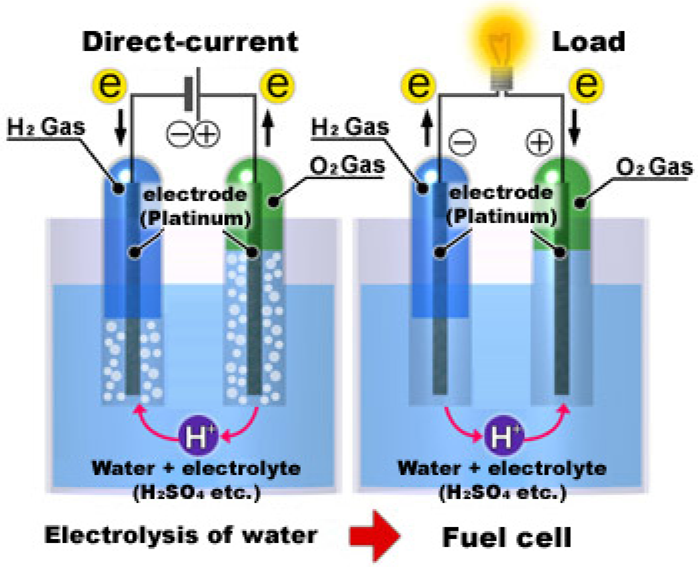

Figure 2.1: The relationship between electrolysis and its reverse reaction, the reaction that occurs in hydrogen fuel cells. Left: Electrolysis of water; Right: Fuel Cell Reaction; Note that the current flows in opposite directions.[4]

Equation 2.2:

$$O_2(g)\ +\ 2H_2\ (g) \rightarrow\ 2H_2O\ (l)$$

At each of the electrodes is a half reaction. At the anode (site of hydrogen consumption/ionization):

Equation 2.3:

$$2H_2\ (g)\ \rightarrow\ 4H^+\ + 4e^-$$

The hydrogen ionizes and releases electrons into the wire to create a current (flowing from - to +) and protons (H^+) that travel through the electrolyte to the cathode. At the cathode:

Equation 2.4:

$$O_2(g) +\ 4e^-\ +\ 4H^+\ \rightarrow\ 2H_2O(l)$$

Oxygen (usually from filtered ambient air), the electrons, and protons (H^+) combine to form water. The electrons flow through the electrical circuit to reach the cathode while the protons travel through the electrolyte. This basic process occurs inside a hydrogen fuel cell. While there are several types of fuel cells, the one examined in this study is the Proton Exchange Membrane FC or PEMFC.

2.1.3. Proton Exchange Membrane Fuel Cells (PEMFCs)

PEMFCs are one way to package the theoretical reactions described above into practical power generation devices, minimizing both space and weight. The reactions at the cathode and anode can only take place where the gas, electrode, and electrolyte all meet. To maximize this area, the electrodes are manufactured into thin porous layers and are "sandwiched" together. PEMFCs have a "sandwich" of cathode, electrolyte, and anode, which is set between two "bipolar" plates. See Figure 2.2 for visualization of this structure.

[4] "Fuel Cell Commercialization Conference of Japan." Available from: http://fccj.jp/eng/aboutfuelcell.html

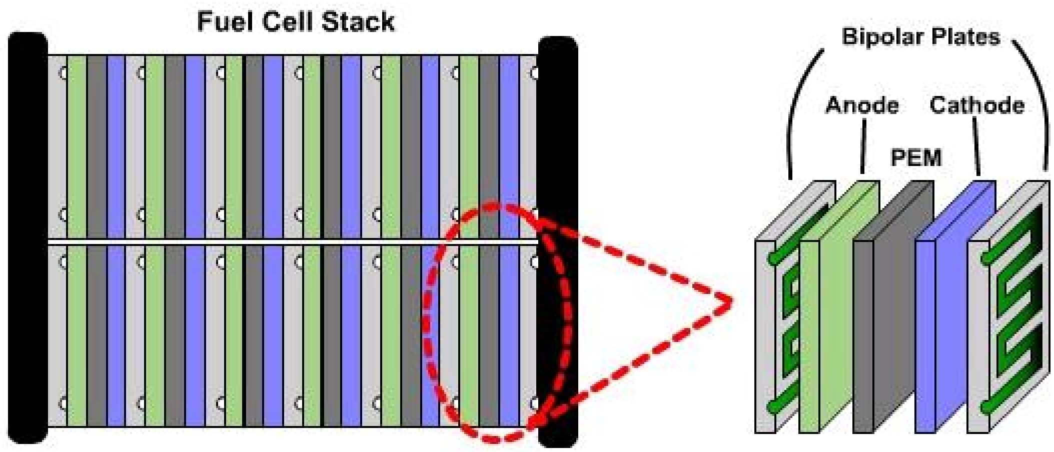

Figure 2.2 Visual graphic of the individual plates that make up a fuel cell stack; note that the bipolar plates have channels etched into them for fueling and ventilation (not to scale)[5]

The electrolyte (noted "PEM" in Figure 2.2) between the cathode and anode is chosen to only allow protons to pass through (prevents air, other gasses, ions, electrons, or anything besides mobile ion [H^+] to pass through), and is commonly made of a material called Nafion. This material operates at a low temperature [60 to 80 degrees Celsius] and can withstand a rapid starts and stops without degradation, necessary for transportation power which can frequently change speeds. The bipolar plates have channels etched into them to allow the entrance of either oxygen or hydrogen on each side (depends which side bipolar plate is facing) and the discharge of produced water. In addition, the bipolar plates connect multiple FCs to form a "stack," and allow the stacks to connect in series to maximize the output.

The only waste products are water vapor and heat; a great advantage over conventional ICEs, which produce GHGs and criteria pollutants. ICEs are also less thermally efficient and expel large amounts of heat. The thermal efficiency of a PEMFC is about 50% compared to 30% by diesel ICE and an even greater thermal efficiency can be achieved by taking excess heat and using it elsewhere in the energy production process (combined cycle fuel cell system).
In addition, PEMFCs operate at a higher efficiency for a greater range of rated power. As seen in Figure 2.3 fuel cell power plants are most efficient around 25% rated power, and the one way to achieve this on a vessel is to spread the load over the entirety of the power plant so that the FCs are at their optimal rated power.

The following describes some advantages of PEMFC technology compared to other fuel cells and to combustion engines:

The advantages of a PEMFC over other fuel cells

- Lower operating temperature (50-100 degrees C)
- Zero emissions when compared to natural gas fuel cells
- Faster growing industry due to demand by automobile companies
- Superior gravimetric and volumetric power specifications

[5] "Visual Encyclopedia of Chemical Engineering." Available from: http://encyclopedia.che.engin.umich.edu/Pages/Reactors/FuelCells/FuelCells.html.

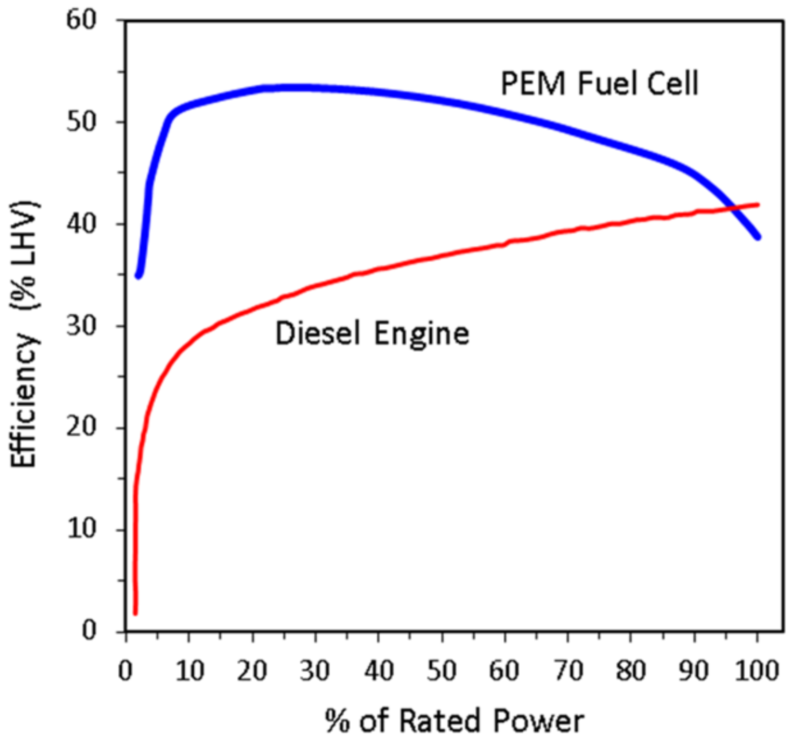

Figure 2.3: Thermal efficiency of a Hydrogenics HD-30 PEM fuel cell (thick blue line) and an MTU 16V4000 diesel engine (thin red line) as a function of the partial load. For the HD-30, the maximal power (100% load) is 33 kW. For one of the MTU 16V4000 diesel engines, the maximal power is 1700 kW. The figure assumes a LHV value of hydrogen of 119.96 MJ/kg, and a LHV value for diesel fuel of 43.4 MJ/kg. Figure from Pratt and Klebanoff[6].

The advantages of PEMFCs over conventional energy production

- Zero emissions
- Lower operating temperature (50-100 degrees C)
- Less mechanical failure and maintenance due to few moving parts
- Much quieter than ICEs – which is less noise pollution and improved ride quality
- Fast start up time (0-100%) in 5-10 sec; (low -100%) less than 1 sec
- Greater thermal efficiency (41-53%)
- Less vibrations that could cause resonance (fractures in structures)

2.1.4. Fuel Cell Data and Specifications

There are two ways to compare fuel cell system power specifications, either through mass (specific power) or through volume (power density). Equation 2.5 and Equation 2.6 illustrate these two specifications below.

Equation 2.5:

$$Specific\ power = \frac{kW}{kg} = \frac{Output\ Power}{Fuel\ Cell\ Mass}$$

Equation 2.6:

$$Power\ density = \frac{kW}{m^3} = \frac{Output\ Power}{Fuel\ Cell\ Volume}$$

[6] J. W. Pratt and L. E. Klebanoff, "Feasibility of the SF-BREEZE: a Zero-Emission, Hydrogen Fuel Cell, High-Speed Passenger Ferry," Sandia National Laboratories report SAND2016-9719, available at: maritime.sandia.gov.

The goal is to achieve a maximum value for both, meaning the FC system will have relatively little mass and a small volume for its power output. This goal is important due to the size and weight limitations on a ship. FCs require auxiliary equipment such as pumps, blowers, power conditioning equipment, heat exchangers, etc. which often takes up more space than the FCs themselves. Some manufactures include this equipment in their product specifications and label them a "system." Table 2.1 gives data for PEMFC systems that are commercially available through several manufacturers. Table 2.2 gives data for PEMFC modules (without the auxiliary equipment) for reference.

It should be noted that in some cases it is difficult to determine the extent of the system equipment included in the specifications. This may result in some variations between these data and actual installations and may introduce some under-prediction of overall system sizes and weights when using the averages. More detailed design studies should work to refine the exact specifications of the fuel cell systems under consideration.

Calculations for the size and weight of the shipboard powerplant will use the trend for system level FC as a more accurate and conservative estimate. The data comes from the following footnoted sources.

Table 2.1: System Fuel Cell Data: Taken from various websites and brochures, some values are calculated in order to get the same data for all fuel cells[7,8,9,10]

SYSTEM FUEL CELL DATA					PROTOTYPE			
COMPANY	UNIT	HYDROGENICS	HYDROGENICS	HYDROGENICS	POWERCELL	US FUELCELL	US FUELCELL	HYDROGENICS
MODEL		HD 90	HD 180	CELERITY	POWERCELL MS-100	Fce 80	FCe 150	POWER RACK (4 x HyPM HD 30)
POWER	kW	93	198	60	100	80	150	120
VOLUME	m^3	0.594	1.19	0.294	0.293	0.494	0.660	1.62
MASS	kg	360	720	275	98	248	474	800
SPECIFIC POWER	kW/kg	0.258	0.275	0.218	1.02	0.323	0.316	0.150
POWER DENSITY	kW/L	0.157	0.167	0.204	0.342	0.162	0.227	0.074
SYSTEM OR MODULE		SYSTEM	SYSTEM	SYSTEM	SYSTEM	SYSTEM	SYSTEM	SYSTEM

[7] "FCe80-Datasheet-170104.pdf." Available: https://www.usfuelcell.com/doc/FCe80-Datasheet-170104.pdf.
[8] "FCe150-Datasheet-160104.pdf."Available: https://www.usfuelcell.com/doc/FCe150-Datasheet-160104.pdf
[9] "HyPM-HD Power Modules," Hydrogenics Corp, April 2016. Available: http://www.hydrogenics.com/wp-content/uploads/HyPM-HD-Brochure.pdf
[10] "PowerCell MS-100 Mobile System (50-100kW) Prototype," Powercell, April 2017. Available: http://www.powercell.se/wp-content/uploads/2017/05/MS-100-Data-Sheet.pdf.

Table 2.2: Module Cell Data: Taken from various websites and brochures, some values are calculated in order to get the same data for all fuel cells (same references as above table, plus Ref. [11])

MODULE FUEL CELL DATA			PROTOTYPES									
COMPANY	UNIT	BALLARD POWER SYSTEMS	POWERCELL	POWERCELL	HYDROGENICS	HYDROGENICS	HYDROGENICS	HYDROGENIC S	HYDROGENIC S	HYDROGENICS	HYDROGENICS	HYDROGENICS
MODEL		FC VELOCITY	POWERCELL S3-335C	POWERCELL S3-455c	HD 4-200	HD 5-200	HD 8-200	HD 8-500	HD 10 -200	HD 15	HD 30	Model HyPM HD 30
POWER	kW	90	98.2	125	4	5	8.5	8.5	10	16.5	31	33
VOLUME	m^3	0.497	0.029	0.037	0.019	0.002	0.025	0.040	0.028	0.052	0.076	0.058
MASS	kg	256	33.1	41.6	25	26	28	52	33	55	72	73.6
SPECIFIC POWER	kW/kg	0.352	2.97	3.00	0.160	0.192	0.304	0.163	0.303	0.300	0.431	0.448
POWER DENSITY	kW/L	0.181	3.41	3.38	0.212	2.484	0.345	0.212	0.363	0.315	0.407	0.566
SYSTEM OR MODULE		MODULE	MODULE	MODULE	MODULE	MODULE	MODULE	MODULE	MODULE	MODULE	MODULE	MODULE

Figure 2.4 and Figure 2.5 plot the specific power and power density, respectively, of the fuel cell system and module data given in Table 2.1 and Table 2.2.

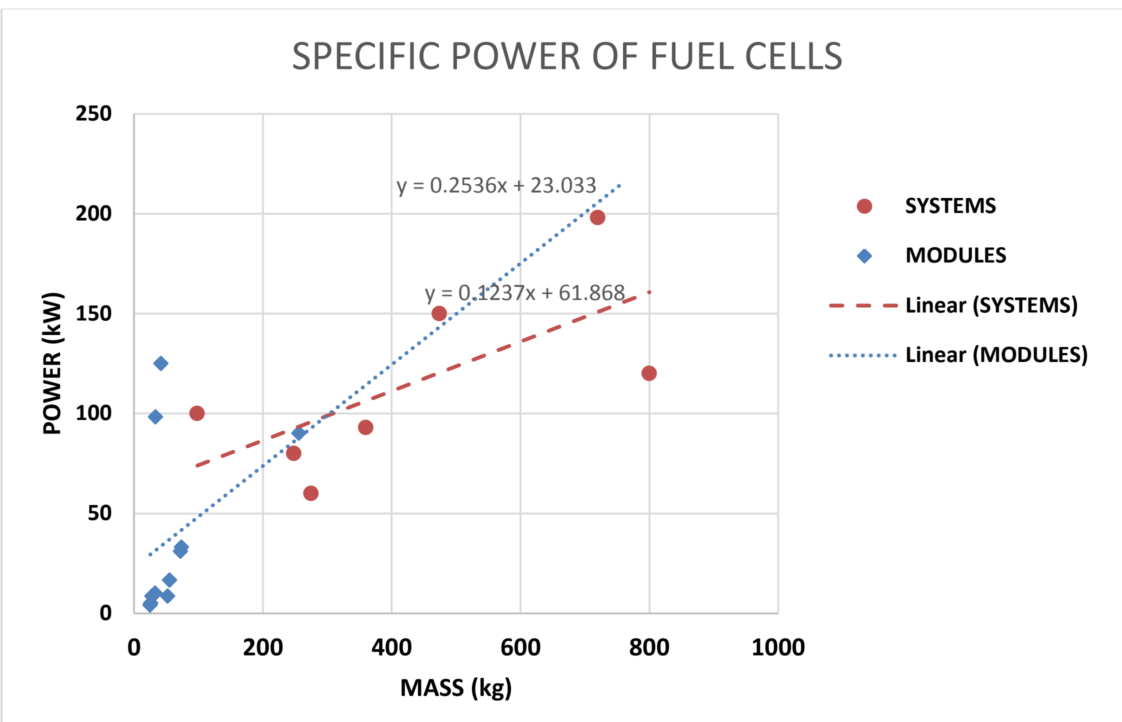

Figure 2.4 Specific Power: Based off values from Table 2.1 and Table 2.2

[11] "PowerCell S3Scalable (30-100 kW) Prototype," PowerCell, April 2017. Available: http://www.powercell.se/wp-content/uploads/2017/05/S3-Fuel-Cell-Data-Sheet.pdf

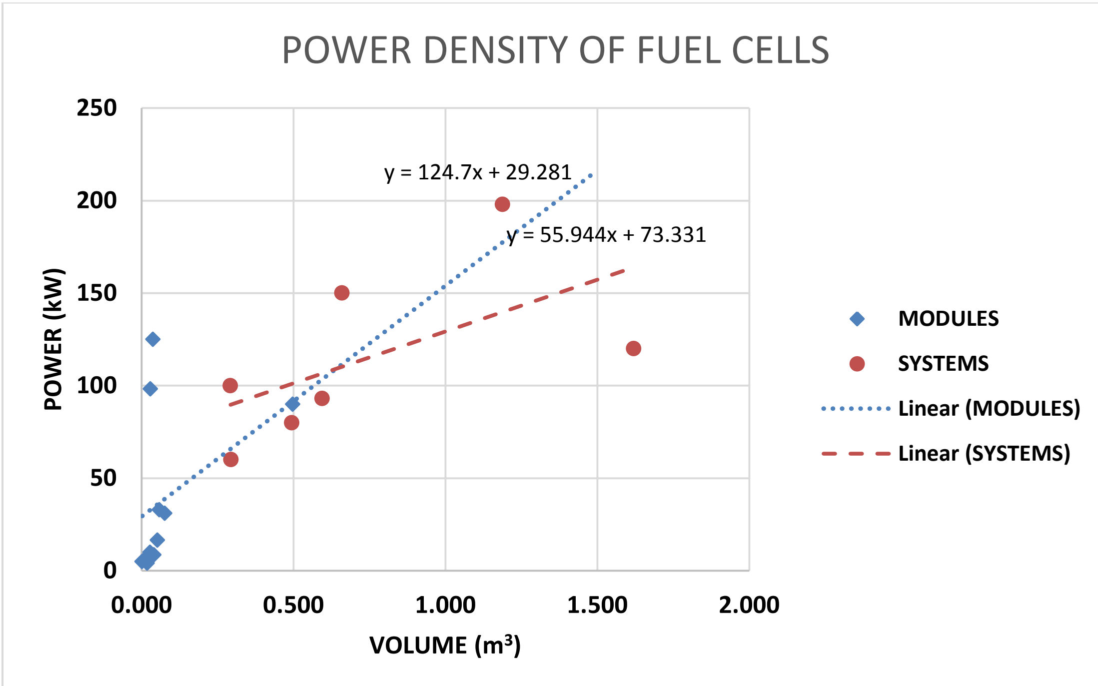

Figure 2.5 Power Density: Based off values from Table 2.1 and Table 2.2

In order to create the most accurate prediction of possible FC systems, the volume and mass numbers used in the study will be for the entire system. Accordingly, Equation 2.7 and Equation 2.8 below present the equations taken from the red (systems) trend lines in Figure 2.4 and Figure 2.5.

Equation 2.7: Specific Power of Fuel Cell System trend

$$Power\ [kW] = 0.1237 * mass\ [kg] + 61.868$$

Equation 2.8: Power Density of Fuel Cell System trend

$$Power\ [kW] = 55.944 * volume\ [m^3] + 73.331$$

2.1.5. Hydrogen Fuel Storage for Fuel Cells

Two ways to store hydrogen fuel are considered in this work, as a high pressure gas at 5,000 psi (350 bar) and as a cryogenic liquid at about 20 K or -252 degrees C. High pressure hydrogen gas is considered because it is easier to manufacture and more widely available than liquid hydrogen (LH_2). However, LH_2 can be transported in much larger quantities and will result in a smaller and lighter overall system on a ship compared to a gaseous storage system. In both cases, the mass and volume of the entire storage container system must be determined, not just that of the hydrogen alone. Therefore calculations that will estimate the mass and volume of the fuel containers will use two sets of different "factors," one for LH_2 storage and one for 5000 psi hydrogen. The factors used in this study are given in Table 2.3 below.

The specs for the 5,000 psi system are based on an existing commercially-packaged array of 8 tanks from Luxfer-GTM and total capacity of about 60 kg. While configurations can vary widely, this product is a good representation on what to expect from a tank array and is modular

Table 2.3: Gravimetric and volumetric specs for the hydrogen storage systems considered in this study.

Tank Type	Gravimetric spec (Empty Tank Mass/H_2 Stored Mass) (kg/kg)	Volumetric spec (Outer Tank Volume/H_2 Stored Mass) (L/kg)
5,000 psi (350 bar) compressed gas[12]	17.92	93.7
Cryogenic liquid[13]	8.7	24.8

so can be reasonably extrapolated to larger gas quantities. These tanks have an aluminum inner shell and a carbon fiber overwrap, making them much 4-5 times lighter than traditional steel tanks. Because individual gaseous tanks do not hold the large quantities of hydrogen needed for ships, an array size is used instead of an individual tank size because of the additional volume and some additional weight that is needed when arranging the tanks in an array.

The specs for the LH_2 system are based on a single tank with 1,200 kg capacity. Larger tank sizes are possible and will reduce the gravimetric and volumetric spec numbers, so using numbers for a 1,200 kg tank is conservative. Arrays of LH_2 tanks will encounter penalties like gaseous tanks, but these penalties can be offset by the better storage efficiency gained by going to larger tanks as part of that array. Therefore, the 1,200 kg tank numbers are used as representative for this study.

2.2. Batteries

2.2.1. Why Batteries?

Batteries are another zero emission alternative to conventional power production. Already, they have become popular transportation options in the automobile industry; battery-electric vehicle models are offered by every major automaker. Battery technology is improving rapidly and is predicted to become more mass and volume efficient in the coming years. According to PBES Norway AS, the amount of energy per battery will increase 40% within five years.[14] Battery charging is also maturing with commercial multi-MW fast charging marine systems already developed and being deployed.

2.2.2. Battery History[15]

Early batteries came about in the 1800s with the “Leyden Jar” and “Voltaic Pile.” A Voltaic Pile consists of stacks of copper (anode) and zinc (cathode) discs separated by sheets of cloth soaked in brine. In the 1850s, Gaston Plante invented the lead acid battery, the predecessor to today’s batteries. In 1891, William Morrison built the first electric vehicle with 24 lead acid batteries producing 48 V, 112 Ah, and 5.4 kWh of energy, weighing 2 tons.

[12] Based on the Luxfer-GTM Constant Pressure Refueler without the trailer assembly, a 60 kg array of 8 tanks. Product overview available at: https://www.luxfergtm.com/uploads/3/5/6/6/3566041/gtm-cpr_2016.pdf
[13] From SF-BREEZE report Table 5; Based on information from Gardner Cryogenics
[14] C. Ianssen, E. Ianssen, and T. Sandblost, “Battery/fuel cell fast ferry,” Selfa AS, April 2017.
[15] This section is largely adapted from J. Warner, “Batteries 101,” presented at the MARAD Hi-Power Battery Workshop, December 15, 2016, Washington DC.

2.2.3. How do Batteries work?[16]

Basic batteries consist of two or more chemicals creating a conductive environment and ions. This set-up creates an electrical potential difference between the two metals. These chemicals in the batteries do not store electricity, instead storing chemical energy which produces electricity through reaction, and thus act as energy conversion devices.

There are two kinds of batteries: primary and secondary. Primary, which are disposable, come in several standard form factors (e.g., AAA, AA, C, D, 9 volt, etc.), and cannot recharge. Secondary batteries have multiple uses, can recharge many times, and have numerous form factors. The batteries that will be in this study are secondary batteries.

There are several types of chemistries for secondary batteries, and different chemistries have advantages and disadvantages. For example, Lithium-based batteries have high energy, power, a large number of life cycles, and have a low mass, which makes them good for transportation applications. Other batteries allow short burst of large current without damage (Starting batteries).

The power output ability of a battery can be quantified through the terminology of “C-rate”, a measurement provided by the manufacturer that describes how much current the battery is capable of providing over time.[17] Different types of batteries have different acceptable C-rates, so C-rate is an important factor to consider when choosing a battery for transportation applications because of the variability in mission requirements. Batteries with low C-rates are used more for longer term energy storage without fast power transient, while those with higher C-rates are designed for fast charge and discharge.

Another important aspect of batteries is the depth of discharge. Depending on the battery type, deep discharge can ruin the recharge ability of a secondary battery over time. The allowable minimum depth of discharge is an important factor in sizing battery systems and means that the installed energy capacity of a battery system will nearly always be some factor higher than the energy available for use.

2.2.4. Battery Data and Specifications

Below are the data for both system level and modular level battery systems. A system is made up of many modules and includes the volume and weight penalties of the array as well as required ancillary equipment such as controllers and cooling hardware. The calculations for determining the size and weight of shipboard battery systems will use the trend for system level battery for as a more accurate estimate. The following data comes from these footnoted sources.[18,19,20]

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[16] Ibid

[17] Warner, The Handbook of Lithium-Ion Battery Pack Design, Chapter 4.

[18] “PBES Specification Sheet: System Specifications for the PBES Power & Energy Systems,” Plan B Energy Storage, May 2017. Available: http://www.pbes.com/wp-content/uploads/2017/06/PBES_Power-Energy_2017-06-16.pdf

[19] “Technology & Specifications | Corvus Energy.” Corvus Energy. Available: http://corvusenergy.com/technology-specifications/

[20] “SpearPowerSystems – Products,” Spear Power Systems. Available: http://www.spearpowersystems.com/?page_id=1391

Table 2.4 below gives system level data for low C-rate battery designs. Table 2.5 gives system level data for high C-rate designs. Table 2.6 gives module data for both types with low C-rate in green shading and high C-rate in red shading. The data shows that high C-rate power-style batteries are larger and heavier than the low C-rate energy-style type.

Table 2.4: System Battery Data for low C-rate battery systems.

SYSTEM BATTERY DATA					
COMPANY	UNITS	CORVUS		PBES	SPEAR
MODEL		ORCA ENERGY		ODIN SERIES STRING	SMAR-11N
DISTINGUISHING FEATURES		ENERGY		ENERGY	Industry-Leading Energy Density
DIMENSIONS		VERT. ARR.	HOR. ARR.		
ENERGY	kWh	125	125	97	11.3
VOLUME	m^3	1.36	1.51	1.22	0.124
MASS	kg	1550	1550	1247	104.6
MODUCLE SPECIFIC ENERGY	kWh/kg	0.0806	0.0806	0.0778	0.1080
MODULE ENERGY DENSITY	kWh/L	0.0920	0.0829	0.0798	0.0910
SYSTEM OR MODULE		SYSTEM		SYSTEM	SYSTEM

Table 2.5: System Battery Data for high C-rate battery systems.

SYSTEM BATTERY DATA								
COMPANY	UNITS	CORVUS		PEBS	SPEAR	SPEAR	SPEAR	SPEAR
MODEL		ORCA POWER		HARPOON SERIES STRING	SMAR-3T	SMAR-2P	SMAR-6A	SMAR-2F
DISTINGUISHING FEATURES		POWER		POWER	Fast Charge / Industry-Leading Cycle Life	High Power Density	High Power / Fast Charge / Long Cycle Life	High Power
DIMENSIONS		VERT. ARR.	HOR. ARR.					
ENERGY	kWh	39	39	65	3.4	2.7	6.2	2.4
VOLUME	m^3	1.00	1.15	1.22	0.1	0.071	0.102	0.071
MASS	kg	680	680	1247	69.4	45	70.5	46.2
MODUCLE SPECIFIC ENERGY	kWh/kg	0.057	0.057	0.052	0.049	0.06	0.088	0.052
MODULE ENERGY DENSITY	kWh/L	0.039	0.034	0.053	0.034	0.038	0.061	0.034
SYSTEM OR MODULE		SYSTEM		SYSTEM	SYSTEM	SYSTEM	SYSTEM	SYSTEM

Table 2.6 Module Battery Data: The green filled cells correspond to batteries marketed for low power output for long periods of time whereas the pink cells correspond to batteries marketed for high power outputs for short periods of time.

MODULE BATTERY DATA								
COMPANY	UNITS	PEBS	SPEAR	PBES	SPEAR	SPEAR	SPEAR	SPEAR
MODEL		ODIN ENERGY SINGLE MODUDLE	SMAR-6N	HARPOON POWER	SMAR-3T	SMAR-2P	SMAR-2F	SMAR-1T
DISTINGUISHING FEATURES		ENERGY	BALANCE OF ENERGY & POWER	POWER	CHARGE RATE, CYCLE LIFE	HIGH POWER	HIGH POWER	HIGH POWER
DIMENSIONS								
ENERGY	kWh	9.7	6	6.5	2.8	2.4	1.9	1
VOLUME	m^3	0.0705	0.0333	0.0705	0.0329	0.0194	0.0188	0.0185
MASS	kg	90	63.2	90	62.2	31.6	28.4	26.3
MODUCLE SPECIFIC ENERGY	kWh/kg	0.108	0.095	0.072	0.045	0.076	0.067	0.038
MODULE ENERGY DENSITY	kWh/L	0.138	0.180	0.092	0.085	0.124	0.101	0.054
SYSTEM OR MODULE		MODULE	MODULE	MODULE	MODULE	MODULE	MODULE	MODULE

Figure 2.6 and Figure 2.7 plot the specific energy and energy density, respectively, of the system and module data in Table 2.4, Table 2.5, and Table 2.6.

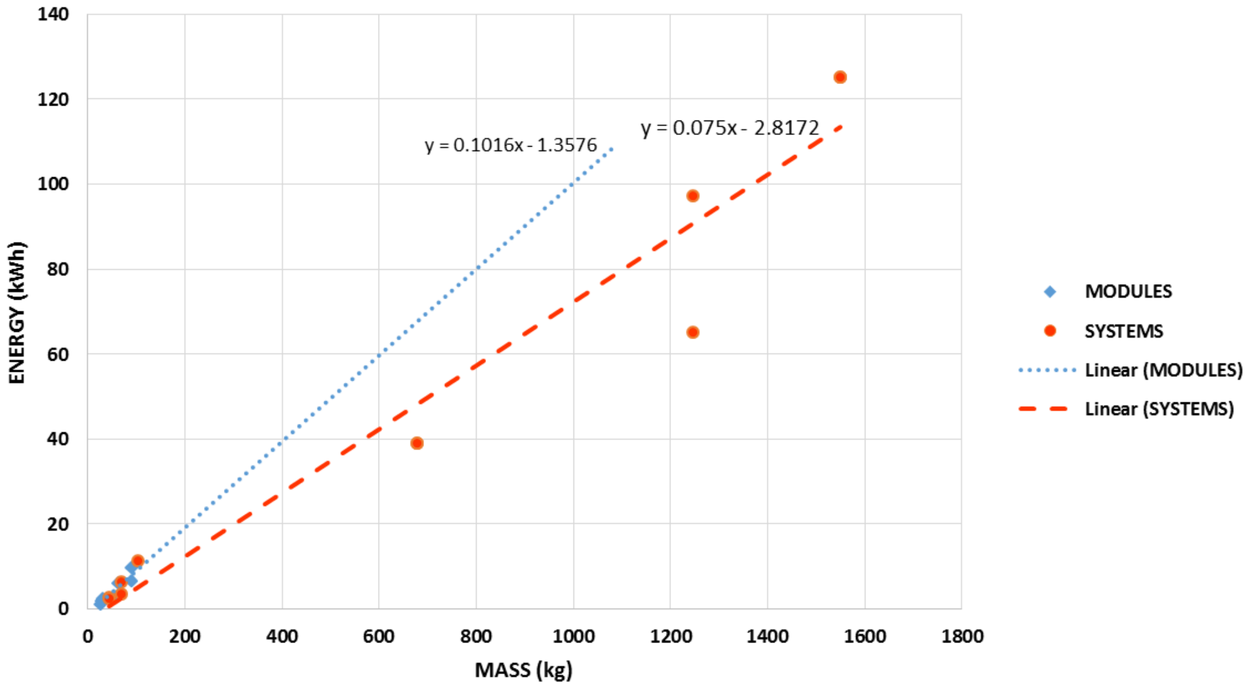

Figure 2.6 Specific Energy for battery modules and systems: Based off of Table 2.4, Table 2.5, and Table 2.6.

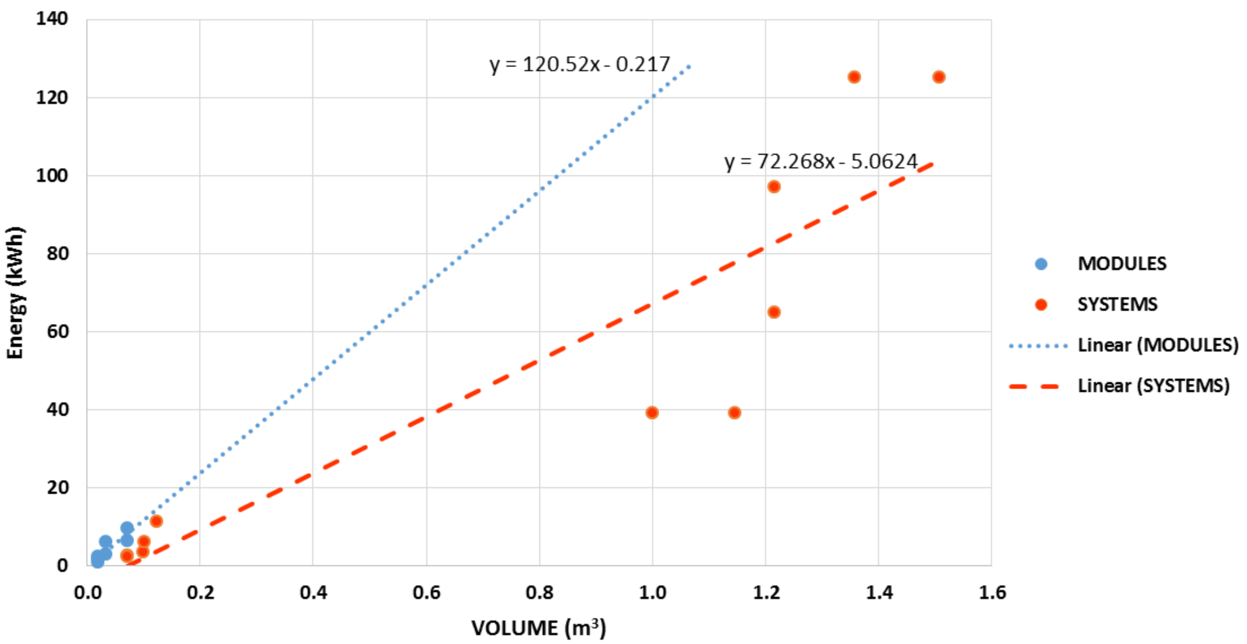

Figure 2.7 Energy Density of battery modules and systems: Based off Table 2.4, Table 2.5 and Table 2.6.

Below are the trend line equations from the Systems lines (red) in Figure 2.6 and Figure 2.7.

Equation 2.9: Specific Energy of Batteries System trend

$$Energy\ [kWh] = 0.075 * mass\ [kg] - 2.8172$$

Equation 2.10: Power Density of Batteries System trend

$$Energy\ [kWh] = 72.268 * volume\ [m^3] - 5.0624$$

If the power style (high C-rate) batteries are removed from the plots in Figure 2.6 and Figure 2.7, the slope of the trend lines Equation 2.9 and Equation 2.10 increase illustrating the higher specific energy and energy density that can be achieved with energy-style (low C-rate) batteries. For this study we use both kinds of batteries to develop the trendline which effectively gives an average of both types. This over-predicts the size and volume of a system that has only energy-type batteries, but under-predicts the size and volume of a system that has only power-type batteries.

3. VESSEL CASE STUDIES

This chapter consists of three sections. The first section, *Calculations*, describes in detail the equations and assumptions used to determine characteristics of the vessels studies and the compatibility of the three zero emission powerplants (battery, fuel cell with gaseous hydrogen, fuel cell with liquid hydrogen). The second section, *Vessel Assessments*, gives the relevant characteristics of each vessel and the results of the calculations when applied to that vessel. The last section, *Combined Results and Discussion*, examines the data as a whole set to uncover broader conclusions with the goal of more general application across the entire maritime sector.

3.1. Calculations

Calculations of the mass and volume of battery and fuel cell systems will estimate the possibility of whether a zero emission system can replace the conventional power plant onboard each ship. This method only examines the power and energy required for propulsion and does not include hotel power or bow/stern thruster power.

Before splitting into the different calculations for FCs and batteries, the required energy for each one-way voyage was calculated using several pieces of information about the vessel and its voyage: the vessel's installed engine power (noted as MCR in Equation 3.2), vessel's max speed, voyage: distance, time duration of voyage, and average speed along the voyage.[21]

The average and maximum speeds are used to find the Load Factor on the engine, which indicates the fraction of power needed by the engine to travel the average speed.[22]

Equation 3.1: Step 1

$$Load\ Factor\ (LF)\ = \left(\frac{Average\ Speed\ [kts]}{Max\ Speed\ [kts]}\right)^3$$

From here, the product of the LF and the installed engine power (MCR) provides the average shaft power over the course of the voyage.

Equation 3.2: Step 2

$$Average\ Shaft\ Power\ [kW] = \ LF\ \times\ MCR\ [kW]$$

[21] Average speed includes the total time from departure of to time of arrival, assuming it does not loiter or make any stops from departure to arrival. However, some average speeds (SOA-Speed of Advance) do include time stopped (i.e. Alfa Nero the mega yacht) so load factor as a function of average speed is not entirely accurate, it is a rough estimate.

[22] The cubic relationship between speed and power, achieved by combining Equations 3.1 and 3.2, is a form of the propeller law and often used to as a first approximation of actual speed-power relationships as in, for example, the *Puget Sound Maritime Air Emissions Inventory* by Starcrest Consulting, Sept. 2012. Large ships have been shown to have a higher order relationship, as high as the power of 4 for high speed container ships, 3.5 for medium sized, medium speed ships such as feeder and RoRo ships, and 3.2 for low speed ships like tankers and bulkers ["Basic Principles of Ship Propulsion," MAN Diesel & Turbo, Dec. 2011]. Assuming a factor of 3 in this study will give conservative results in those cases, that is, this study will show higher energy and power needs than actual. In the case of planing hulls, the opposite is true: the coefficient may be less than 3. In those cases the method presented here will under-predict the true power and energy requirements.

In order to find the total energy needed for the voyage, the time and average shaft power are multiplied.

Equation 3.3: Step 3

$$Energy\ Needed\ for\ Voyage\ [kWh]\ =\ Average\ Shaft\ Power\ [kW] \times Time\ [hr]$$

At this point, the steps are different for batteries and fuel cells and the calculations continue from Equation 3.3 in the next two sections.

3.1.1. Fuel Cell and Hydrogen System Mass and Volume

For hydrogen fuel cell systems the calculation picks up from Equation 3.3 to calculate the amount of hydrogen to be stored in the containers of LH_2 or 5000 psi hydrogen. Since the FC is not 100% efficient, the loss of energy due to thermal inefficiency needs to be accounted for. Assuming the efficiency of FCs is 45%, the required energy of hydrogen can be calculated by dividing the energy needed for voyage by the efficiency (0.45).[23]

Equation 3.4: Step 4A

$$Energy\ H_2[\mathrm{kWh}]\ =\ \frac{Energy\ Needed\ for\ Voyage\ [kWh]}{0.45}$$

Next, convert from kWh to kg by using the conversion of kWh to MJ and lower heating value of hydrogen (LHV) to find the mass of the required hydrogen.

Equation 3.5: Step 5

$$Mass\ of\ H_2[\mathrm{kg}]\ =\ Energy\ H_2[\mathrm{kWh}]\ \times \frac{3.6\ {}^{MJ}/_{kWh}}{119.96\ {}^{MJ}/_{kg}}$$

Now that the mass of H_2 is calculated, the mass and volume of the tanks of LH_2 and 5000 psi hydrogen can be easily calculated using the values in Table 2.3 and the formulas below:

Equation 3.6

$$Mass\ of\ Tank\ [kg] =\ Mass\ of\ H2\ [kg] \times Gravimetric\ spec\ [\frac{kg\ tank}{kg\ H2}]$$

(The total mass of the fuel and tank is then found by summing the tank mass and the fuel mass.)

Equation 3.7

$$Volume\ of\ Tank\ [L] =\ Mass\ of\ H2\ [kg] \times Volumetric\ spec\ [\frac{L\ tank}{kg\ H2}]$$

[23] The assumed efficiency of the hydrogen fuel cell is 45%. Even though the max efficiency is about 53%, the fuel cell will not always operate at its highest efficiency point. This may be somewhat conservative and overpredict the amount of hydrogen needed.

Next, find the mass and volume of the FC system. This will be the same for both types of hydrogen because both can power a fuel cell.[24] Using Equation 2.7 and Equation 2.8, solve for mass and volume using the vessel's installed power (MCR).

The total hydrogen and fuel cell system mass is found by adding the tank mass to the fuel cell system mass. Total volume is found the same way.

3.1.2. Battery System Mass and Volume

Calculating the mass and volume of the battery system is similar to the calculation for the fuel system, but Equation 2.9 and Equation 2.10 are used instead. The total energy of the installed battery system will more than required by the voyage because of the depth of discharge factor as described in Section 2.2.3. Depth of discharge will be set at 50% (0.50).[25] The installed energy then becomes:

Equation 3.8: Step 4B

$$Battery\ Energy\ [kWh] = \frac{Energy\ Needed\ for\ Voyage\ [kWh]}{0.50}$$

Using the value of *Battery Energy* for the *Energy* term in Equation 2.9 and Equation 2.10 estimates the total mass and volume of the battery system.

3.1.3. Maximum Available On-board Mass and Volume

Once system mass and volume are known the next step is to determine if the ship has sufficient available mass and volume to accommodate it. This is done by finding the combined mass and volume is currently attributed to each vessel's conventional fossil fuel engine and fuel tanks. No attempt to redesign the vessel is made in this study.

While the method is simple, it requires information that is not available in the open literature. Consultation with the vessel designer, builder, or operator may reveal this information but the effort to do so was not consistent with the scope of this project. Therefore, what information was available for some ships was used to find trends of volume and displacement among ship types, and then applied to those ships where data were not available.

Engine mass and volume was determined from manufacturer specifications for the ships where the make and model were known. More generic engine data from MTU, MAN, and Wartsila were used to develop trendline relationships between power and mass and volume, which are presented in Figure 3.1 and Figure 3.2. So in cases where engine data were not known, these trends were used to estimate the engine mass and volume by using the MCR of the ship.

[24] Assumes that both LH_2 and 5000-psi hydrogen power FCs in the same way, only difference is the container for the storage of the fuel.
[25] Ayers, Will. "Comparative Payback of Lithium-Ion Batteries for Pacific NW Ferries." Elliott Bay Design Group, 2016.

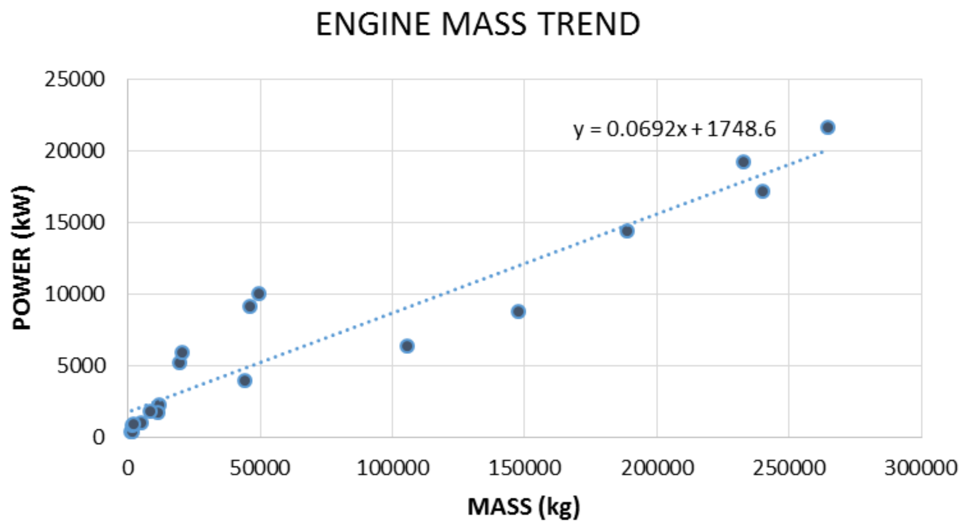

Figure 3.1: General power-mass characteristics of common marine diesel engines used today.

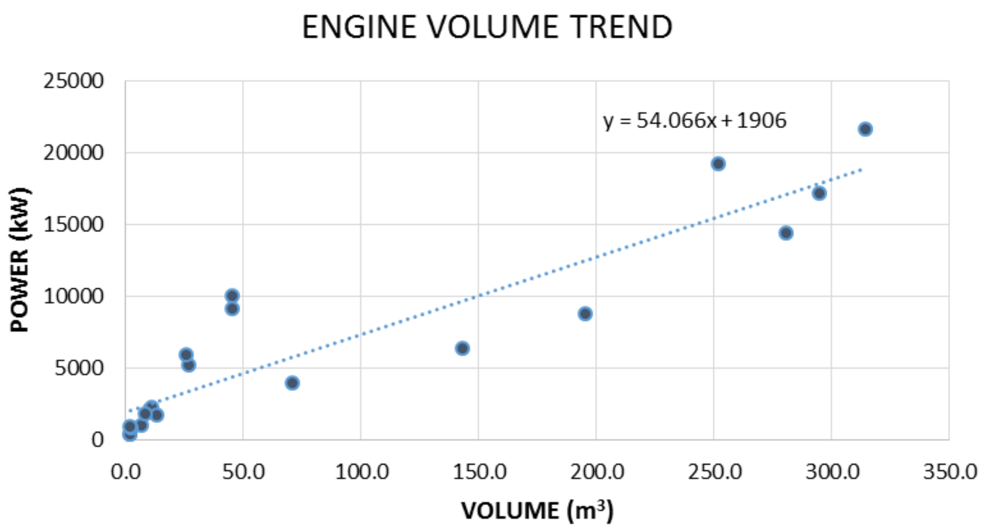

Figure 3.2: General power-volume characteristics of common marine diesel engines used today

Engine rooms typically have much more volume than just the volume of the engine itself. From observations by the authors and available layout details of similar types of vessels in this study, it appears most engine rooms have an available volume of at least 5-times that of the engine(s) due to clearances required for access and maintenance; that is, the engine utilizes about 20% of the total engine room volume. Because fuel cells and batteries come in many small modules, the maintenance clearances are greatly reduced. A notional battery or fuel cell room could utilize at least 50% of the available volume and still have enough access for maintenance and repair. Combining these effects, the engine room volume on the vessel available for a battery or fuel cell installation was set at 2.5 times the volume of the combustion engine itself.

Fuel volume was able to be found for nine of the vessels in the study[26]. For the others, estimates based on similar vessels were made using information in NOAA's Office of Spill Response and

[26] Pride of Hull, Atlantic Klipper, Spiegelgracht, Alfa Nero, Maersk Frontier, and Atlantic Dawn information came from *Ship Knowledge*, Trearddor Bay information came from http://www.turbinetransfers.co.uk/portfolio/trearddur-

Table 3.1: Summary of available volume and mass characteristics for the vessels in the study.

Vessel	Length (m)	Fuel volume (m^3)	Engine volume (m^3)	**Total volume (m^3)**	Fuel mass (MT)	Engine mass (MT)	**Total mass (MT)**
Emma Maersk	397	15,000	3,615	18,615	13,950	1,132	15,082
Colombo Express	335	12,000	3,086	15,086	11,160	1,971	13,131
Pride of Hull	215	1,000	1,660	2,660	930	521	1,451
Spiegelgracht	168	1,880	470	2,350	1,688	149	1,837
Atlantic Klipper	165	2,269	572	2,841	2,104	181	2,285
Capricorn	119	1,200	89	1,289	1,116	30	1,146
Atlantic Dawn	112	594	97	691	549	33	582
Maersk Frontier	83	1,349	160	1,509	1,255	52	1,307
Alfa Nero	82	294	235	529	259	23	281
Zalophus	47	30	10	40	25	4	28
Northwestern	38	174	17	191	145	5	150
Trondheimsfjord 2	25	5	12	17	4	4	8
Hein Senior	24	15	6	21	12	2	14
Trearddur Bay	21	5	11	16	4	4	9

Restoration[27], Washington State Department of Ecology[28], and personal communication with the World Shipping Council[29].

Table 3.1 summarizes the estimated available volume and mass for the 14 vessels in this study.

3.2. Vessel Assessments

The vessel assessments have the following components:

- General description of the vessel
- Vessel Specifications
- Route Information
- Zero Emission Powertrain Results

Vessel specifications are from *Ship Knowledge*[30] unless otherwise noted. All pictures were obtained from www.marinetraffic.com. Information for actual routes was from www.marinetraffic.com unless otherwise noted.

bay/, Northwestern information from http://fvnorthwestern.com/northwestern/marco-press-release-1977/, and Zalophus information from personal communication with J. Burgard of Red and White Fleet.

[27] https://response.restoration.noaa.gov/about/media/how-much-oil-ship.html

[28] "Guidelines for Determining Oil Spill Volume in the Field," Washington State Department of Ecology, 1996

[29] Personal communication with B. Wood-Thomas of the World Shipping Council

[30] Van Dokkum, Klaas. *Ship Knowledge*. 9th ed. Vlissingen, The Netherlands: DOKMAR Maritime Publishers BV, 2011.

3.2.1. Emma Maersk – 9321483

The *Emma Maersk* is one of the largest containerships in use today. Her relevant specifications were estimated from information on a dedicated website[31] and given in Table 3.2.

The route studied was an actual voyage from Tanjung Pelepas, Malaysia to Port Said, Egypt with characteristics shown in Table 3.3. The distance and time were obtained from marinetraffic.com and average speed was calculated. Average shaft power and energy used were obtained using Equation 3.2 and Equation 3.3, respectively.

Table 3.2: Estimated specifications of the Emma Maersk

Name	Emma Maersk
Type	Container
Overall Length	397 m
Beam	56 m
Main Engine Power (MCR)	80.08 MW
Fuel Capacity	15,000 m^3
Maximum Speed	25.5 knots
Available Volume	18,615 m^3
Available Mass	15,082 MT

Table 3.3: Route information used for the Emma Maersk.

Departure Port	Tanjung Pelepas
Arrival Port	Suez Canal/Port Said
Distance	5005 nm
Total Voyage Time	256 hr
Average Speed (SOA)	19.6 knots
Average Shaft Power	36.1 MW
Energy Used	9,240 MWh

[31] "Emma Maersk - Container Vessel." Available: http://www.emma-maersk.com/specification/

Table 3.4: Characteristics of zero emission power systems needed on the Emma Maersk for the route studied.

		Fuel cell with liquid hydrogen	Fuel cell with 350 bar hydrogen gas	Battery
Single Trip	**Battery Capacity (MWh)**	-		18,500
	Fuel Cell Power (MW)	80		-
	Hydrogen Fuel (MT)	616		-
	Mass (MT) (15,082 avail)	6,620	12,300	246,000
	Volume (m^3) (18,615 avail)	16,700	59,000	284,000
Possible One-Way Trips		1	0	0

Table 3.4 shows the resulting characteristics of battery and fuel cell power systems (including hydrogen fuel) for a single trip, and how many one-way trips over the route could be accomplished with each solution. Despite the large power and energy requirements, the available mass and volume is able to accommodate a hydrogen fuel cell powerplant using liquid hydrogen as the fuel. The fuel cell system with 350 bar hydrogen meets the mass requirements but is more than 3-times the available volume. The battery system is over 15-times too large and massive.

3.2.2. Colombo Express – 9295244

The *Colombo Express* is a large containership with 8,750 TEU capacity. Her relevant specifications were estimated and given in Table 3.5.

The route studied was an actual voyage from Singapore to Colombo, Sri Lanka with characteristics shown in Table 3.6. The distance and time were obtained from marinetraffic.com and average speed was calculated. Average shaft power and energy used were obtained using Equation 3.2 and Equation 3.3, respectively.

Table 3.7 shows the resulting characteristics of battery and fuel cell power systems (including hydrogen fuel) for a single trip, and how many one-way trips over the route could be accomplished with each solution. The available mass and volume is able to accommodate a hydrogen fuel cell powerplant using liquid hydrogen as the fuel and could accommodate enough hydrogen to travel the route three times before the volume becomes too much. The fuel cell system with 350 bar hydrogen meets the mass requirements but is a little above the available volume. The battery system is over 5-times too large and massive.

Table 3.5: Estimated specifications of the Colombo Express

Name	Colombo Express
Type	Container
Overall Length	335 m
Beam	43 m
Main Engine Power (MCR)	68.6 MW
Fuel Capacity	12,000 m^3
Maximum Speed	25 knots
Available Volume	15,086 m^3
Available Mass	13,131 MT

Table 3.6: Route information used for the Colombo Express.

Departure Port	Singapore
Arrival Port	Colombo
Distance	1581 nm
Total Voyage Time	79.5 hr
Average Speed (SOA)	19.9 knots
Average Shaft Power	34.6 MW
Energy Used	2,750 MWh

Table 3.7: Characteristics of zero emission power systems needed on the Colombo Express for a single trip on the route studied.

		Fuel cell with liquid hydrogen	Fuel cell with 350 bar hydrogen gas	Battery
Single Trip	Battery Capacity (MWh)	-		5,500
	Fuel Cell Power (MW)	68.6		-
	Hydrogen Fuel (MT)	183		-
	Mass (MT) (13,131 avail)	2,330	4,020	73,200
	Volume (m^3) (15,086 avail)	5,770	18,400	84,500
Possible One-Way Trips		3	0	0

3.2.3. Pride of Hull – 9208629

The *Pride of Hull* is a large vehicle and passenger (Ro-Pax) ferry able to accommodate 1,360 passengers and 1,380 vehicles. Her relevant specifications were estimated and given in Table 3.8.

The route studied was an actual voyage from Hull, UK to Rotterdam, Netherlands with characteristics shown in Table 3.9. The distance and time were obtained from marinetraffic.com and average speed was calculated. Average shaft power and energy used were obtained using Equation 3.2 and Equation 3.3, respectively.

Table 3.8: Estimated specifications of the Pride of Hull

Name	Pride of Hull
Type	Ro-Pax
Overall Length	215 m
Beam	32 m
Main Engine Power (MCR)	37.8 MW
Fuel Capacity	1,000 m^3
Maximum Speed	22 knots
Available Volume	2,660 m^3
Available Mass	1,451 MT

Table 3.10 shows the resulting characteristics of battery and fuel cell power systems (including hydrogen fuel) for a single trip, and how many one-way trips over the route could be accomplished with each solution. The available mass and volume is able to accommodate a hydrogen fuel cell powerplant using either liquid hydrogen or gaseous hydrogen as the fuel. The amount of liquid hydrogen carried can be increased within the available volume and mass to allow the ferry to travel over 5 trips (about 2.5 days) before requiring refueling. Using gaseous hydrogen the ferry can travel one trip – increasing the gaseous hydrogen storage any more will reach the volume limit. The required battery system is over 4 times too massive and 2 times too large.

Table 3.9: Route information used for the Pride of Hull.

Departure Port	Hull
Arrival Port	Rotterdam
Distance	211 nm
Total Voyage Time	11.9 hr
Average Speed (SOA)	17.8 knots
Average Shaft Power	20.0 MW
Energy Used	237 MWh

Table 3.10: Characteristics of zero emission power systems needed on the Pride of Hull for a single trip on the route studied.

			Fuel cell with liquid hydrogen	Fuel cell with 350 bar hydrogen gas	Battery
Single Trip	**Battery Capacity (MWh)**		-		475
	Fuel Cell Power (MW)		37.8		-
	Hydrogen Fuel (MT)		15.8		-
	Mass (MT)	**(1,451 avail)**	459	605	6,330
	Volume (m^3)	**(2,660 avail)**	1,070	2,160	6,570
Possible One-Way Trips			5	1	0

3.2.4. Spiegelgracht – 9197911

The *Spiegelgracht* is a general cargo ship that can carry containers and bulk cargo. Her relevant specifications were estimated and given in Table 3.11.

The route studied was an actual voyage from Zeebrugge, Belgium to Philadelphia, USA with characteristics shown in Table 3.12. The distance and time were obtained from marinetraffic.com and average speed was calculated. Average shaft power and energy used were obtained using Equation 3.2 and Equation 3.3, respectively.

Table 3.11: Estimated specifications of the Spiegelgracht

Name	Spiegelgracht
Type	Cargo
Overall Length	168 m
Beam	25 m
Main Engine Power (MCR)	12.1 MW
Fuel Capacity	1,880 m^3
Maximum Speed	19.6 knots
Available Volume	2,350 m^3
Available Mass	1,837 MT

Table 3.12: Route information used for the Spiegelgracht.

Departure Port	Zeebrugge
Arrival Port	Philadelphia
Distance	3,431 nm
Total Voyage Time	271 hr
Average Speed (SOA)	12.7 knots
Average Shaft Power	3.25 MW
Energy Used	881 MWh

Table 3.13: Characteristics of zero emission power systems needed on the Spiegelgracht for a single trip on the route studied.

		Fuel cell with liquid hydrogen	Fuel cell with 350 bar hydrogen gas	Battery
Single Trip	**Battery Capacity (MWh)**	-		1,960
	Fuel Cell Power (MW)	12.1		-
	Hydrogen Fuel (MT)	58.7		-
	Mass (MT) (1,837 avail)	667	1,210	23,500
	Volume (m^3) (2,350 avail)	1,670	5,720	27,100
Possible One-Way Trips		1	0	0

Table 3.13 shows the resulting characteristics of battery and fuel cell power systems (including hydrogen fuel) for a single trip, and how many one-way trips over the route could be accomplished with each solution. Over this long route, the available mass and volume is only able to accommodate a hydrogen fuel cell powerplant using liquid hydrogen as the fuel. The fuel cell system with 350 bar hydrogen meets the mass requirements but is more than 2-times the available volume. The battery system is over 11-times too large and massive.

3.2.5. Atlantic Klipper – 9454761

The *Atlantic Klipper* is a cargo ship designed to carry primarily bulk and containerized refrigerated cargo. Her relevant specifications were estimated and given in Table 3.14.

The route studied was an actual voyage from Hamburg, Germany to Rotterdam, Netherlands with characteristics shown in Table 3.15. The distance and time were obtained from marinetraffic.com and average speed was calculated. Average shaft power and energy used were obtained using Equation 3.2 and Equation 3.3, respectively.

Table 3.14: Estimated specifications of the Atlantic Klipper

Name	Atlantic Klipper
Type	Refrigerated Cargo
Overall Length	165 m
Beam	25 m
Main Engine Power (MCR)	14.3 MW
Fuel Capacity	2,269 m^3
Maximum Speed	23.9 knots
Available Volume	2,841 m^3
Available Mass	2,285 MT

Table 3.15: Route information used for the Atlantic Klipper.

Departure Port	Hamburg
Arrival Port	Rotterdam
Distance	307 nm
Total Voyage Time	20.5 hr
Average Speed (SOA)	15 knots
Average Shaft Power	3.5 MW
Energy Used	72.2 MWh

Table 3.16 shows the resulting characteristics of battery and fuel cell power systems (including hydrogen fuel) for a single trip, and how many one-way trips over the route could be accomplished with each solution. All zero emission powertrains are possible. The battery system could handle one trip and then require recharging. The gaseous hydrogen storage system size could be increased within the available mass and volume to allow two trips, and the liquid hydrogen storage system could be increased to allow four trips between refuelings.

It should be noted that, as mentioned in Section 3.1, the method used in this work does not consider auxiliary power needs in calculating the necessary powerplant size and mass on the grounds that those power needs are typically small in comparison to the powerplant. However, for refrigerated cargo ships such as this one, they can be significant. The *Atlantic Klipper* has

Table 3.16: Characteristics of zero emission power systems needed on the Atlantic Klipper for a single trip on the route studied.

			Fuel cell with liquid hydrogen	Fuel cell with 350 bar hydrogen gas	Battery
Single Trip	Battery Capacity (MWh)		-		144
	Fuel Cell Power (MW)		14.3		-
	Hydrogen Fuel (MT)		4.8		-
	Mass (MT)	(2,285 avail)	162	206	2,140
	Volume (m^3)	(2,841 avail)	373	705	2,220
Possible One-Way Trips			4	2	1

6.5 MW of auxiliary engine power installed and if that power is constantly utilized for the refrigeration systems then the required powerplant sizes and masses must be increased. Because the battery systems are close to the upper limit on mass and volume with one trip, adding this additional requirement may make them infeasible, and both hydrogen fuel cell systems should also be checked.

3.2.6. Capricorn – General Cargo – 8728098

The *Capricorn* is a general cargo ship primarily for bulk goods. Her relevant specifications were estimated and given in Table 3.17.

The route studied was a notional voyage from Famagusta, Cyprus to Kherson, Ukraine with characteristics shown in Table 3.18. The distance and time and average speed were estimated based on similar trips. Average shaft power and energy used were obtained using Equation 3.2 and Equation 3.3, respectively.

Table 3.17: Estimated specifications of the Capricorn

Name	Capricorn
Type	Cargo
Overall Length	119 m
Beam	15 m
Main Engine Power (MCR)	3.8 MW
Fuel Capacity	1,200 m^3
Maximum Speed	14 knots
Available Volume	1,289 m^3
Available Mass	1,146 MT

Table 3.18: Route information used for the Capricorn.

Departure Port	Famagusta
Arrival Port	Kherson
Distance	1500 nm
Total Voyage Time	214 hr
Average Speed (SOA)	7 knots
Average Shaft Power	480 kW
Energy Used	103 MWh

Table 3.19: Characteristics of zero emission power systems needed on the Capricorn for a single trip on the route studied.

		Fuel cell with liquid hydrogen	Fuel cell with 350 bar hydrogen gas	Battery
Single Trip	**Battery Capacity (MWh)**	-		206
	Fuel Cell Power (MW)	3.8		-
	Hydrogen Fuel (MT)	6.86		-
	Mass (MT) (1,146 avail)	44.3	160	2,740
	Volume (m^3) (1,289 avail)	237	710	3,160
Possible One-Way Trips		7	1	0

Table 3.19 shows the resulting characteristics of battery and fuel cell power systems (including hydrogen fuel) for a single trip, and how many one-way trips over the route could be accomplished with each solution. This is a relatively low power but long duration trip and as a consequence highlights the energy storage advantage of using liquid hydrogen rather than gaseous hydrogen to achieve up to seven trips within the available volume as opposed to just one trip with gaseous hydrogen. The battery system is more than twice the available mass and volume and will not work for even a single trip.

3.2.7. Atlantic Dawn – 9671450

The *Atlantic Dawn* is a multipurpose cargo ship. Her relevant specifications were estimated and given in Table 3.20.

The route studied was an actual voyage from Fuzhou, China to Singapore with characteristics shown in Table 3.21. The distance and time were obtained from marinetraffic.com and average speed was calculated. Average shaft power and energy used were obtained using Equation 3.2 and Equation 3.3, respectively.

Table 3.20: Estimated specifications of the Atlantic Dawn

Name	Atlantic Dawn
Type	Cargo
Overall Length	112 m
Beam	17 m
Main Engine Power (MCR)	4.0 MW
Fuel Capacity	594 m^3
Maximum Speed	17 knots
Available Volume	691 m^3
Available Mass	582 MT

Table 3.21: Route information used for the Atlantic Dawn.

Departure Port	Fuzhou
Arrival Port	Singapore
Distance	1800 nm
Total Voyage Time	223 hr
Average Speed (SOA)	8.1 knots
Average Shaft Power	430 kW
Energy Used	95.7 MWh

Table 3.22 shows the resulting characteristics of battery and fuel cell power systems (including hydrogen fuel) for a single trip, and how many one-way trips over the route could be accomplished with each solution. Like the *Capricorn*, this is another relatively low power but long duration trip with similarly sized power systems. However, because of the smaller amount of available volume compared to the *Capricorn*, mostly due to the smaller fuel tanks on the *Atlantic Dawn*, both hydrogen fuel cell systems can only achieve a single trip. (The volume required for two trips using a fuel cell with liquid hydrogen is 703 m^3, just over the available limit, and may still be possible.) The battery system is more than four-times the available mass and volume and will not work for even a single trip with this vessel.

Table 3.22: Characteristics of zero emission power systems needed on the Atlantic Dawn for a single trip on the route studied.

			Fuel cell with liquid hydrogen	Fuel cell with 350 bar hydrogen gas	Battery
Single Trip	Battery Capacity (MWh)		-		191
	Fuel Cell Power (MW)		4.0		-
	Hydrogen Fuel (MT)		6.38		-
	Mass (MT)	(582 avail)	93.7	153	2,840
	Volume (m^3)	(691 avail)	229	668	2,940
Possible One-Way Trips			1*	1	0

*The volume required for two trips using liquid hydrogen is 703 m^3, which is just over the volume limit and may still be possible.

3.2.8. Maersk Frontier – 9034767

The *Maersk Frontier* is an offshore supply vessel. Her relevant specifications were obtained from a company brochure[32] and are summarized in Table 3.23.

The route studied was an actual voyage from Aberdeen, UK to the Janice offshore platform in the North Sea between the UK and Denmark, with characteristics shown in Table 3.24. The distance and time were obtained from marinetraffic.com and average speed was calculated. Average shaft power and energy used were obtained using Equation 3.2 and Equation 3.3, respectively.

Table 3.23: Estimated specifications of the Maersk Frontier

Name	Maersk Frontier
Type	Offshore Supply
Overall Length	82.5 m
Beam	19 m
Main Engine Power (MCR)	5.37 MW
Fuel Capacity	1,349 m^3
Maximum Speed	14 knots
Available Volume	1,509 m^3
Available Mass	1,307 MT

Table 3.24: Route information used for the Maersk Frontier.

Departure Port	Aberdeen
Arrival Port	Janice offshore facility
Distance	166 nm
Total Voyage Time	17.2 hr
Average Speed (SOA)	9.7 knots
Average Shaft Power	1.77 MW
Energy Used	30.4 MWh

[32] "Platform Supply Vessel Maersk Frontier," Maersk Supply Service, Version Number 1.1 (no date).

Table 3.25: Characteristics of zero emission power systems needed on the Maersk Frontier for a single trip on the route studied.

		Fuel cell with liquid hydrogen	Fuel cell with 350 bar hydrogen gas	Battery
Single Trip	Battery Capacity (MWh)	-		60.7
	Fuel Cell Power (MW)	5.37		-
	Hydrogen Fuel (MT)	2.02		-
	Mass (MT) (1,307 avail)	62.5	81.2	810
	Volume (m^3) (1,509 avail)	145	284	934
Possible One-Way Trips		28	7	1
Possible Round Trips		14	3	0

Table 3.25 shows the resulting characteristics of battery and fuel cell power systems (including hydrogen fuel) for a single trip, and how many one-way trips over the route could be accomplished with each solution. All zero emission powertrains are possible for a single one-way trip. However, because there is likely little ability for the vessel to recharge or refuel at the platform, the feasibility of this vessel was set at a round-trip. Even then, this vessel likely loiters at the platform for many hours so some margin over this would be important.

Using the round-trip criteria, the battery system is not able to meet the requirements. The gaseous storage system could be increased in capacity to handle three round trips and the liquid storage system could handle 14. Additional investigation is needed to determine whether the margin is enough to accomplish the entire mission of this kind of vessel.

3.2.9. Alfa Nero – 1009376

The *Alfa Nero* is a luxury “mega” yacht. Her relevant specifications were estimated and given in Table 3.26.

Table 3.26: Estimated specifications of the Alfa Nero

Name	Alfa Nero
Type	Yacht
Overall Length	82 m
Beam	14 m
Main Engine Power (MCR)	6.9 MW
Fuel Capacity	294 m^3
Maximum Speed	20 knots
Available Volume	529 m^3
Available Mass	281 MT

Table 3.27: Route information used for the Alfa Nero.

Departure Port	Antibes
Arrival Port	Antibes
Distance	64 nm
Total Voyage Time	10 hr
Average Speed (SOA)	6.4 knots
Average Shaft Power	229 kW
Energy Used	2.29 MWh

The route studied was a notional 10 hour cruise originating in Antibes, France and returning to the same port with characteristics shown in Table 3.27. The distance and average speed were estimated. Average shaft power and energy used were obtained using Equation 3.2 and Equation 3.3, respectively.

Table 3.28 shows the resulting characteristics of battery and fuel cell power systems (including hydrogen fuel) for a single trip, and how many one-way trips over the route could be accomplished with each solution. It is a low-power, low-energy voyage but the high power capability installed on-board makes the fuel cells the dominant contributor to mass and volume for the single trip. This allows the battery to be the preferred solution if this vessel stays close to shore and can be recharged after the equivalent of four similar trips. However if the vessel needs

Table 3.28: Characteristics of zero emission power systems needed on the Alfa Nero for a single trip on the route studied.

			Fuel cell with liquid hydrogen	Fuel cell with 350 bar hydrogen gas	Battery
Single Trip	**Battery Capacity (MWh)**		-		4.58
	Fuel Cell Power (MW)		6.9		-
	Hydrogen Fuel (kg)		153		-
	Mass (MT)	**(281 avail)**	57.4	58.8	61.0
	Volume (m^3)	**(529 avail)**	127	138	70.4
Possible One-Way Trips			107	28	4

to have the capability for longer duration missions between refuelings, the hydrogen fuel cell would be able to satisfy 28 trips using gaseous storage and over 100 such trips with liquid hydrogen.

3.2.10. Zalophus

The *Zalophus* is a passenger boat in the San Francisco Bay used for Bay tours and charters. Her relevant specifications were obtained from the operator[33] and given in Table 3.29.

The route studied was a notional 1 hour Bay tour cruise originating and ending at the Port of San Francisco, USA with characteristics shown in Table 3.30. The average speed and time were obtained from the operator and distance was calculated. Average shaft power and energy used were obtained using Equation 3.2 and Equation 3.3, respectively.

Table 3.29: Estimated specifications of the Zalophus

Name	Zalophus
Type	Passenger
Overall Length	47 m
Beam	10 m
Main Engine Power (MCR)	800 kW
Fuel Capacity	29.5 m^3
Maximum Speed	13 knots
Available Volume	40 m^3
Available Mass	28 MT

Table 3.30: Route information used for the Zalophus.

Departure Port	San Francisco
Arrival Port	San Francisco
Distance	11 nm
Total Voyage Time	1 hr
Average Speed (SOA)	11 knots
Average Shaft Power	485 kW
Energy Used	485 kWh

[33] Personal communication with J. Burgard, Vice President of Operations, Red and White Fleet

Table 3.31: Characteristics of zero emission power systems needed on the Zalophus for a single trip on the route studied.

		Fuel cell with liquid hydrogen	Fuel cell with 350 bar hydrogen gas	Battery
Single Trip	Battery Capacity (kWh)	-		969
	Fuel Cell Power (kW)	800		-
	Hydrogen Fuel (kg)	32.3		-
	Mass (MT) (28 avail)	6.28	6.58	13.0
	Volume (m^3) (40 avail)	13.8	16.0	15.0
Possible One-Way Trips		33	8	2

Table 3.31 shows the resulting characteristics of battery and fuel cell power systems (including hydrogen fuel) for a single trip, and how many one-way trips over the route could be accomplished with each solution. All zero emission solutions are possible. If the vessel can recharge after every one or two trips the battery system will be sufficient. A gaseous hydrogen fuel cell system could be sized within available space to allow the vessel to operate for a full day (8 trips) before refueling, and a liquid hydrogen fuel cell system could operate for several days (33 trips).

3.2.11. Northwestern – 7719179

The *Northwestern* is a fishing boat used for Alaskan crab. Her relevant specifications were estimated from information obtained from the vessel's website[34] and given in Table 3.32.

The route studied was an actual voyage from Seattle, USA to Dutch Harbor, USA, with characteristics shown in Table 3.33. The distance and time were obtained from marinetraffic.com and average speed was calculated. Average shaft power and energy used were obtained using Equation 3.2 and Equation 3.3, respectively.

[34] See: fvnorthwestern.com

Table 3.32: Estimated specifications of the Northwestern

Name	Northwestern
Type	Fishing Trawler
Overall Length	38 m
Beam	8.8 m
Main Engine Power (MCR)	950 kW
Fuel Capacity	174 m^3
Maximum Speed	12 knots
Available Volume	191 m^3
Available Mass	150 MT

Table 3.33: Route information used for the Northwestern.

Departure Port	Seattle
Arrival Port	Dutch Harbor
Distance	1707 nm
Total Voyage Time	217 hr
Average Speed (SOA)	7.9 knots
Average Shaft Power	267 kW
Energy Used	58.0 MWh

Table 3.34 shows the resulting characteristics of battery and fuel cell power systems (including hydrogen fuel) for a single trip, and how many one-way trips over the route could be accomplished with each solution. The long endurance combined with the small vessel size (and available mass and volume) results in the only possible solution being the fuel cell with liquid hydrogen. The fuel cell with gaseous hydrogen meets the mass requirements but is nearly twice too large. The battery system is about 10-times too massive and large.

This assessment does not consider the energy and endurance requirements of the vessel when engaged in crab fishing operations, which could affect feasibility of a zero emission powerplant.

Table 3.34: Characteristics of zero emission power systems needed on the Northwestern for a single trip on the route studied.

			Fuel cell with liquid hydrogen	Fuel cell with 350 bar hydrogen gas	Battery
Single Trip	**Battery Capacity (MWh)**		-		116
	Fuel Cell Power (kW)		950		-
	Hydrogen Fuel (MT)		3.87		-
	Mass (MT)	**(150 avail)**	44.7	80.3	1,550
	Volume (m^3)	**(191 avail)**	112	378	1,780
Possible One-Way Trips			1	0	0

3.2.12. Trondheimsfjord 2 – 9432189

The *Trondheimsfjord* is a high-speed passenger ferry made of carbon fiber. Her relevant specifications were estimated from information obtained from a recent feasibility study[35] and given in Table 3.35.

The ferry operates on a route between Trondheim, Norway and Vanvikan, Norway, with characteristics shown in Table 3.36. The route characteristics were obtained from the feasibility study and the average speed of advance was calculated. Average shaft power and energy used were obtained using Equation 3.2 and Equation 3.3, respectively.

Table 3.35: Estimated specifications of the Trondheimsfjord 2

Name	Trondheimsfjord 2
Type	High speed passenger ferry
Overall Length	24.5 m
Beam	8 m
Main Engine Power (MCR)	1.62 MW
Fuel Capacity	5.3 m^3
Maximum Speed	32.5 knots
Available Volume	17 m^3
Available Mass	8 MT

Table 3.36: Route information used for the Trondheimsfjord 2.

Departure Port	Trondheim
Arrival Port	Vanvikan
Distance	8 nm
Total Voyage Time	19 min
Average Speed (SOA)	25.3 knots
Average Shaft Power	760 kW
Energy Used	241 kWh

[35] C. Ianssen, E. Ianssen, and T. Sandblost, "Battery/fuel cell fast ferry," Selfa AS, April 2017.

Table 3.37: Characteristics of zero emission power systems needed on the Trondheimsfjord 2 for a single trip on the route studied.

		Fuel cell with liquid hydrogen	Fuel cell with 350 bar hydrogen gas	Battery
Single Trip	Battery Capacity (kWh)	-		481
	Fuel Cell Power (MW)	1.62		-
	Hydrogen Fuel (kg)	16.0		-
	Mass (MT) (8 avail)	12.7	12.9	6.46
	Volume (m^3) (17 avail)	28	29	7.5
Possible One-Way Trips		0	0	1

Table 3.37 shows the resulting characteristics of battery and fuel cell power systems (including hydrogen fuel) for a single trip, and how many one-way trips over the route could be accomplished with each solution. The only zero emission solution that can fit in the available space and mass allowance in the demihulls is the battery. The high power but short endurance requirement means that the volume and mass of the fuel cell itself accounts for most of the hydrogen fuel cell power system and makes it too large to fit within the demihulls of this catamaran. This case study shows the advantage that battery systems can have for high power, short endurance missions as well as a need for more compact fuel cell solutions for this market.

3.2.13. Hein Senior - 9092642

The *Hein Senior* is a fishing trawler. Her relevant specifications were estimated and given in Table 3.38.

The route studied was an actual voyage starting in Harlingen, Netherlands, to Eenshaven, Netherlands with time spent in the North Sea fishing for about 4 days, with characteristics shown in Table 3.39. The distance and time were obtained from marinetraffic.com and average speed was calculated. Average shaft power and energy used were obtained using Equation 3.2 and Equation 3.3, respectively.

Table 3.38: Estimated specifications of the Hein Senior

Name	Hein Senior
Type	Fishing trawler
Overall Length	24 m
Beam	6.2 m
Main Engine Power (MCR)	224 kW
Fuel Capacity	15 m^3
Maximum Speed	11.5 knots
Available Volume	21 m^3
Available Mass	14 MT

Table 3.39: Route information used for the Hein Senior.

Departure Port	Harlingen
Arrival Port	Eenshaven
Distance	484 nm
Total Voyage Time	101 hr
Average Speed (SOA)	4.8 knots
Average Shaft Power	16 kW
Energy Used	1.64 MWh

Table 3.40 shows the resulting characteristics of battery and fuel cell power systems (including hydrogen fuel) for a single trip, and how many one-way trips over the route could be accomplished with each solution. This is another example of a low power, long endurance trip that is particularly amenable to hydrogen fuel cell systems. The system with gaseous hydrogen can accomplish one trip, and the system with liquid hydrogen could be sized to accomplish up to six trips within the mass and volume allowance. The battery system is twice too large and three-times too massive for the single trip requirements.

Table 3.40: Characteristics of zero emission power systems needed on the Hein Senior for a single trip on the route studied.

			Fuel cell with liquid hydrogen	Fuel cell with 350 bar hydrogen gas	Battery
Single Trip	**Battery Capacity (MWh)**		-		3.29
	Fuel Cell Power (kW)		224		-
	Hydrogen Fuel (kg)		110		-
	Mass (MT)	**(14 avail)**	2.37	3.38	43.9
	Volume (m^3)	**(21 avail)**	5.4	13	51
Possible One-Way Trips			6	1	0

3.2.14. Trearddur Bay

The *Trearddur Bay* is a high-speed catamaran service boat used in the off-shore wind industry. Her relevant specifications were obtained from the literature[36][37] and given in Table 3.41.

The vessel operates out of Newhaven, UK. The route studied was an actual voyage starting and ending in Newhaven and presumably servicing a nearby windfarm, with characteristics shown in Table 3.42. The distance and time were obtained from marinetraffic.com. Calculating average speed resulted in just 6.6 knots. It is very likely rather than travelling at 6.6 knots for the entire trip the vessel went out and back at somewhere near top speed and then loitered at low speed through the wind farm, so the trip was divided into three segments (out-loiter-back) to make the power and energy requirements more realistic. There is a wind farm about 5 nm SW of Newhaven which was used as the service location so the route assumed a total of 10 nm (round trip) at 28 knots (80% MCR) which would take 40 minutes, and a loitering segment of 41 nm over the remaining 7 hours (average 5.9 knots). For these segments the average shaft power and energy used were still obtained using Equation 3.2 and Equation 3.3, respectively.

Table 3.41: Estimated specifications of the Trearddur Bay

Name	Trearddur Bay
Type	High speed catamaran
Overall Length	20.6 m
Beam	7 m
Main Engine Power (MCR)	1.8 MW
Fuel Capacity	5.3 m^3
Maximum Speed	30 knots
Available Volume	16 m^3
Available Mass	9 MT

[36] "Turbine Transfers Trearddur Bay," Voith Turbo (no date)
[37] "Trearddur Bay – Turbine Transfers" Turbine Transfers Ltd, 2015, Available: http://www.turbinetransfers.co.uk/portfolio/trearddur-bay/

Table 3.42: Route information used for the Trearddur Bay. Refer to text for clarifications on the route.

Departure Port	Newhaven
Arrival Port	Newhaven
Distance	51 nm (10 nm out and back, 41 nm loiter)
Total Voyage Time	7.7 hr (0.7 hr out and back, 7 hr loiter)
Average Speed (SOA)	28 knots (out and back) | 5.9 knots (loiter)
Average Shaft Power	1,460 kW (out and back) | 14 kW (loiter)
Energy Used	981 kWh (out and back) | 96 kWh (loiter)

Table 3.43: Characteristics of zero emission power systems needed on the Trearddur Bay for a single trip on the route studied.

			Fuel cell with liquid hydrogen	Fuel cell with 350 bar hydrogen gas	Battery
Single Trip	Battery Capacity (kWh)		-		2,154
	Fuel Cell Power (MW)		1.8		-
	Hydrogen Fuel (kg)		72		-
	Mass (MT)	(9 avail)	14.7	15.4	28.8
	Volume (m^3)	(16 avail)	32.6	37.6	33.2
Possible One-Way Trips			0	0	0

Table 3.43 shows the resulting characteristics of battery and fuel cell power systems (including hydrogen fuel) for a single trip, and how many one-way trips over the route could be accomplished with each solution. None of the zero emission systems can be accommodated within the available space and volume in the demihulls. Previous studies have shown hydrogen fuel cell systems implemented on high speed catamarans is possible if the components are located above deck or on the roof rather than in the demihulls.[38,39] The inherent higher stability of a multi-hull vessel compared to a monohull allows this higher center of gravity without compromising performance.

3.3. Combined Results and Discussion

3.3.1. Power and Energy Limits

The vessel case studies showed that the application limit of a battery system was reached before the gaseous hydrogen fuel cell system, and in turn the limit of the gaseous hydrogen system was reached before the liquid hydrogen fuel cell system. (The one exception being the *Trondheimsfjord 2*, which could be powered by a battery system but not by either hydrogen fuel cell option.) Figure 3.3 aggregates the results from all of the vessel case studies and illustrates

[38] J. W. Pratt and L. E. Klebanoff, "Feasbility of the SF-BREEZE: a Zero-Emission, Hydrogen Fuel Cell, High-Speed Passenger Ferry," Sandia National Laboratories report SAND2016-9719, October 2016, available through: maritime.sandia.gov

[39] T. Stromgren, "The Norwegian Hydorgne Powered Speed Passenger Ferry," August 2017, available: https://prosjekt.fylkesmannen.no/Documents/Klimaomstilling/Dokument/2017%20torsdag/5%20-%20STR%C3%98MGREN.pdf

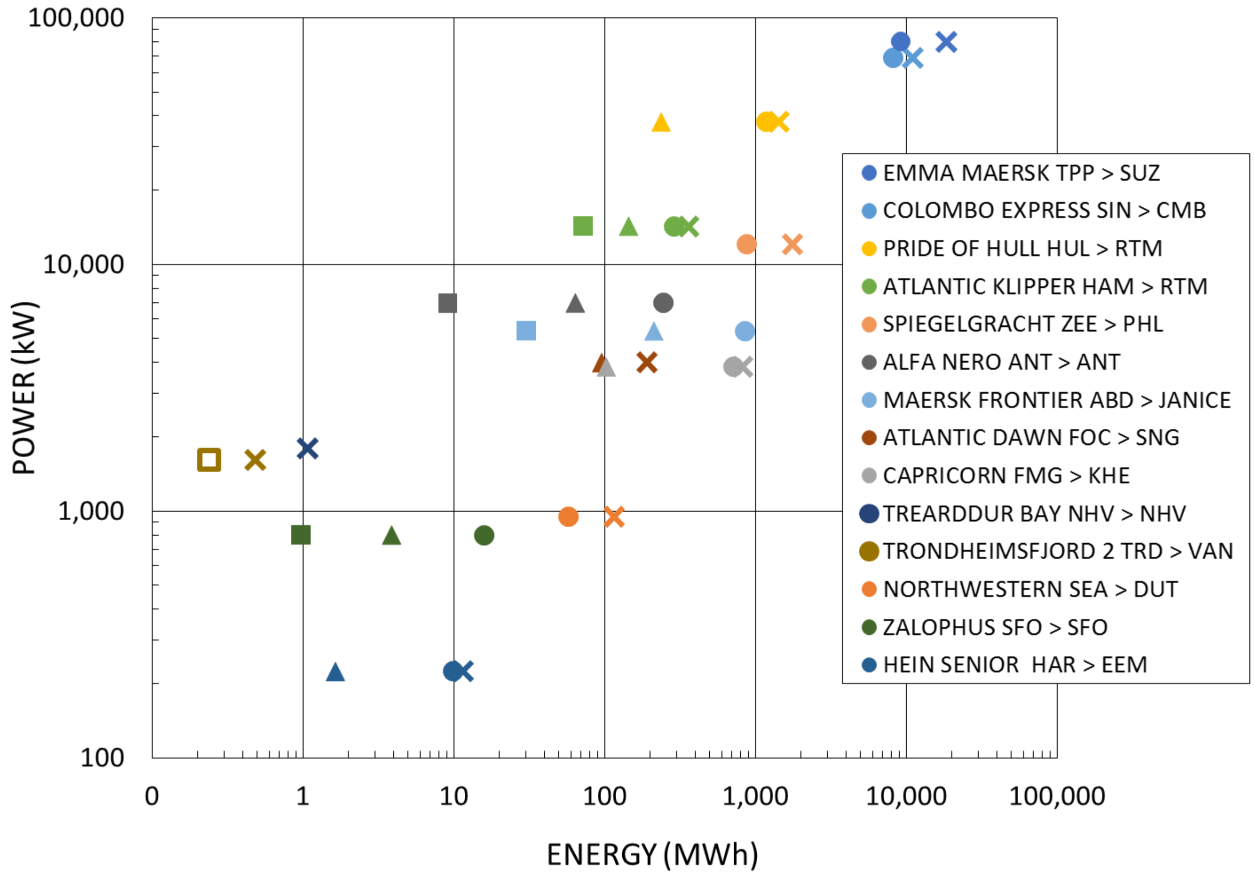

Figure 3.3 Installed Power of a vessel (MCR) versus the Energy required for a specific route and multiples of that route

this by showing the limit of each technology for each vessel studied. The points on the chart represent the limits of feasibility for each of the three powertrains studied.

The meanings of the symbols used for the different points in Figure 3.3 are given in Table 3.44.

The case of the *Atlantic Klipper* (green symbols) is used to illustrate how to read the chart. The power of the *Atlantic Klipper* is 14,300 kW so all points are on the same horizontal line corresponding to 14,300 on the Y-axis. The *Atlantic Klipper* route uses 72.2 MWh per trip. It was found in the case study that the limit of the battery system is one trip (72 MWh, the solid

Table 3.44: The code for the different shapes on Figure 3.3. Note that the battery-only symbol is rarely used.

Symbol	Meaning
■	Limit of a battery system
▲	Limit of a gaseous hydrogen system
●	Limit of a liquid hydrogen system
X	None of the systems work, “one trip past possible”
□	Only a battery system works

square), the limit of the gaseous hydrogen fuel cell system is two trips (144 MWh, the solid triangle) and the limit for the liquid hydrogen fuel cell system is four trips (289 MWh, the solid circle). Five trips (361 MWh, the X) are not possible with any system.

If a powertrain limit symbol is not present for a particular vessel that means that powertrain option will not meet any trips. An example of this can be seen with the *Emma Maersk*, the dark blue symbols at the top of the chart. Only a solid circle and an X are present, but the solid triangle (battery system limit) and solid square (gaseous hydrogen limit) are missing, meaning that neither the battery nor the gaseous hydrogen system will work for any trips. The *Treadddur Bay* is an example which only has an X and illustrates that no powertrains are capable of meeting the energy requirements of just one trip. (If there is no visible X symbol, such as for the *Zalophus*, *Alfa Nero*, and *Maersk Frontier*, it is because it is hidden behind the solid circle on the chart meaning that the incremental energy of one more trip is small compared to the total energy.)

Some trends can be seen in Figure 3.3. In general, no hard limit of power or energy was found for zero emission power systems: from a small fishing trawler to a large containership, the systems were shown to be quite versatile in their ability to supply both the energy and power needs of these vessels. Both fuel cell systems work in almost every vessel and can be implemented in longer distances than the battery systems. It is only at the longer voyages that the 5000 psi hydrogen powered fuel cell fails to meet the requirements. For the greatest versatility and efficiency, the LH_2 FC system prevails; even in the *Emma Maersk* the LH_2 system is possible.

As noted above the battery systems proved to be the only viable option for the *Trondheimsfjord 2*'s requirements. This is most likely due to the combination of a few factors that differentiate this vessel from the rest. It is a catamaran, high speed, planing vessel. Also the vessel mission is shorter than most other vessels in the study, so it requires relatively little energy relative to the power of its engine. This leads to the success of the battery systems because they have a low "overhead" in terms of mass and volume. This is illustrated in the fact that the battery system sizing is only based on the required energy for the trip whereas fuel cell systems must also take into account the maximum power requirement. The battery system is a power and energy producing unit all in one piece of equipment and can store a relatively low quantity of energy more efficiently than the FC because the FC systems require a fuel cell as well as a fuel container regardless of the length of the voyage.

3.3.2. Volume, Displacement, and Energy Limits

The power and energy chart of Figure 3.3 illustrates that neither power nor energy is a limiting factor by itself. To try and find the limiting factor, the case studies were examined in more detail and it was found that in each case the first limit reached for every powertrain was the volume limit. This is a factor of both the available volume of the vessel as well as the volume of the powertrain.

Figure 3.4 illustrates that the type of powertrain that will work for a certain required amount of stored energy depends on the available volume. Figure 3.5 is the same data zoomed-in to provide detail around the origin. The dashed lines roughly represent the upper limit of each

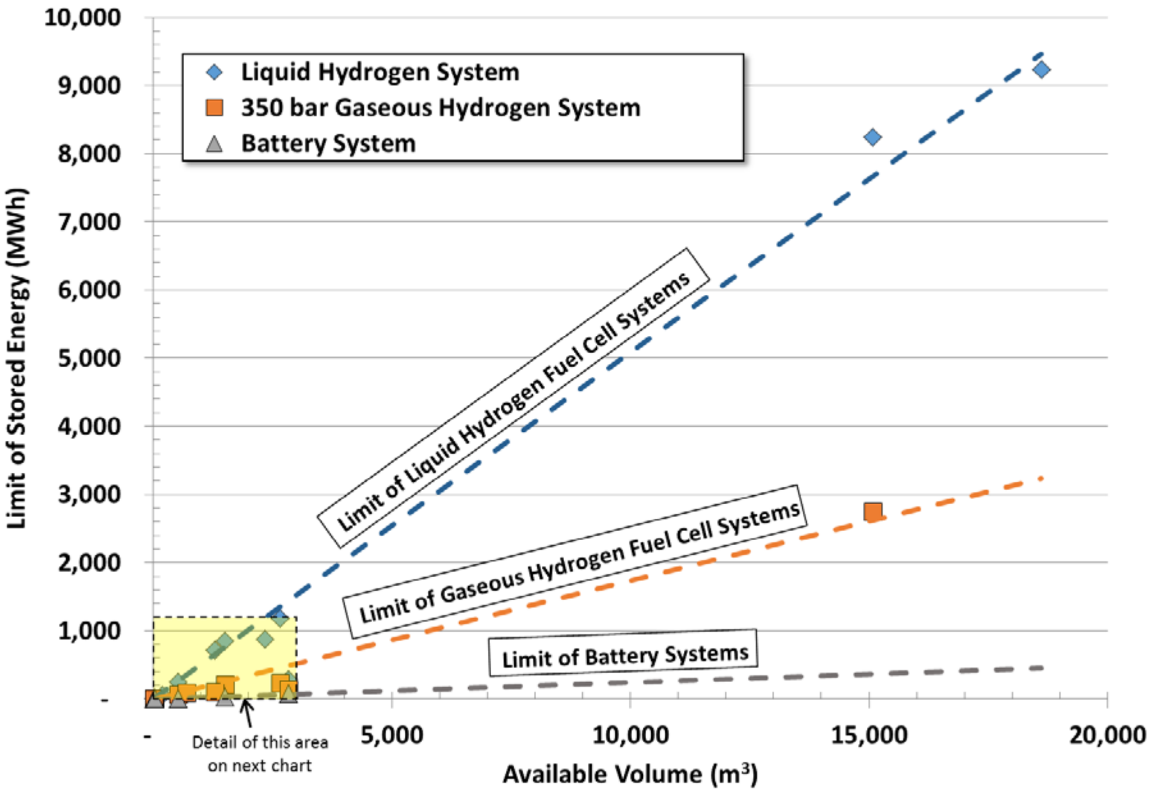

Figure 3.4: Approximate mission energy upper limits of zero emission powertrain technology based on available volume.

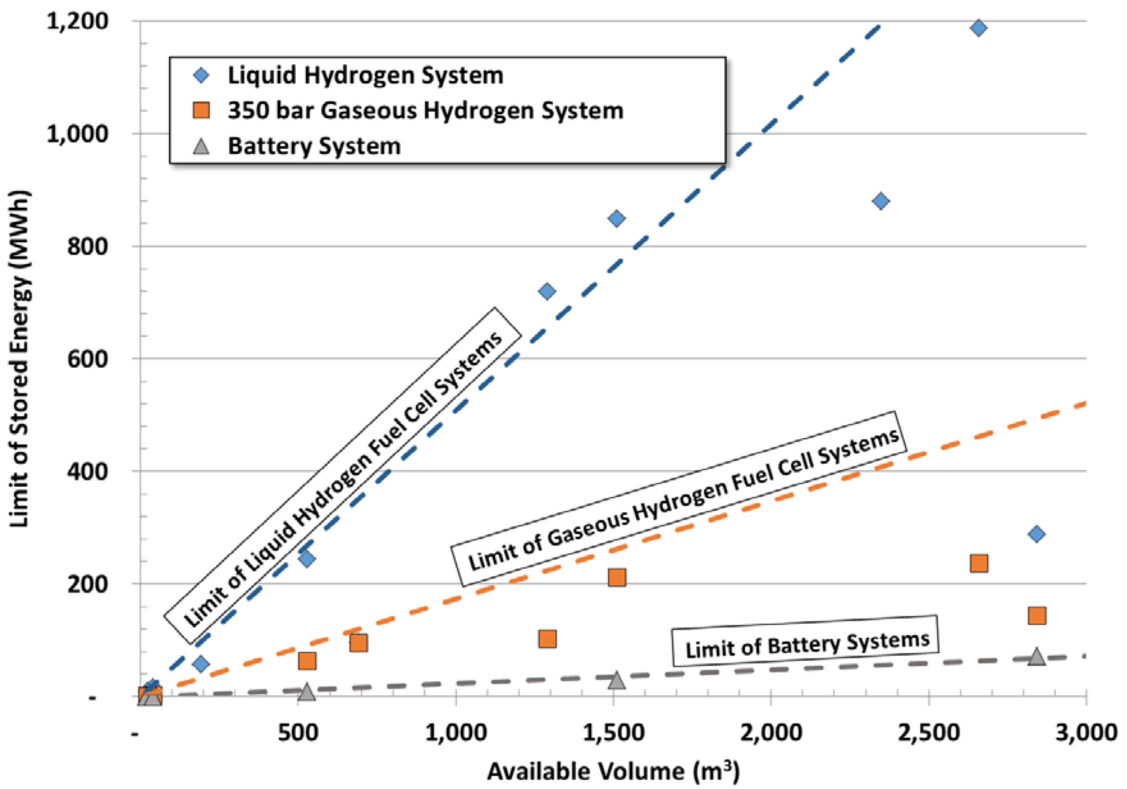

Figure 3.5: Approximate mission energy upper limits of zero emission powertrain technology based on available volume, zoomed in to show detail around the origin.

powertrain technology in terms of energy stored for volume available. Battery systems are primarily suited for vessels with large available volume and/or small amounts of stored energy. Liquid hydrogen fuel cell systems can meet much higher required amounts of stored energy for the same volume, and gaseous hydrogen fuel cell systems fall in between.

Displacement is a more readily-available parameter than available volume. Figure 3.6 illustrates the strong correlation between vessel displacement[40] and available volume for the vessels in this study, showing it is acceptable to substitute one for the other for these purposes.

Figure 3.7, with zoomed-in versions in Figure 3.8 and Figure 3.9, show the results using vessel displacement rather than available volume.

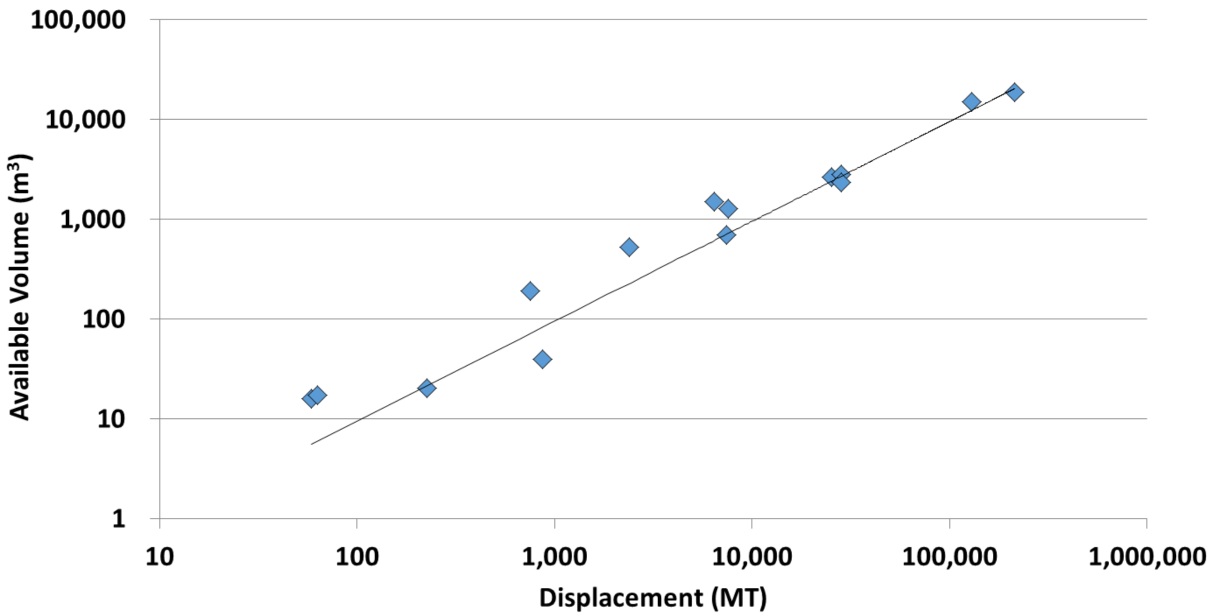

Figure 3.6: Relationship between estimated available volume and overall vessel displacement showing that one can generally be substituted for the other for purposes of estimating the applicability of different powertrain types to different vessel sizes.

[40] The method used to estimate vessel displacement is described in Appendix A

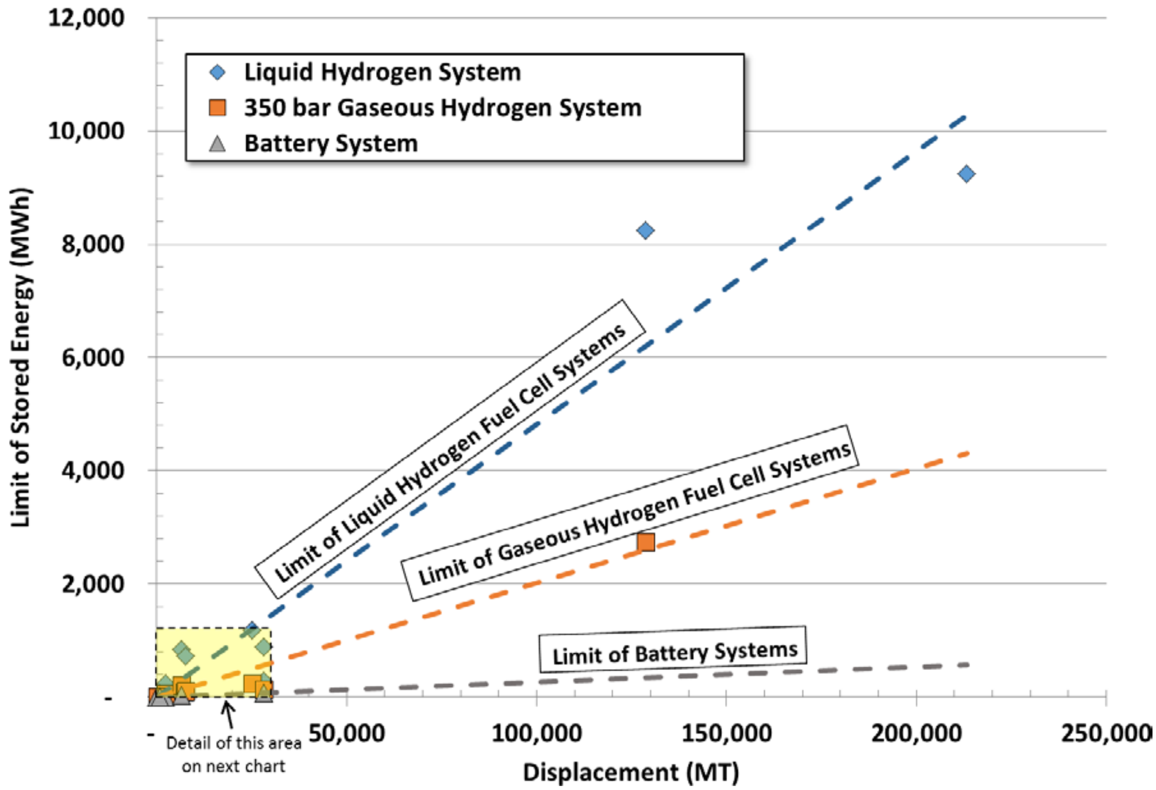

Figure 3.7: Approximate mission energy upper limits of zero emission powertrain technology based on vessel displacement.

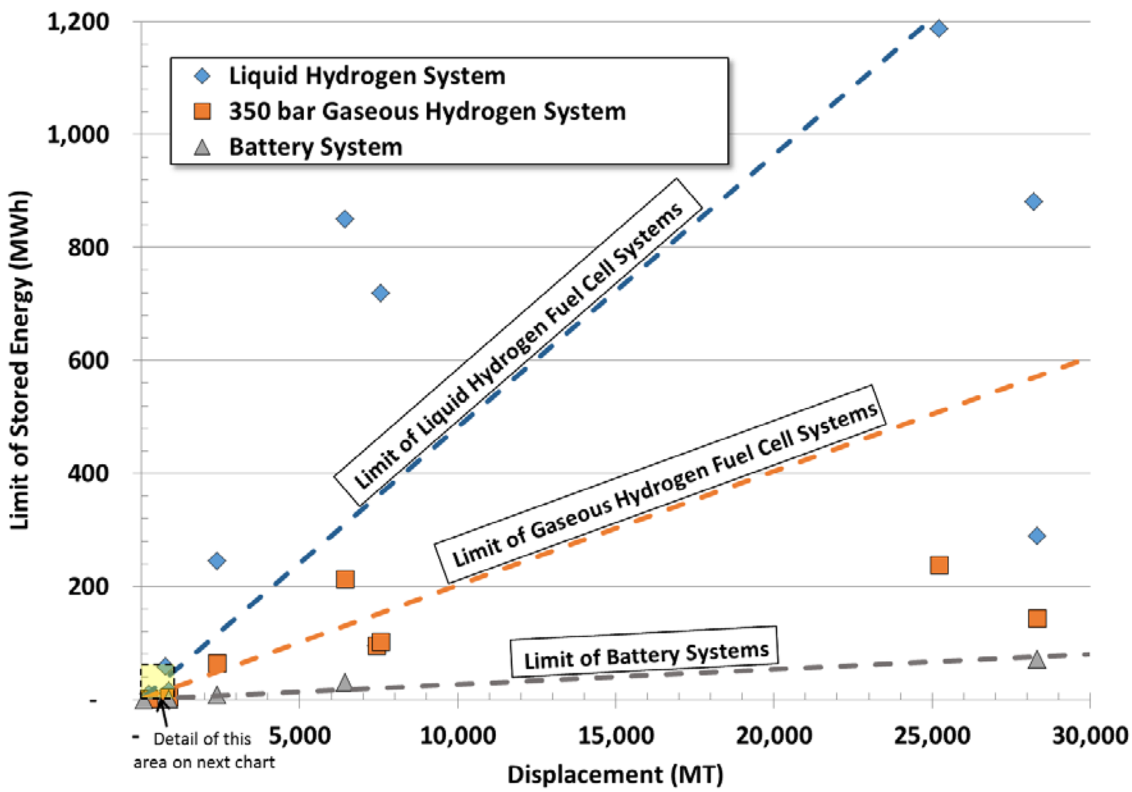

Figure 3.8: Approximate mission energy upper limits of zero emission powertrain technology based on vessel displacement, zoomed in to show some detail near the origin.

Using these charts a vessel designer can quickly get an estimate of the zero emission powertrain solution that may work for a given vessel size. This relationship could guide the design of zero emission ships by taking a specific mission for a vessel and working backwards to design it. For example, if a ship has a displacement of 100,000 MT and requires 4,000 MWh of energy, Figure 3.7 shows that only a fuel cell system using liquid hydrogen could power that ship. Another example, if a ship requires 40 MWh of energy to travel from Port A to Port B then Figure 3.8 shows it would have to have a displacement of at least 1,000 MT to hold a fuel cell system using liquid hydrogen, 2,000 MT to hold a fuel cell system using gaseous hydrogen, and about 15,000 MT to hold a battery system.

One reason the studied zero emission powertrains continually are able to meet requirements even when looking at very long distances and very high power levels is that as the power and range of a vessel increases, the size of the vessel is also increasing. This is a result of economies of scale in the shipping industry but is a characteristic that benefits the application of these powertrains.

Figure 3.9 shows a close-up of the area near the origin, relevant to the smaller passenger vessels studied. The wide scatter in the data compared to the trend line becomes more obvious at this scale. This shows that the trends observed for larger ships may not be directly transferrable to small vessels and that more detailed studies should be conducted.

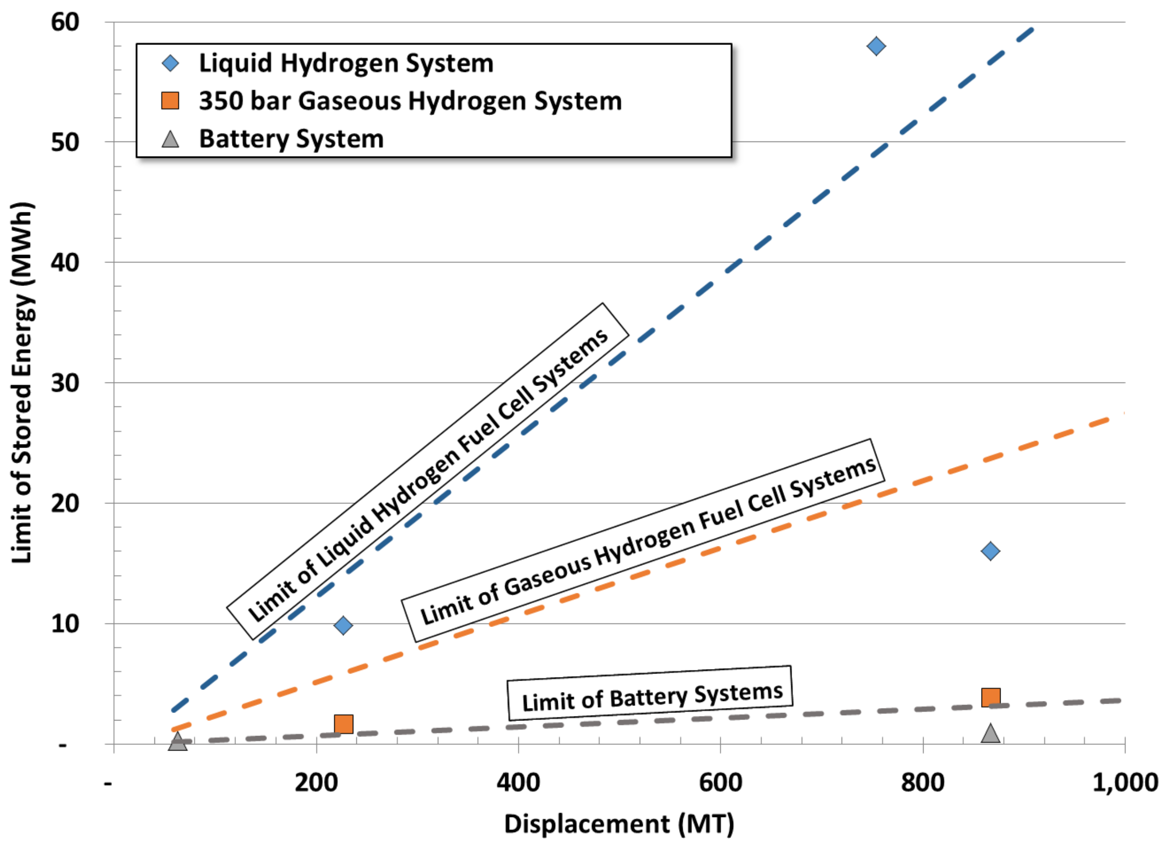

Figure 3.9: Approximate mission energy upper limits of zero emission powertrain technology based on vessel displacement, zoomed in to show points very close to the origin relevant to small vessels.

4. CONCLUSIONS AND RECOMMENDATIONS

4.1. Conclusions of the Study

The case studies presented here show that today's zero emission powertrains can meet the propulsion power and energy storage requirements of a wide range of vessels, from small passenger ferries and fishing boats to the largest cargo ships in the world.

The powertrains examined were battery-only, fuel cell systems with hydrogen stored as a gas, and fuel cell systems with hydrogen stored as a liquid.

The high energy storage density of liquid hydrogen tanks (1.3 kWh/L) compared to gaseous hydrogen tanks (0.36 kWh/L) and battery systems (~0.09 kWh/L) made liquid hydrogen-based systems the most capable in terms of its ability to meet a wide variety of vessel sizes and mission requirements. Longer endurance missions favored hydrogen fuel cell systems because of this. As endurance increases the energy component of the system increases. For fuel cell systems this is just the fuel tank; the fuel cell itself remains constant at the level needed for the power. For battery systems the entire battery system size must increase even though the power level is constant. Since the energy density of battery systems is less than 1/10 that of liquid hydrogen, battery systems quickly become much larger than hydrogen systems as stored energy demand increases.

However, an interesting phenomenon was observed for small vessels requiring high power for short durations: the fuel cell systems were not able to meet the volume requirements while the battery system was. This was found to be due to the size of the fuel cell system. For a high-power system that does not require a lot of stored energy, a battery-only system can meet both the power and energy requirements with just the batteries whereas the hydrogen fuel cell system also requires a large fuel cell to convert the hydrogen to power. The fuel cell size dominates over the battery size in these instances.

The study also showed that the available volume of the vessel is what constrained all systems. Available volume was shown to be correlated with overall ship displacement and a series of charts was produced to enable vessel designers to quickly determine the approximate suitability of different zero emission powertrain options based on the vessel size and energy requirements of the mission.

The mass of the powertrain was never a limiting factor, but one aspect of system mass deserves mention. The specific energy (J/kg) of hydrogen is about 3-times that of maritime liquid fossil fuels (HFO, IFO, MDO, and diesel). Even considering the added mass of the hydrogen tank, the fuel system on board a vessel powered by hydrogen can be significantly lighter than one powered by liquid fossil fuel. This can translate to lower power requirement, and it can also lead to higher cargo capacity. Regarding the latter, the capacity of a cargo ship is based on the draft, which is a function of displacement, which depends on the on-board mass of systems and cargo. If the fuel system takes up less of the total displacement then the ship can transport more containers. Also, if the fuel cell and hydrogen fuel takes up more volume but less weight, the net result may be no change in cargo-carrying capacity.

This study makes many assumptions and uses many estimates and averages, so should be considered just a first approximation of defining applicability of zero emission powertrains on maritime vessels today. This study also did not consider alternative designs – it only looked at existing vessels as opposed to new builds. Because none of the zero emission powertrains connect directly to the shaft, there is an opportunity to locate the energy storage and power systems around the vessel in non-traditional locations, which can potentially have more available volume than the traditional engine room location. The next step for a vessel designer is to consider the actual available mass and volume of the powertrain, the actual mission profile, and the actual hydrogen, fuel cell, and/or battery system to be employed. Technology in this industry continues to improve yearly, and improvements in hydrogen, fuel cell, and battery systems will enable more capabilities in the future.

4.2. Recommendations and Questions for Future Studies

Future studies can be made more accurate in the following ways:

- To make the current assessment more accurate, pieces of information that would aid with this study are actual values for: displacement, installed engine power, submerged volume (Block Coefficient), fuel capacity, type of fuel used, engine fuel consumption, engine system mass and volume. Information that would help extensions of this study including the size of engine rooms (Volume), amount of space used up for maintenance for fuel cell racks, and possible sizes of 10+ MW fuel cell systems.
- To find the exact limit of each power plant, more than one route for the studied vessels should be analyzed. Differences in routes should include different speeds and distances.
- Additional case studies would create a more detailed map of the limits of batteries and fuel cells. Particularly, look in more detail at the types of vessels that the powertrains have difficulty meeting to further define the limits, and explore the power/endurance tradeoff between the two types of powertrains.
- More study on the tradeoff of fuel mass and cargo mass, i.e., quantifying whether and how a low-weight fuel such as hydrogen can increase cargo carrying capacity.

This study can serve as a starting point for examining related topics such as:

- This study did not examine economics. Future studies should be done to compare the prices of different zero emission power plants and weigh out the differences in the cost of fuels, infrastructure for refueling, and cost of power plants.
- This study did not examine emissions. Although both types of powerplants are zero emission on the ship, the energy used to recharge the batteries or make the hydrogen may not be zero emission. Full “well-to-waves” emissions analysis with comparison to conventional diesel technology is needed to understand the true global impact of converting vessels to zero emission.
- Further studies should also be made into how this type of power plant system changes job demand. Shipyards will need less conventional engine specialists and more information technology or “IT” professionals. The demand for a specialty in fuel cells and batteries is going to increase significantly. How will widespread deployment of zero emission technologies affect jobs, employment, education, families, industries, and regulations?

- Since batteries and fuel cells output electrical energy, an electrical motor is needed for propulsion. Electric motors convert electrical energy to mechanical energy. These electric motors run on Alternating Current (AC). However, both fuel cell and batteries produce Direct Current (DC) and require a converter. A converter could occupy a significant amount of space on a marine vessel. This becomes important when designing a battery or fuel cell power plant and its location on a ship. What is the availability of electric motors in the 10's of MW and how do they change the assessment? How does the selection of AC or DC motor change the other equipment required and which solution is better?
- Safety of large battery systems containing large amounts of chemical energy and hydrogen storage systems should be understood and may affect the location and space assumptions in this work.

APPENDIX A

METHOD USED TO ESTIMATE SHIP DISPLACEMENT

When displacement wasn't available from the open literature it was estimated from ship dimensions. The first step in calculating displacement is to find the submerged volume:

$$Submerged\ Volume\ [m^3] = C_b \times (L_{pp}[m] \times B\ [m] \times T\ [m])$$

Where *Cb* is the non-dimensional block coefficient, *Lpp* is the length between perpendiculars (approximately the length of the ship along the waterline), *B* is the beam, and *T* is the draft. Due to limited availability of Lpp data, the overall length (LOA) was substituted instead, which introduces an over-estimate of actual submerged volume and thus displacement. Block coefficients for each vessel were also not known so typical block coefficients for different ship classes were used instead, as shown in the table below[41]. Where a range is given the average was used.

SHIP TYPE	BLOCK COEFFICIENT (Cb)	AVG Cb
LIGHTER	0.9	0.9
BULK CARRIER	0.80-0.85	0.825
TANKER	0.80-0.85	0.825
GENERAL CARGO	0.55-0.75	0.65
CONTAINERSHIP	0.50-0.70	0.6
FERRY	0.50-0.70	0.6
FISHING VESSEL		0.55

Total ship displacement was then calculated through the submerged volume and the density of seawater:

$$Displacement\ [kg] = Submerged\ Volume\ [m^3] * \rho_{Seawater}[\frac{kg}{m^3}]$$

Where 1025 kg/m^3 was used for the seawater density.

[41] Van Dokkum, Klaas. *Ship Knowledge*. 9th ed. Vlissingen, The Netherlands: DOKMAR Maritime Publishers BV, 2011.

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