System efficiency of heat integrated H_2-fueled PEMFC power generation on cruise ships

An evaluation of heat and power system layouts on a modern passenger carrying vessel

Master's thesis in Sustainable Energy Systems

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DEPARTMENT OF MECHANICS AND MARITIME SCIENCE

CHALMERS UNIVERSITY OF TECHNOLOGY
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Abstract

With the drive to decarbonize the majority of transport sectors, the shipping industry has developed a selection of different concepts to lower the emissions of different ship-types. Different fuel in form of e-fuels, bio-fuels and gaseous fuels like hydrogen and natural gas are promising developments. With the change of fuel types different power conversion technologies comes in to question, with the fuel cell being of interest thanks to it's high efficiency and in the case of the PEM type fuel cell powered by hydrogen, no emissions while producing power.

This work evaluates the implementation of a hydrogen fueled PEM fuel cell power system onboard a cruise ship, describing the original studied ships system and the parameters that governs the fuel cells, modeling the use of the fuel cells to meet the power demand over several different case days in different setups, and testing several types of system to fulfill the heat demand of the vessel for the same cases. Also evaluating the effects of changed demand for heat and power, and resulting fuel consumption and efficiency of the different setups are presented and discussed. The amount of systems evaluated in this work limits the accuracy of the results, and is primarily used to evaluate different setups. The cases different power demand are extracted as 15-min average data, and thus lacks the accuracy to evaluate the demand response of the fuel cells in sub-minute scale.

Higher efficiency were found where the load factors of the fuel cells were low, indicating the potential of an oversized power generating system. The fuel cell capacity is however the main system cost driver, highlighting the sensitivity to system costs of fuel cells, and pointing to the trade-off that has to be made during design of a fuel cell powered vessel between efficiency and investment cost. The heat flows of the vessel are changed with the introduction of the low temperature waste heat expelled from the fuel cells, highlighting the need to move away from steam use onboard in favor of low temperature heat or electricity. The production of steam onboard can however be fulfilled with the use of hydrogen fired boilers, and can be combined with heat pumps and/or thermal energy storage.

Keywords: Fuel cell; Low temperature heat recovery; Maritime Hydrogen; Low carbon shipping; Ship energy systems.

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Firstly I would like to extend my deepest gratitude to Maria Grahn and Selma Brynolf, supervisor and examiner to this thesis respectively. Maria, our weekly meetings has been one of the many highlight of this work, equal parts interesting and valuable for the finished work presented here. And thank you for guiding and encouraging me from the first idea that later became this thesis.

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The making of this thesis has also provided opportunity to talk to several experts in their respective fields at other companies than PowerCell. I will not name everyone of you, but the discussion that you enabled has been ever so interesting, thank you for taking the time to spread your knowledge and insights.

A special thank you is dedicated to Martin Gombrii, a long time colleague and boss. If it was not for you I would not even have ended up in this Chalmers program, and the idea for this thesis would not have been formulated. I have many things to thank you for.

Lastly, thank you to my family and friends. These friends are the encouragement and point of joy all students should be exposed to. Thank you to my fiancé, Linnea, your understanding of the academic world has made this project so much easier to navigate, along with being the greatest source of joy, every day. And thank you to my sister Karin, the interest you, as a someone coming from the world of the social sciences, have shown this project is surprising, but the feedback on my writing has been invaluable.

Jesper Lidqvist, Gothenburg, May 2023

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

AC	Alternating Current (Electrical System)
AFC	Alkline Fuel Cell
Aux Boiler	Auxiliary Boiler (Steam production)
BWTS	Ballast Water Treatment System
CAPEX	CAPital EXpenditure
CCS	Carbon Capture and Storage
Bio-CCS	Bioenergy Carbon Capture and Storage *Indicates that the carbon source is biogenic*
CER	Cold Energy Recovery
CNG	Compressed Natural Gas
COP	Coefficient Of Performance
DAC	Direct Air Capture (of CO_2)
DC	Direct Current (Electrical system)
EGB	Exhaust Gas Boiler
Electrofuels	Energy carriers made from H_2 and CO_2 in a synthesis reactor
EVAP	Evaporator (in this paper referring to a desalination plant for fresh water)
FC	Fuel Cell
Genset	Engine and connected electric generator
GHG	Greenhouse Gas
HP	Heat Pump
HPD	High Power Demand (Referring to one of the "typical days".)
HVAC	Heating, Ventilation, and Air-conditioning
HVDC	High Voltage Direct Current (Electrical System)
HTHRS	High Temperature Heat Recovery System
IMO	International Maritime Organization (part of the UN)
LEL	Lower Explosive Limit
LFL	Lower Flammability Limit
LNG	Liquefied Natural Gas
MCFC	Molten Carbonate Fuel Cell
MDO	Marine Diesel Oil
NO_x	Different types of nitrogen oxides

O&M	Operation and Maintenance (referring to a cost factor)
OPEX	Operational Expenditure
PAX	Passenger
PEM	Proton Exchange Membrane
PEMFC	Proton Exchange Membrane Fuel Cell
PFAS	Per- and polyfluoroalkyl substances
RO	Reverse Osmosis (in this paper refereeing to a desalination plant for potable water)
SOFC	Solid Oxide Fuel Cell
SOLAS	International Convention of Safety of Life at Sea
TCO	Total Cost of Ownership
TES	Thermal Energy Storage
TNT	TriNiTrotoluene
VFD	Variable Frequency Drive
WHO	World Health Organization
WHR	Waste Heat Recovery

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1
Introduction

Hydrogen has been identified as a promising future fuel for applications that are hard to de-carbonize with other means (IEA 2022a). One applications is the cruise shipping industry - an interesting prospect for the application of hydrogen, and fuel cells, enabling quiet and GreenHouse Gas (GHG) emission free operation (Dall'Armi, Pivetta, and Taccani 2022). Reducing emissions in sensitive areas of the world where these ships normally operate, and improving passenger comfort can be of great benefit for several stakeholders. The variation of load that is inherent to a cruise ship and the associated nature of its heat demand may prove a good fit for fuel cells. This work aims to examine this fit further, by evaluating how a fuel cell system can meet these demands of a modern cruise ship, looking at heat, power, how the system is controlled and how some main sub-systems can be integrated via MATLAB simulation.

1.1 Background

In the light of the EU Green Deal or the Fourth International Maritime Organization (IMO) Initial GHG Reduction Strategy there is little doubt that there is urgency in the work to reduce GHG emissions of our shipping industries and society (IMO 2018b, European Commission 2019).

The international shipping sector has between the years of 2012 and 2018 increased its share of global CO_2 emissions from 2.76% to 2.89% and is projected to increase even more in the years to come, up to 30% more than 2018 levels by 2050 (Faber et al. 2020). While the shipping industry is far from the largest emitter it faces challenges from new regulation limiting emissions that is hard to meet with traditional power-trains such as diesel engines running on heavy fuel oils (S. Brynolf et al. 2014).

Adding to this, the IMO is aiming for a 50% reduction of total GHG emissions for shipping by 2050 compared to 2008 levels (IMO 2018b).

While fossil fuels are the major source of fossil CO_2 and thus the major driver when it comes to climate change, there is also the issue of social and ethical aspects when it comes to sourcing the fuels, often taking place in parts of the world where regulatory protection of land and individuals are lacking (Olson and Lenzmann 2016).

Cruise ships, along with a few other ship types, are notable cases in that propulsion only uses around half of the produced energy, and the rest is used for other onboard loads (Faber et al. 2020). Other loads for example constitute Heating, Ventilation, and Air-Conditioning (HVAC), galley equipment, hot water production and a multitude of other loads needed to operate the ship and cater for the accommodation (Baldi, Ahlgren, et al. 2018). In one case study only 45.6% of the yearly energy production is spent on propulsion, and an additional 2.1% is spent on fuel heating that supports the operation of the engines that are used together with generators to produce electricity onboard (this engine and generator combination is usually called Genset) (Baldi, Ahlgren, et al. 2018).

In order to reach the IMO goals for the cruise industry many things can be done to improve the efficiency of the ship design, technical systems or operation. Efficiency measures could give total efficiency gains in the range of 10-50% (Andersson et al. 2016). Another pathway can be taken however, that of switching what the energy is generated from, i.e., change of fuel. This could mean moving to bio-fuels to only emit biogenic CO_2, or move to a fuel that does not contain carbon, like ammonia (NH_3) or pure hydrogen (H_2). Another well discussed fuel option is electro-methanol (CH_3OH) - an electrofuel where electricity is the main energy source for the fuel - providing hydrogen to be combined with CO_2 (Lehtveer, Selma Brynolf, and Grahn 2019). If this latter part is sourced from DAC or Bio-CCS the fuel can be considered CO_2-neutral making it a viable option for a sustainable future. Combining alternative fuels, with efficiency improvement measures would reduce the fuel consumption, thus reducing the logistical burden or cost of these new fuel types in the shipping industry.

One additional option for electrification/de-carbonizing shipping is to have a battery-electric system, where energy is stored in batteries. This is certainly a viable option, and has been shown to work on relatively large ships, for example the 4.7km ferry trip between Helsingborg-Helsingør (Sweden-Denmark) as of 2022 (ABB Press Release n.d.). In general there are however some limitations, as the cost scales directly with the range and weight of the vessel, limiting large ships to very short trips. There is also the need for fast charging infrastructure in all ports - an option certainly possible for ferries - but might not be a suitable solution for cruise vessels calling different ports or pure cargo ships.

Another option is to change the way we use the fuels. Pure hydrogen, or ammonia and methanol as hydrogen carriers, can be fed either to combustion engines or to fuel cells. While combustion engines is the classic way of generating onboard power it does not improve efficiency to switch fuel. Efficiency is the one clear benefit of switching to fuel cells, with 40-60% total efficiency being for most cases higher than the normal combustion engine (Tronstad et al. 2017, Kanchiralla et al. 2022). Pure hydrogen is in contrast to ammonia, non-toxic, and can be used in most types of fuel cells making it an attractive option (Tronstad et al. 2017).

Fuel cells can provide an efficiency gain thanks to it generating power in a very different way compared to fossil fuel powered gensets or main engines. A fuel cell converts its fuel to electricity via an electrochemical reaction, this happens at the interface between an anode, cathode and electrolyte membrane. This is similar to how batteries works, with the difference that fuel and oxygen is continuously supplied to the reaction in a fuel cell (Tronstad et al. 2017). The residual product from this reaction is water (H_2O) from the combination of oxygen (O_2) and hydrogen (H_2). Heat is also created, in similarity with combustion engines, that needs to be cooled off to keep the fuel cell within it's operating parameters. In comparison to combustion engines which coverts chemical energy first to mechanical energy and then by a generator to electricity, fuel cells do not include the conversion step to and from mechanical energy, instead converting directly from chemical energy to electrical, reducing losses. Fuel cell systems also include equipment for fuel and gas processing in addition to the electrochemical cell, normally called balance-of-plant equipment (Tronstad et al. 2017).

There are several types of fuel cells available on the market and currently being developed, with many of them having been tested on marine vessels to different extents (Tronstad et al. 2017). One of the main areas where the various types differ is the operating temperature and type of electrolyte. A selection of the most prominent types are listed below:

- Alkaline Fuel Cell (AFC): Electrolyte is an alkaline solution, normally potassium hydroxide, Nickel anode and silver cathode. The lack of any expensive catalyst or advanced electrolyte makes them relatively cheap to produce. While being one of the earliest designs of Fuel Cells (FCs), it does present favorable characteristics when it comes to size, cost and cycling tolerance, and efficiency for low temperature FCs. The major issue with AFC fuel cells is that it requires high purity hydrogen and is sensitive to CO_2 as this might poison and degrade the alkaline solution. (Tronstad et al. 2017)

- Proton Exchange Membrane Fuel Cell (PEMFC): Electrodes with a platinum catalyst and humidified polymer membrane that only permits transfer of hydrogen ions. The fact that the membrane needs to be hydrated makes this type sensitive to operating temperatures, where too high temperatures risks dehydrating and damaging the membrane. This limits the waste heat temperature, thus lowering the quality and usefulness of the rejected heat. This type also has a low relative cost, good cycling tolerance and small size, and a considerably lower fuel sensitivity compared to the the AFC type. Efficiency is similar to that of the AFC. (Tronstad et al. 2017)

- Molten Carbonate Fuel Cell (MCFC): Molten carbonate electrolyte, nickel alloy anode and nickel oxide and lithium cathode. With operating temperatures between 600 and 700°C and no noble-metal catalyst, the MCFC has some interesting properties worth noting, such as flexibility when it comes to fuel, being able to run on hydrogen and many hydrocarbons, Liquefied Natural Gas

(LNG), diesel and methanol due to internal reforming of the fuel utilizing the high operating temperatures. The high operating temperatures do increase the quality of waste heat, which means WHR can be used, increasing the system efficiency to 85% in some cases. While the high temperature can give high efficiency and accepts several fuels, the same trait limits the cycling tolerance and high relative cost. The size is also considered the largest of the alternatives. (Tronstad et al. 2017)

- Solid Oxide Fuel Cell (SOFC): Porous ceramic electrolyte, for example yttrium stabilized zirconia, anode of a nickel alloy but a cathode has to be matched with the electrolyte and can be of a multitude of materials. The SOFC has a very high operating temperature between 500 and 1000°C. This gives some of the same benefits when it comes to fuels and WHR as with the MCFC type, but at a smaller size. (Tronstad et al. 2017)

While all of these have their own merits in marine application, the PEM fuel cell type is the most mature among them, and has been tested in several marine applications (Tronstad et al. 2017). The good cycling performance lends itself to quick ramping and quick startup and shutdown. The abundance of good cooling water also decreases the problem that PEM fuel cells have in trucks, where very large cooling surfaces are needed to effectively cool such a low temperature waste heat to the surrounding air.

As with all subjects there are other aspects than the purely economical and technical. While FCs can provide higher efficiency than a combustion engine there are other aspect when it comes to environmental impacts that should be considered. The platinum used in PEMFCs, for example, is considered a scarce metal. This not only drives up the cost of the fuel cells systems, but also depletes an already limited stock. PEM is usually made up of the DuPont product Nafion, which have a known residual product (NBP2) that is in itself a sub-group of the PFAS family, known to be toxic for both animals and humans, being bio-accumulating (Weber 2017,Conley et al. 2022). The environmental and ecological effects of fuel cell production should not be neglected and care should be taken to minimize the detrimental effects of production.

Another aspect that should also be considered is how the hydrogen, used in the fuel cell, is produced. While hydrogen has the benefit that it can be produced with electrolyzers, it's not the main pathway for its production today. As of 2021, 99% of the hydrogen produced in the world by dedicated production facilities had its energy from fossil sources (where less than 1% utilized CCS). This feed-stock was 70% natural gas and 30% coal (IEA 2022b). In essence, a move away from the fossil feed-stock for hydrogen production is necessary not only for environmental reasons, but also for social and ethical reasons. These reasons also apply to the production of ammonia and methanol as produced hydrogen is a part of the production of these fuels as well.

1.2 Aim

This works aim is to study the non-propulsion related benefits of PEM fuel cell power generation onboard modern cruise ships. This includes studying change in energy flows for supporting systems and added value in utilization of FC by-products such as heat and water, the flows will be simulated in several cases and compared.

1.3 Research Questions

To narrow down the scope of this report a few research questions are presented below:

- How will different heat flows change when PEM fuel cells are introduced instead of combustion engines for power generation?
- To what extent can produced water from the fuel cell displace other water treatment plants onboard?
- What are the most significant parameters when it comes to efficiency?
- How efficiently can the low temperature waste heat of a PEM fuel cell be used?

1.4 Limitations

In this project only H_2 fueled PEM type FCs are considered for onboard power generation. Some of the findings can be applied to other types of fuel cells, as well, but some characteristics limit the results, for example, the low temperature of the waste heat.

The technical issue of fuel storage is in parts left to other work. Notes on regulation, cost and complexity will be discussed, but the physical size and how to accommodate such a system in the design of the ship is not included in the scope.

The same applies for physical space for the fuel cell stacks, supporting systems and power electronics (DC to AC conversion). General arrangement of the ship machinery space is hence not covered by this work.

In this work it is assumed that all power required onboard is to be supplied by a hydrogen fueled PEMFC system, although this setup has not been tested yet at such scale that this project is considering. The real case could very well be that for the near future FC are installed together with other power generation equipment such as diesel, methanol, or hydrogen fueled internal combustion engines or gas-turbines. Assessing these alternative options also lies beyond the scope of this thesis.

2

Technical Background & Theoretical Framework

The work is divided into two main sections; first is the definition / technical background of the fuel cell system and a run-through of a modern cruise ship's main machinery components. Understanding of energy flows and other system requirements of a current ship is key to understanding how a FC system will interact with the ship. The second part is defining the FC system and evaluating what added value can be gained from the removal of combustion engines and fuel oil, and added production of heat and water from the FCs. The basic workflow is presented in Figure 2.1.

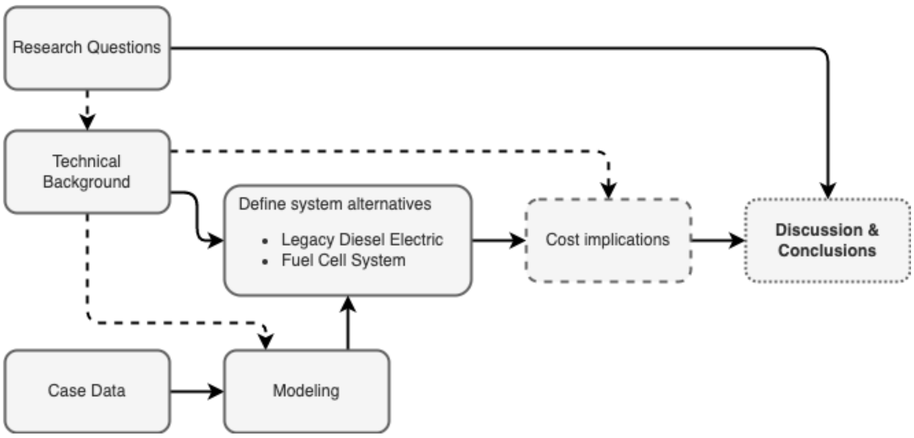


Figure 2.1: Schematic layout of workflow.

These main steps are presented and methods described in the following sections.

2.1 Case Data

The case data relates primarily to subsection 2.2.1 where data is needed to size the components or characterize the system. This is required to size the FC system and judge what can be integrated.

The case data comes from a real world cruise ship, operated on a daily cruise in the Baltic sea, between Stockholm on the Swedish Baltic coast, to the island of Åland, situated in between Sweden and Finland in the Baltics (and is territory of Finland). Table 2.1 outlines the main characteristics of the studied ship.

Table 2.1: Main characteristics of the studied ship (Baldi, Ahlgren, et al. 2018, Ancona et al. 2018, Dall'Armi, Pivetta, and Taccani 2022).

Overall length	176.9m
Max beam	28.6m
Gross Tonnage	34924
Built	Aker Finnyards, Raumo Finland, 2004
Design speed	21 knots
Passenger capacity	1800
Maximum crew compliment	155
Main engines	4pc Wärtsilä 6L46 (Rated: $5850kW_M/6081kW_T$)
Auxiliary engines	4pc Wärtsilä/Leroy-Somer 6L32
	(Rated: $2760kW_E/3049kW_T/3312$kVa)
Auxiliary boilers	2pc (Combined power: $4500kW_T$)
Fuel type / Consumption	MDO / 9000t/yr

The sources of the ship characteristics comes from a series of previous works based on the same vessel and vessel data. Subscripts M, T and E denotes Mechanical power, Thermal power and Electrical power respectively.

The ships typical speed over the day, with added notation for operational stage of the route is presented in Figure 2.2.

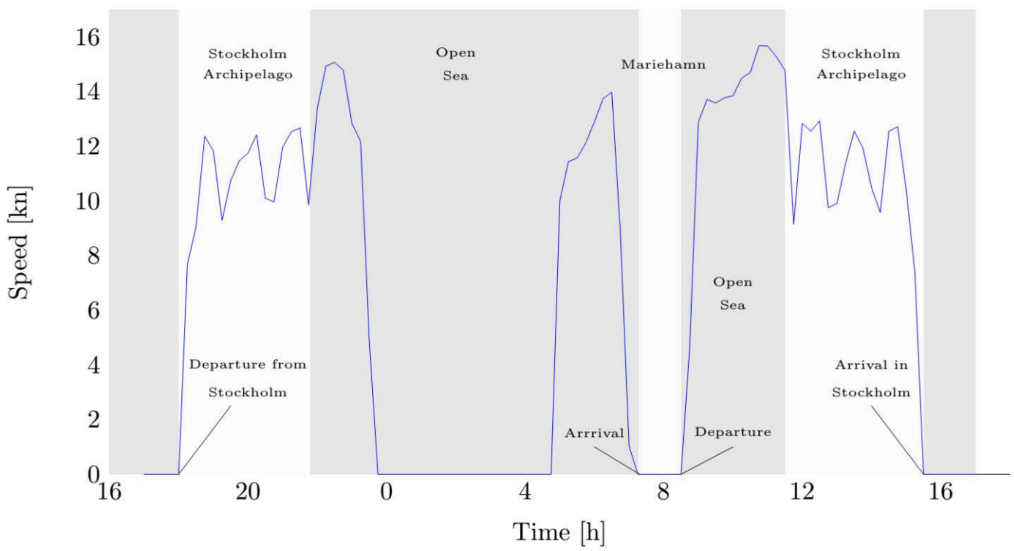


Figure 2.2: Reference speed/time profile of the studied vessel showing one round trip per 24h period (Figure 1, Baldi, Ahlgren, et al. 2018).

With reference to Figure 2.2, the relatively short route the ship traverses while carrying passengers makes the running of the ship interesting, as the ship normally slows down significantly or stops completely during overnight trips, as to arrive in port in the early morning. High variation in power-levels over every 24h period makes this a good case to study when it comes to power generation. While traversing such a short route it does differ from some other cruise ships as the operation case is more similar to that of a PaxCar or RO-PAX (Roll on and roll off cargo decks and Passenger carrying) ferry, and not a classical cruise ship that would be expected to take on different routes from day to day. While this affects the endurance requirements, it does not greatly alter power requirements, as the ship lacks car or cargo carrying capacity it is in structure similar to a dedicated cruise ship, with a relatively large passenger capacity.

Data from the studied vessel is presented for 5 different "case days". This data was first published in (Baldi, Ahlgren, et al. 2018), where four different energy demands are presented as:

- Mechanical Power Demand: Power for propulsion, further described in subsubsection 2.2.1.1.
- Electrical Power Demand represents all the electricity used onboard, further described in subsubsection 2.2.1.5.
- High Temp (HT) Heat Demand is a part of the heat system assumed to be steam at 110°C, further described in subsubsection 2.2.1.4.
- Low Temp (LT) Heat Demand is the lower temperature heat system operated between 40°C and 60°C, further described in subsubsection 2.2.1.3.

The "case days" is based on full year data, then divided into clusters of days that present similar properties. These clusters are:

- Mid-season - Hot (112 days)
- Winter (31 Days)
- High-speed (9 days)
- Summer (41 days)
- Mid-season - Cold (172 days)

Where the mid-season is divided into hot and cold days, roughly representing the early parts of spring, late parts of fall and parts of the winter for the cold days and early fall and late spring for the warm. High-speed is a special case where high propulsion demand is required, as usually required in heavy weather.
Figure 2.3 presents the energy demand for the case days in 15 min resolution:

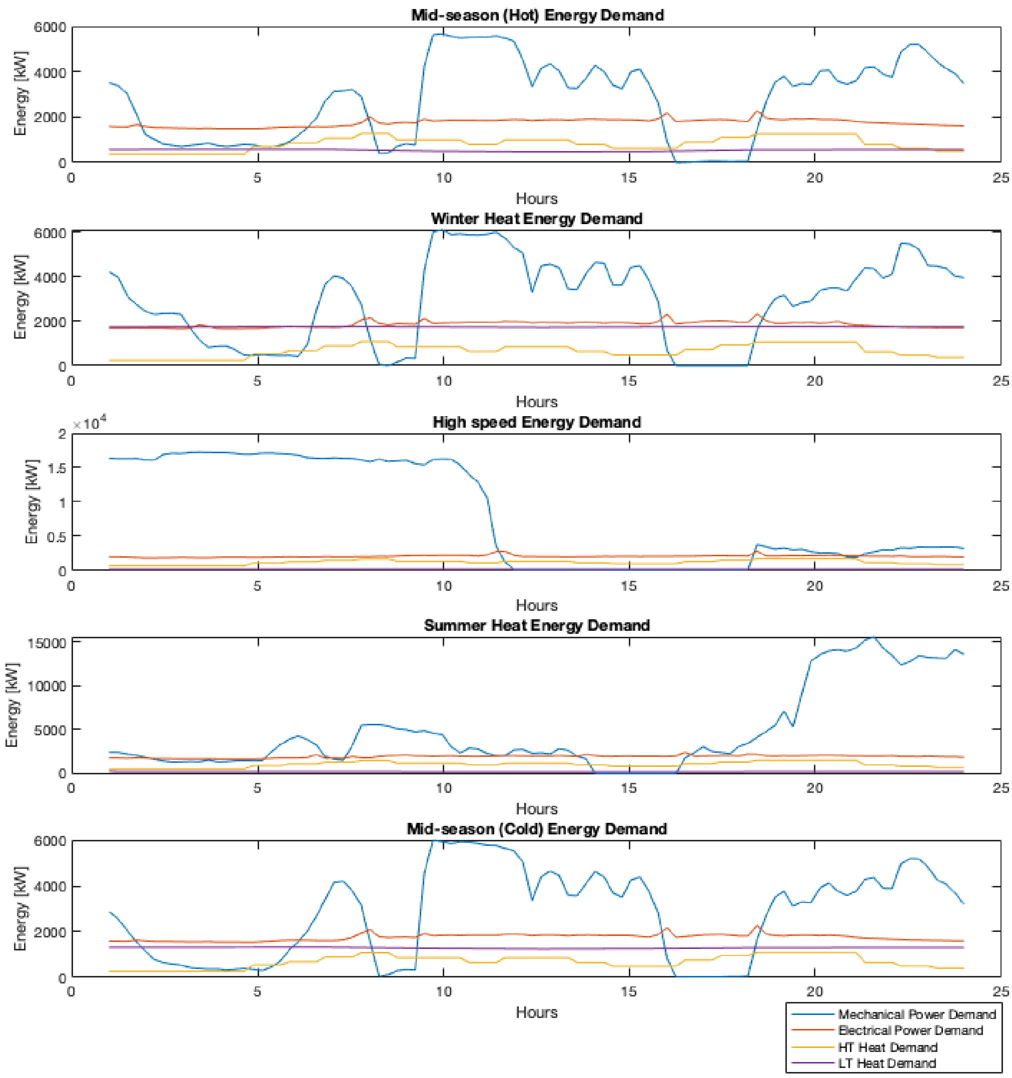


Figure 2.3: Energy demand for the case vessel for 5 different "case days".

The data is given for a full 24h in kW. High temp heat demand stays similar for all cases while the low temp heat demand increase with decreasing ambient temperatures.

Propulsion demand is similar for most days, except the "High-speed" and "Summer" case. While this is expected for the first of the two cases due to its definition, the "summer" case probably differs due to a change in itinerary over parts of the summer months.

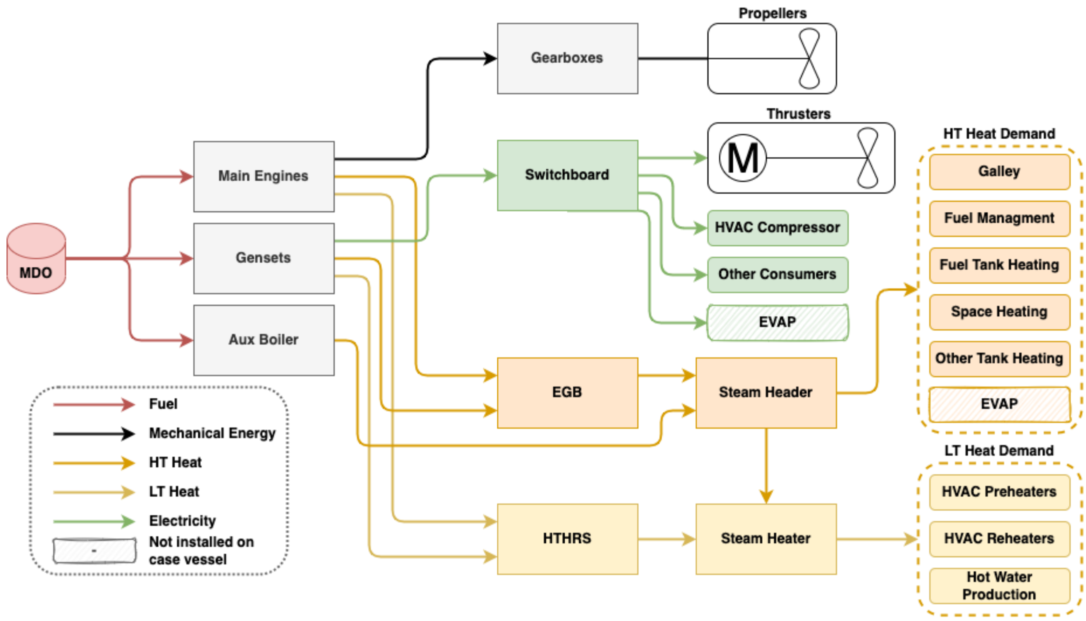


Figure 2.4: Simplified graphical representation of the onboard heat and power -flows of the studied ship.

In Figure 2.4 the flow of energy goes from left to right, from the Marine Diesel Oil (MDO) to the energy conversion steps, main engines, aux engines, and aux boilers. The next step is the gearboxes (combining gear), switchboard (electricity distribution), Exhaust Gas Boiler (EGB), High Temp Heat Recovery System (HTHRS), steam header (steam distribution network) and steam heater, used to provide extra heat to the LT heat system. On the right side the consumers of the different energy flows are presented, with EVAP not being represented on this ship but would be a considerable demand on other ships of similar type.

2.2 Technical Background

This part of the work will provide the technical background for continued analysis making up part of the discussion and conclusions.

The technical background is based on literature search primarily in the database Scopus, starting the search around a few keywords listed below, then following applicable references in the relevant papers. This is often referred to as a snowballing approach.

Keywords:
- Fuel Cells
- Shipping
- Maritime application
- Low carbon shipping
- Ship energy system
- Ship propulsion
- Energy efficiency
- Ship heat system
- Fuel cell heat integration

A series of subjects are described, first the ship systems, followed by the general fuel cell requirements and governing equations, lastly a section on other equipment or systems that can be used in combining the studied ships demand with the fuel cell system.

2.2.1 Current Ship Systems

The goal of this section is mapping out main energy flows and main equipment in the studied cruise ship that is either effected by, or can interact with, a fuel cell system. This ranges from parts of today's diesel electric propulsion systems such as gensets, fuel management, generators and power control systems, to things such as water management, heat and cooling needs and power-electronics. This will provide the technical background that the FC system will have to be integrated with.

2.2.1.1 Propulsion

The studied vessel utilizes four medium speed (500rpm), four-stroke diesel engines for propulsion (further details are presented in Table 2.1). The engines are driving two propeller shafts, with the engines mounted in pairs, each pair connected to a combining gear driving one propeller shaft per main engine pair, and example of this layout is presented in Figure 2.5.

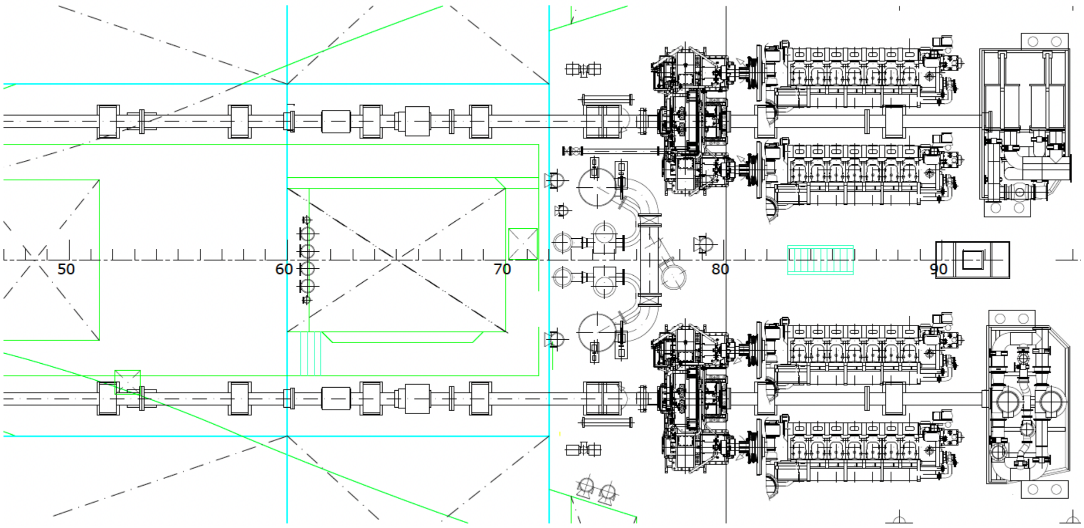


Figure 2.5: Example (not from the case ship) of four Main Engines feeding power to two combining gears and shaft drives. Propeller shafts seen going towards the propeller outside the figure to the left.

When running at slow speed where there is lower propulsion demand the studied vessel can run on one main engine per pair, only having one engine drive each shaft (Baldi, Ahlgren, et al. 2018).

While direct shaft drives was the norm since propellers where first used on vessels, for the last few decades there has been a move to diesel-electric propulsion. This type of propulsion system disconnects the mechanical linkage between the engine generating power and the propeller, and instead use an electric connection to transfer power. This removes the defining difference between main engines and auxiliary engines or gensets, where all engines are connected to a generator to produce electric power, that is then transferred to electrical motors that drives the propellers and trusters. All electric loads are thus connected and can provide a more efficient energy system for a vessel that has significant other electrical loads or that has very varying propulsion demand. It can however reduce the propulsion efficiency for ships that traverses long distances on constant load as extra energy conversion steps are introduced in the drive-train.

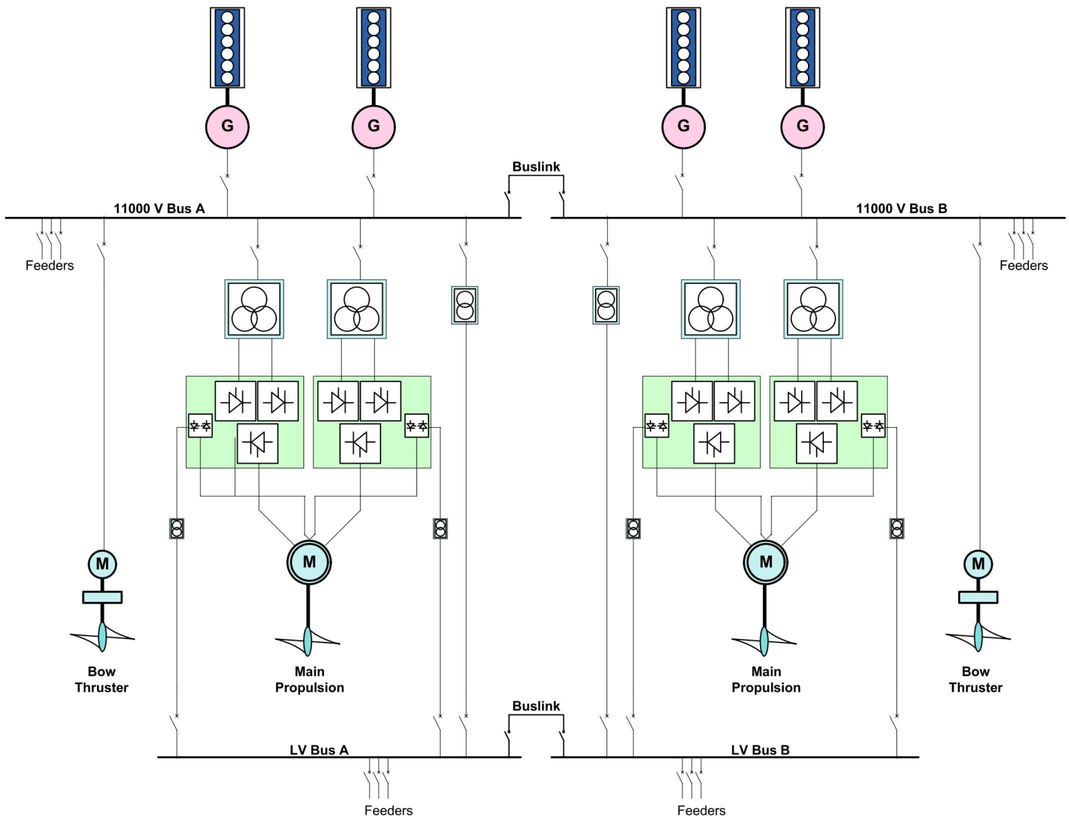


Figure 2.6: Example of early type diesel-electric drive system using 4pc gensets, 2pc propellers and 2pc thrusters ("Diesel-Electric Propulsion Systems Power under Control" 2016).

Figure 2.6 shows an example of how early diesel electric propulsion systems could approximately look like from an electrical standpoint. These systems are still used and provide the closest mach to legacy systems where economy in high power range is required and high degree of control of propeller speed in both forward and reverse direction is needed ("Diesel-Electric Propulsion Systems Power under Control" 2016). Note that the "bow thrusters" do not have speed control, only the main propulsion drives. There is also separation between the two sides of the system, providing redundancy in case of faults on one side, they can be separated to act independently.

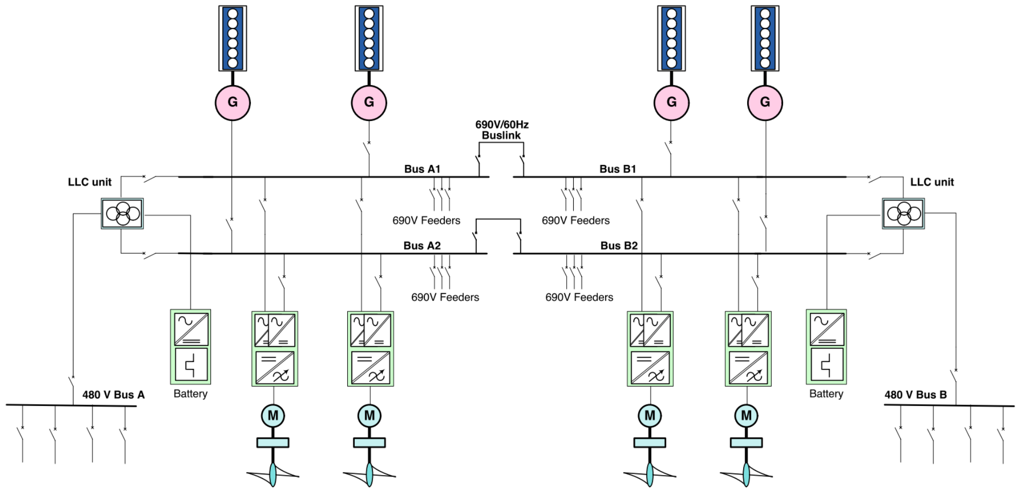


Figure 2.7: Example of a modern hybrid diesel-electric drive using a total 4pc gensets and 4pc frequency controlled thrusters, and one battery storage bank per bus ("Diesel-Electric Propulsion Systems Power under Control" 2016).

A modern setup is presented in Figure 2.7, where large transformers are avoided to decrease losses and space requirement. In this case all thrusters are connected via Variable Frequency Drives (VFD) that can give greater control of propeller speed and power, while further increasing efficiency. This setup is also stated to be well adapted to accept energy storage solutions such as batteries ("Diesel-Electric Propulsion Systems Power under Control" 2016) that can enable hybrid-electric operation.

In both diesel-electric alternatives there is the added benefit that the engines are not constrained in there positioning within the ship structure based on where the propeller shafts are routed. This adds flexibility to the arrangement of the machinery space.

2.2.1.2 Heat Demand

Onboard heat demand of the case vessel is fulfilled by two different heat streams, low and high temperature heat. The heat consumers are grouped into main areas, as seen in Figure 2.3.

Only separating the heat flows into high and low temperature heat is in itself an assumption, where many heat recovery steps are omitted and cooling systems are not included for auxiliary equipment. In one paper (Dall'Armi, Pivetta, and Taccani 2022) utilizing the same case vessel the heat system is instead divided into high, medium, and low temperature heat (steam, 45-70°C and 25-45°C respectively), which might be useful for deeper analysis and optimization of the heat system.

2.2.1.3 Low Temperature Heat

LT heat comes in the form of liquid water at 40-60°C from the HTHRS, removing heat from the engines high temperature cooling system. The HTHRS system extracts heat from all main and auxiliary engines. The heated water is then fed to a steam heater, taking heat from the steam distribution network (high temp), to heat the low temp circuit to 90°C.

According to (Baldi, Ahlgren, et al. 2018) the yearly energy consumption of the LT heat system is divided as per below for the main consumers:

Table 2.2: Share of total energy demand per low temp heat consumer (Baldi, Ahlgren, et al. 2018).

Consumer	**Share of total yearly energy demand**
HVAC Preheater	15.1%
HVAC Reheater	0.8%
Hot water production	4.8%

Table 2.2 shows that HVAC heat demand is the largest consumers. On the studied ship there is one installed HVAC-Preheater rated at $3500kW_T$ and one HVAC-Reheater rated at $1780kW_T$. While hot water presents quite a small percentage of the LT heat use, hot water heating is also assumed to be part of the HT heat demand as part of the galley consumption of steam. According to WHO hot water is recommended to exit the water heater at minimum of 60°C and if circulation systems are in use, have a return temperature of at least 50°C (World Health Organization 2011).

2.2.1.4 High Temperature Heat

The studied vessel has a multitude of high temp heat consumers. This heat is provided primarily by Exhaust Gas Boilers (EGB), fitted to two of the main engines and all four auxiliary engines. The EGB uses the heat in the exhaust gases from the engines to evaporate water to stem that is fed into the steam distribution system/-header. Typical inlet temperatures of exhaust gas is 300°C and is cooled to around 200°C (Baldi, Ahlgren, et al. 2018). 25% of the yearly heat demand is fulfilled by the auxiliary boilers that only produce steam when EGB and HTHRS systems cannot supply sufficient power, burning fuel to create steam for the HT heat network.

As with LT heat the same paper (Baldi, Ahlgren, et al. 2018) provides the share of heat demand per consumer:

Table 2.3: Share of total energy demand per high temp heat consumer (Baldi, Ahlgren, et al. 2018).

Consumer	**Share of total yearly energy demand**
Galley	3.1%
Fuel management	2.1%
Space heating	0.9%
Other tank heating	0.4%

Galley: The specific use of steam for galley (i.e. the ships kitchen) purposes in the studied ship is not clear, but in general steam does have a few purposes for galley equipment, mainly local water heaters and cleaning/de-greasing of equipment and galley areas. There are also cooking equipment that can take heat from steam, these types are however being gradually replaced by electrical appliances on modern vessels.

Fuel management comprises the HFO heater and HFO tank heaters and fuel tank heating. HFO requires heating to be used in the fuel injection system. The case vessel was at the time of data collection running on 1% sulfur fuel, but with the implementation of IMO regulation capping the sulfur content of marine fuels at 0.5% the energy use for fuel management might have been further reduced. (Baldi, Ahlgren, et al. 2018, IMO 2018a)

Space heating is the space heating demand for the machinery space running on a separated heating and ventilation system. It's noted in (Baldi, Ahlgren, et al. 2018) that this need should be able to be supplied by low temperature cooling water heat recovery, as high quality heat such as steam is not required for such a low temperature demand.

Other tank heating there can be many other tanks onboard a ship that require heating apart from fuel tanks and systems. Heating of bilge-water settling tanks or bio-reactors for black and grey water treatment are example of other tanks that need or can benefit from heating.

Additionally for the case that a vessel utilizes on board fresh-water generation there might be an added steam demand for evaporators (EVAP), see further details in subsubsection 2.2.1.6.

2.2.1.5 Electrical Power

The studied vessel utilizes 4pc medium speed (750rpm), four-stroke diesel engines as auxiliary-engines (further details are presented in Table 2.1), or gensets to provide the ship with electrical power.

There are a multitude of small consumers onboard any ship. For the studied vessel these are a varied loads associated with hotel services (lighting, refrigerators, etc.) and machinery (pumps, control systems, navigation, etc.). The largest loads for the studied ship are the HVAC system and thrusters. These consume electricity in different ways. The HVAC system is in charge of climate control, where air conditioning is the largest consumers when cooling is required (mainly over the summer months), where large compressors require a substantial amount of electrical power. "Thrusters" represents the bow-thrusters, assisting ship maneuvering, mainly in port, providing propulsion side to side to turn the ship at slow speeds. These thrusters are directly driven, thus lack speed control when in use. The power-full electrical motors together with on/off operation makes thruster a large peak load for short periods of time. The thursters are relatively small consumers summarized over the full year, but are important as the system needs to be dimensioned to provide large amounts of power over a small time-frame (Baldi, Ahlgren, et al. 2018).
As with LT and HT heat the same paper (Baldi, Ahlgren, et al. 2018) provides the share of electricity demand:

Table 2.4: Share of total energy demand per electricity consumer (Baldi, Ahlgren, et al. 2018).

Consumer	**Share of total yearly energy demand**
HVAC	0.8%
Thrusters	0.4%
Other users	26.0%

In Table 2.4 the HVAC demand is relatively small over a full year, but does provide a significant load when compressor driven coolers are utilized during the summer months.

As discussed further in subsubsection 2.2.1.6, the studied ship does not have installed or utilize any onboard fresh-water production, but for many ships there is a need for onboard fresh-water production. This would in the case for passenger ships be an significant additional load on the electric power system that needs to be considered.

The studied vessel utilizes a 3-phase AC (Alternating Current) based electrical distribution system, where AC power is produced by the gensets and distributed among the ships consumers (with step-down transformers) for most of the system. This has been the way that most ships handle electrical power for a long time, and is the basis for the example systems in Figure 2.6 and Figure 2.7 (Baldi, Ahlgren, et al. 2018, Baldi, Moret, et al. 2020, "Diesel-Electric Propulsion Systems Power under Control" 2016). Recently, there have been talk of alternatives, according to ABB. There paper (Lindtjørn 2017) lays out the main characteristics of a DC (Direct Current) onboard power architecture.

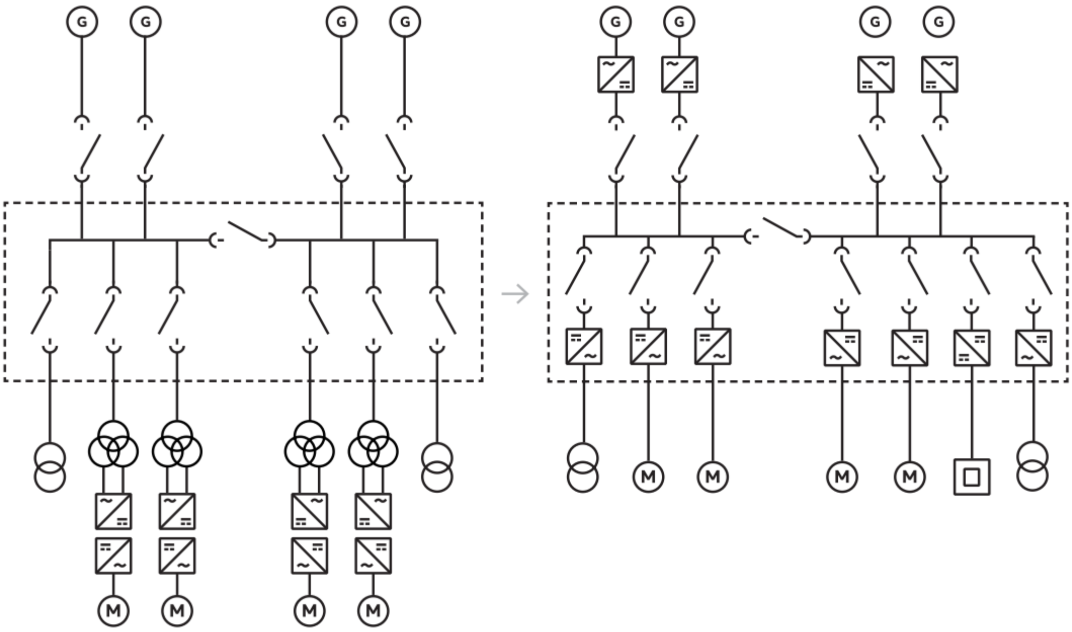


Figure 2.8: Simplified difference between an AC based and DC based power system (AC to the left and DC right) (Lindtjørn 2017).

It is stated that DC architecture can simplify the onboard system, both in design and operation. The removal of large transformers along with the simplified operation of not having to handle synchronisation of generators before connecting does provide an interesting prospect. Another benefit that is highlighted is the ease of integrating primarily DC based equipment, such as batteries and/or fuel cells (Lindtjørn 2017,Baldi, Moret, et al. 2020). Both types of equipment produce or store energy in DC form, and have to use inverters to produce AC power from DC. The forced use of inverters for AC power can also bring efficiency gains as precise control of frequency for rotating equipment has a known efficiency advantage (Baldi, Moret, et al. 2020).

Shore power while in port can also be an option to reduce the need for onboard power generation for those times while the ship is tied up to a dock. Taking power from the electricity grid while in port can eliminate the need for electrical power generation for certain times of the ships operation. This is especially useful for cruise ships that require a substantial amount of electrical power for the hotel loads at all times. For fossil fueled ships this can reduce fuel consumption, and thereby emissions and additionally reduce sound and vibrations stemming from the engines. Emissions can also be reduced on a wider scale if the electricity provided by the grid has a low carbon intensity. Shore power cannot however completely eliminate the need for fuel use as heat is still required (Gabrielii 2021). In the case ship the heat demand could potentially be met by the auxiliary boilers if the ship was to be connected to shore power. How heat demand could be met would be highly dependent on the ship's heat system, and for a ship designed to run on shore power the heat could potentially be produced by heat pumps or utilization of onboard thermal storages.

For many cruise ships that do not operate on a fixed route but instead cruise different parts of the world the ships often lay at anchor outside a port and use tender boats to ferry passengers to and from the ship. In this type of ship, shore power would not provide the same benefits as if the ship was sailing on a fixed route and calling the same few ports, and would depend more on onboard power and heat generation. This is due to inability to connect to shore power either as the ship is not at a dock, or, the proper provisions for shore power are lacking.

2.2.1.6 Water Use

The studied ship is neither equipped with nor utilizes any onboard fresh-water production, instead the water is taken onboard during the twice daily port calls (Baldi 2023). Onboard water heating is however installed for galley and other uses. Water heating is previously discussed in subsubsection 2.2.1.3. In an effort to make the results of this work more applicable to a wider variety of vessels some baseline figures are of use for fresh-water generation.

On many cruise ships fresh-water of all qualities are produced by evaporator (EVAP), often also called distillers, taking heat from the steam circuit to evaporate seawater to gain distilled water. While this is a mature technology there are alternatives (Marty et al. 2016, Moore 2014). One modern EVAP plant (Alfa Laval MEP) have a specific electricity demand is between $1.3kWh_E/m^3$ and $3.9kWh_E/m^3$, and specific thermal power demand at 128-$385kWh_T/m^3$ (Alfa Laval n.d.). One alternative to EVAP is a Multi Stage Flash (MSF) system , for example reported to have a specific thermal power demand of $191kWh_T/m^3$ and $3kWh_E/m^3$ (Wärtsilä Water and Waste 2021, Moore 2014). The governing parameter that affects an evaporation plant's energy need is the feed-water temperature.

An alternative to the evaporator is what is called a Reverse Osmosis (RO) plant, where an osmosis membrane is utilized to "filter" the water using osmotic pressure to filter our the water molecules from any salt or other pollutants of the feed-water. RO plants do not use heat as the driving force, instead it uses pressure supplied by one low-pressure and one high-pressure pump, making electric energy the main source of energy. According to one RO manufacturer the salinity and other feed-water pollutants is the main factor in energy consumption, while feed-water temperature also have a smaller effect (Karlsson 2023). For a relatively simple system supplying a 20-30 person crew compliment operating in the Atlantic ocean energy need is estimated at around 4-$5.5kWh_E/m^3$, while a large and more advanced system utilizing energy recovery would see the energy requirement drop to around $2.4kWh_E/m^3$ of produced fresh-water (Karlsson 2023). According to the International Organization for Standardisation (ISO), fresh-water for onboard consumption that has not been heated above 80°C , which is the case for most RO systems, must be further disinfected (Mulić and Tomić 2020).

While EVAP plants and RO plants can desalinate water for around the same amount of electrical energy, the EVAP plants does require more thermal energy for the same work. This might be worth it for vessels where high quality waste heat is easily available, but might not be the optimal solution for FC powered vessels where waste heat is of too low quality. One added benefit that EVAP plants can bring compared to RO is the decreased need for maintenance and lower sensitivity, and where the RO's membranes can be damaged by low feed-water quality, the EVAP plants have less sensitive parts and output is predictably effected by the sea-temperature. Membrane replacements on RO plants differ greatly between applications, while ships with little to no filtration and operating in areas where the feed-water has high salinity and particle content the time between filter membranes can be as little as one year of operation, ships with high quality sand filters for the feed-water can operate the same membranes for up to 10 years (Karlsson 2023). In general, minerals also have to be added to both types of desalination plants effluent water to be safe for human consumption, as the produced water is in essence distilled-water.

Passenger ships requires around 200 liters of fresh-water per passenger and day. This number is relatively high compared to a merchant ship where the corresponding consumption is said to be around 60 liters per person and day (Mulić and Tomić 2020). Calculation for water use is presented below:

$$Water\ use = 0.2[m^3/person/day]n_{PAX} + 0.06[m^3/person/day]n_{Crew} \tag{2.1}$$

Where total daily water use is calculated in m^3, and n represents number of crew or PAX onboard. For the studied ship, the combined PAX and crew number is a maximum 1955 (Table 2.1), making the assumed water consumption to be 369.3 m^3/day of fresh-water. This is a significant amount of water, and the total PAX + Crew number can be assumed to be significantly lower for most trips.

2.2.2 Fuel Cell System

This section aims to provide a technical description of the PEMFC, its requirements and characteristics along with the system aspects that is to support the FC in its operation. It also provides the method that is the basis for some modeling that follows by mapping out the governing equations, how efficiency is effected, as well as presenting some data on hydrogen fuel that is part of the modeling.

2.2.2.1 Fuel Cell Stack Requirements

Based on a $200kW_E$ FC system adapted to a marine application (PowerCell AB 2022), where these systems are intended to both be able to work as individual plant, and can also be integrated into a larger combined system of several fuel cells to provide a significantly greater total system output. In general these systems require balance of plant equipment supporting the systems such as hydrogen supply, air supply for the cathode reaction and ventilation, cooling systems, HVDC supply, and data and power connection for system control and communication.

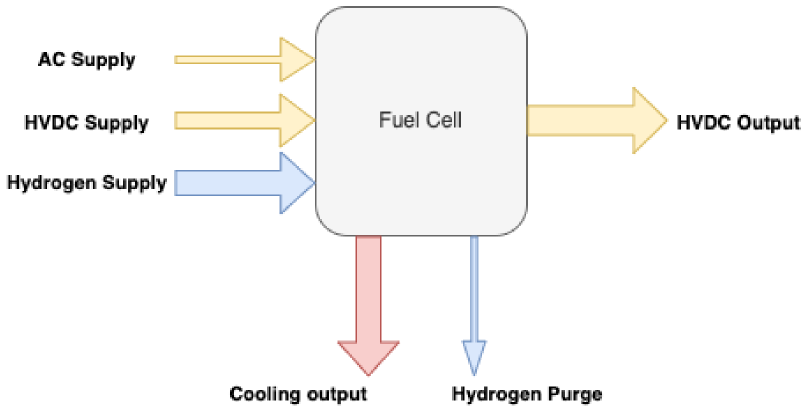


Figure 2.9: Schematic layout of the power conversion within a FC system.

Each FC stack does include provisions such as compressors for the air feed, and heat exchangers for the cooling circuit (PowerCell AB 2022).

2.2.2.2 Air & Hydrogen Supply

As air is a reactant in the FC the air feed is important for the operation. To avoid interfere with the FCs electrochemical reaction there should be some sort of filtration for the air feed to avoid particles (conducting or not), chemicals, salt or water. Filters can be individual to each FC stack or have larger filters for several stacks (PowerCell AB 2022).

Hydrogen can come in liquid or gaseous form on a ship, while the fuel cell require pure hydrogen in gaseous form and in a specified pressure range where the hydrogen gas should be above $0°C$ to avoid any risk of water freezing within the FC stack. The hydrogen supply system can be combined for all installed fuel cells systems (PowerCell AB 2022).

2.2.2.3 Air Exhaust

After the oxygen and hydrogen has reacted the exhaust is containing both water and air due to an excess of air supplied and that the fuel cell only consumes oxygen, and not the nitrogen or other gases in ambient air. In general the exhaust air should be vented such that it will not provide a hazard for crew or passengers. As the exhaust air also contains water it should be routed to not be blocked by condensate that's allowed to accumulate. The air exhaust is also where water can be recovered if needed. The paper *Recovery and quality of water produced by commercial fuel cells* (Tibaquirá et al. 2011) highlights that a PEMFC can produce water that is close to fresh-water quality, and can with some filtration and additives be used as drinking-water. The same paper noted that during their tests the accumulation of water was only around 8% of the theoretical production, highlighting the need to have some system for water recovery if substantial amounts of water is to be collected.

2.2.2.4 Cooling System

Stack cooling is in some applications a challenge, as the systems can produce a large amount of heat at relatively low temperature (around $65°C$). For ships this is easier to accommodate as cooling can be handled against relatively cool and abundant sea-water. In sizing the cooling system, degradation of the fuel cells needs to be considered. As degradation takes place the efficiency of the fuel cells decreases, thus producing more heat per electricity unit produced (PowerCell AB 2022). The system should be able to handle the full heat load of maximum power output at end-of-life conditions in the fuel cell system, also considering the ambient sea-water temperature.

2.2.2.5 Electrical Integration

Output voltage of a FC stack depends on the number of cells in the stack and the load factor of these cells as the cells are connected in series and voltage goes down with higher output (for reference see Figure 2.10) for each cell (Dicks and Rand 2018c). As voltage varies during different loads there is a need for DC/DC converters to link up to a onboard DC grid or DC/AC inverters to provide power to an AC grid. There should be individual converters/inverters for each FC stack to allow for differences in load on each stack and allow for control of each stack.

2.2.2.6 Safety

Hydrogen can be seen as the main question when it comes to safety. There are also risks associated with fire of other materials and high voltage accidents. While these are non-trivial issues, fire risk management along with electrical safety are questions that the industry has provided answers to since a long time for existing equipment, and applicable regulation is in place.

The paper *Safety Considerations of Hydrogen Application in Shipping in Comparison to LNG* (Depken et al. 2022) provides a great overview for safety risks and applicable regulations for hydrogen onboard sea-going vessels.

Regulation regarding hydrogen as ship-fuel are not fully developed at this time. The set of SOLAS (International convention of Safety Of Life At Sea) rules under the IMO where Chapter II provide minimum standard regulation for ship construction where the IGF-Code (International code of safety for ships using Gases or other low-flashpoint Fuels) is found. The IGF-code went into force in 2017 is the most relevant regulation under Chapter II. For now the IGF-Code does not directly mention hydrogen, only natural gas fuels (compressed/liquefied), but can be used as a basis for SOLAS approval as an alternative design (Depken et al. 2022). Others have also highlighted that another big challenge for hydrogen fueled ships are the lack of established global regulations and standards on the loading and unloading of liquefied hydrogen, which pose a challenge for the whole supply-chain of liquid hydrogen ship fuel (Atilhan et al. 2021).

The main safety concern with hydrogen is its high flammability, it can burn at concentrations between 4 and 75%, and thus burns at a much wider concentration range than natural gas (5.3-15%) that is already used as ship-fuel. Hydrogen is hard to detect, it lacks odor, color and taste, and is the lightest gas that we have. Its highly buoyant, and rises upward, while the same property also makes it able to permeate through some materials. The properties of hydrogen makes it both harder to properly contain and store than other gaseous fuels and leaks are hard to detect. Ignition of hydrogen is relatively easy, it can happen both from low powered sparks (discharge of static electricity from a person discharge around 500 times the energy required to ignite hydrogen gas), and from high pressure leaks where auto-ignition can occur. If ignited the flame has very low radiation from pure hydrogen, and is hard to detect visually. The flame velocity in turbulent flow can be several hundred m/s and if the concentration of hydrogen is above 18% it can detonate at up to 2000m/s (Depken et al. 2022). Keeping a hydrogen fuel system safe comes down to avoiding concentrations that can ignite or detonate. The light weight of the molecule makes the gas able to quickly rise and diffuse in air, which can be utilized for safety. If all spaces that can experience a hydrogen leak have good ventilation that allows hydrogen to escape upwards at a great enough rate with few obstructions, concentrations can be kept at a safe in the case of a leak. The choice of material in any fuel handling system must also be a priority, as some metals can become brittle by being exposed to hydrogen over time, creating a potential leakage source.

There are also safety concerns regarding storing hydrogen at cryogenic temperature due to the embrittlement of materials at such low temperatures ($\leq$20 K). If liquid hydrogen and oxygen make contact in a cryogenic state the oxygen will solidify; this mixture of liquid hydrogen and solid oxygen can be detonated by impact alone and contains more energy that an equivalent amount of TNT (Depken et al. 2022). To avoid solidification of air or oxygen the fuel system should be kept at over-pressure and/or be purged with nitrogen before filling of system. Detonation of a hydrogen oxygen mix inside the fuel system poses a grave danger to personnel and to the integrity of a ship with over-pressure in enclosed spaces and high velocity shrapnel.

While ventilation is important to avoid reaching concentrations above the explosive limit to avoid fire it's also important to avoid concentrations that go high enough that it would replace too much oxygen in the air posing a asphyxiation risk for personnel in an area. Hydrogen is not known to be toxic to humans and should pose minimum danger if kept below its lower explosive limit (Depken et al. 2022).

Another safety related aspect of FC power generation onboard ships is the opportunity for more distributed power generation onboard. With FCs in the sub MW scale, a substantial amount of fuel cells are required for large ships. This can provide opportunities to have very robust power generation onboard in that the FCs can be distributed over several flooding and fire control zones. If fuel and other supporting systems include some degree of redundancy (with a few separate fuel systems, separated control and air supply systems, etc.) the power generation system can possibly separate out faults in one block of FCs and still provide power from the unaffected part of the system, creating a less sensitive power generation system than with a few gensets located in the same compartment as is often the case on today's ships.

2.2.2.7 Governing Equations

Andrew L. Dicks and David A. J. Rand's book *Fuel Cell Systems Explained* provides a good overview of the basic equations required in this work, and is the basis for whats presented in this chapter (Dicks and Rand 2018a).

The simplest equation for the PEMFC, lets remind ourselves, is the stociometric relation between H_2, O_2 and H_2O as below:

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O(+Heat) \tag{2.2}$$

Which describes the simplest representation of the chemical reaction in a hydrogen-fueled fuel cell. What is important to note is that Equation 2.2 represents the lower limit of reactants that needs to be supplied, and would in a real life case both have excess of H_2 and O_2.

This is based on the anode reaction:

$$2H_2 + 4OH^- \rightarrow 4H_2O + 4e^- \tag{2.3}$$

And the cathode reaction:

$$O_2 + 4e^- + 4H_2O \rightarrow 4OH^- \tag{2.4}$$

To expand these equation into something more useful, the ideal open-circuit voltage is needed, presented below:

$$V_r = \frac{-\Delta \bar{g}_f}{2F} \tag{2.5}$$

In Equation 2.5 the $\Delta \bar{g}_f$ represents the ΔG of the reaction in kJ/mol, and F is the Faraday's constant (this term stems from the two electrons moved per two H_2 used, thus representing the electric work in joules [J]). The resulting V_r is given as a voltage [V]. The real voltage is always less than the ideal open-circuit voltage, and is described by a polarisation curve as in Figure 2.10, showing a typical voltage open-circuit voltage of 1.2V, and the real voltage against the current density of fuel cell.

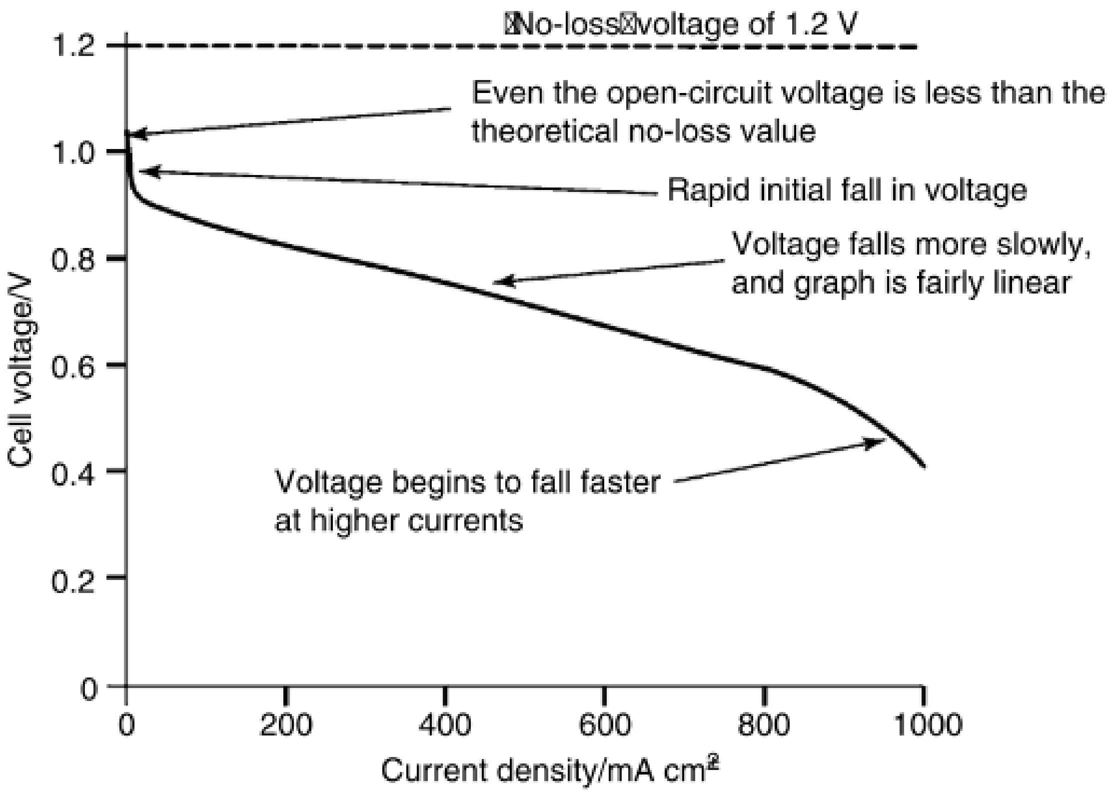


Figure 2.10: Example of a polarization curve for a low temperature and pressure fuel cell (Fig. 3.1 Dicks and Rand 2018b)

The cell voltage on the Y-axis in Figure 2.10 is denoted V_c and is the average potential difference of each cell of the FC stack. An expected number for V_c is said to be around 0.65V for a low pressure and temperature FC such as the PEM type.

Power P_e is given for a FC stack of n cells as:

$$P_e = V_c \cdot I \cdot n \tag{2.6}$$

Where I is the current in Ampere [A]. Equation 2.6 can then be re-written as:

$$I = \frac{P_e}{V_c n} \tag{2.7}$$

To calculated air-usage of a single cell in a fuel cell stack Equation 2.2 is first used where we can derive that:

$$Oxygen\ use = \frac{I}{4F} mol\ s^{-1} \tag{2.8}$$

Combining Equation 2.8 and Equation 2.7, and as Charge transfer= $I = Oxygen\ use \cdot 4F$, while dividing by time we also get:

$$Oxygen\ use = \frac{P_e}{4V_c F} mol\ s^{-1} \tag{2.9}$$

This can also be written in kg/s, which is more useful for the analysis:

$$Oxygen\ use = \frac{(32 \cdot 10^{-3})P_e}{4V_c F} kg\ s^{-1} \tag{2.10}$$

As the oxygen is typically taken from the ambient air this equation can then be converted to air use:

$$Air\ use = \lambda \frac{(3.58 \cdot 10^{-7})P_e}{V_c} kg\ s^{-1} \tag{2.11}$$

Where λ is the stoichiometric ratio of air (excess air), and the airs molar mass has been multiplied in $(28.97 \cdot 10^{-3} kg\ mol^{-1})$.

With Equation 2.11 one can easily get the exit air flow rate from Equation 2.11 and Equation 2.10:

$$Exit\ air = \lambda \frac{(3.58 \cdot 10^{-7})P_e}{V_c} - \frac{(32 \cdot 10^{-3})P_e}{4V_c F} kg\ s^{-1} \tag{2.12}$$

Fuel (hydrogen) use is another important parameter essential for the modeling. Hydrogen use is calculated in much the same way as air usage. The main difference is that of the reaction taking place, referencing Equation 2.3 and Equation 2.4, one notes that there are two electrons per mole of hydrogen, instead of the four that is the case for oxygen.

Similarly to the two oxygen use Equations, 2.8 and 2.9, the corresponding hydrogen use case becomes:

$$Hydrogen\ use = \frac{I}{2F} mol\ s^{-1} \tag{2.13}$$

$$Hydrogen\ use = \frac{P_e}{2V_c F} mol\ s^{-1} \tag{2.14}$$

Where Equation 2.13 is for a single cell in a fuel cell stack, and Equation 2.14 percents the hydrogen use for the full stack thanks to Equation 2.6 including the n term. Both for ideal stochiometric fuel and oxygen use. Equation 2.14 can then, similarly to the air use case be written as kg/s by multiplying in the hydrogen molar mass ($2.02 \cdot 10^{-3} kg/mol$):

$$Hydrogen\ use = \frac{(1.05 \cdot 10^{-8}) P_e}{V_c} kg\ s^{-1} \tag{2.15}$$

The two "waste" products that a hydrogen fueled FC produces is heat and water. In this work theses two products are of great interest and calculating them is important for the analysis.

Water production is calculated in a similar way to oxygen and hydrogen use. The relation is actually the same as for hydrogen in a one-to-one ratio on a molar basis, making the calculation identical to Equation 2.14:

$$Water\ production = \frac{P_e}{2V_c F} mol\ s^{-1} \tag{2.16}$$

Adding in the molar mass of water ($18.02 \cdot 10^{-3} kg\ mol^{-1}$) to get:

$$Water\ production = \frac{(9.34 \cdot 10^{-8}) P_e}{V_c} kg\ s^{-1} \tag{2.17}$$

Heat production is the other important wast product from FC use. Waste heat is simply created from the efficiency deficit of the operation, i.e. the energy not converted to electricity is rejected as waste heat.

$$Heat\ rejection = I \cdot n(V_r - V_c) \tag{2.18}$$

Gives the heat generated in watts [W] for a current I and n number of cells in the stack. V_r is the open-circuit voltage (typically 1.2V for a low temperature FC).

Heat rejection can also be written in terms of electrical power P_e:

$$Heat\ rejection = P_e \left(\frac{V_r}{V_c} - 1 \right) \tag{2.19}$$

2.2.2.8 Efficiency

As with many types of energy conversion equipment systems efficiency is an important measure, and there is normally many types of efficiency measures. In this section the main types of measures are described that's later used in this work.

$$Gross\ efficiency = \eta_G = \frac{V_c}{V_r} = \frac{V_c}{1.48} \tag{2.20}$$

Equation 2.20 describes efficiency of the fuel cell at 100% fuel utilization (Dicks and Rand 2013). Including no external system losses this "ideal" efficiency is denoted *gross efficiency*, giving it the subscript G in the efficiency symbol.

Net efficiency is another type of efficiency closely related to the gross efficiency. Net efficiency is a reduced gross efficiency due to other power consumers in the fuel cell system, such as heat management, air compressors and other supporting equipment.

Both gross and net efficiencies are effected by degradation, where degradation is a reduction in the performance of the electrochemical cell. Degradation can occur in several places and by many different reasons in a PEMFC. Running the cell at $V_c < 0.5V$ risks the reaction favouring a peroxide reaction instead of water and can accelerate electrode degradation. Another area that is sensitive is the platinum catalyst, where platinum sintering or dissolution can take place, or the carbon support can corrode, all affecting the effectiveness of the catalyst by reducing the surface area. Protecting the catalyst layer comes down to operating parameters of the fuel cell, limiting ramping speeds and minimizing start-stop cycles of the FC. Oxidation can also take place, and can be limited by purging hydrogen from the negative side of the cell or purging oxygen from the positive side. Mechanical stress is also said to be a factor in degradation, stress created by dimension change of the hydrated membrane during different operating modes, that need to be considered during design of the FC (Dicks and Rand 2018c).

When degradation has taken place, V_c goes down and thus reduces both gross and net efficiency of the FC. When V_c is reduced relative to V_r the specific heat rejection relative to produced power is increased, as seen in Equation 2.18 and Equation 2.19.

2.2.2.9 Hydrogen Fuel

The energy content of hydrogen can be measured in a multitude of units. A selection of the hydrogen specific values are presented below:

Table 2.5: Sample of hydrogen energy content in different units (Dicks and Rand 2013). Note that the *Effective specific electrical energy* takes into account the efficiency of the fuel cell based on Equation 2.20.

Specific enthalpy (HHV)	39.7 kWh/kg
Specific enthalpy (LHV)	33.6 kWh/kg
Effective specific electrical energy	26.8 $\cdot V_c$ kWh/kg
Energy density at STP (HHV)	3.29 kWh/m^3
Energy density at STP (LHV)	2.78 kWh/m^3

2.2.3 Additional Systems

Before the cases can be defined, some added technical equipment has been identified during the literature search. This equipment is mainly to handle the heat demand of the studied ship, heat pumps to supply the HTH demand, integration of the hydrogen vaporization system to supply cooling power to the HVAC system during the warm months of the year.

2.2.3.1 Heat Pump (HP)

As presented in previous chapters and sections, the heat demand onboard a modern cruise ship is both substantial and complex. The system is built around the large quantity of heat produced by the combustion engines. PEMFCs do not produce the same amount of high grade heat that conventional power-trains does, but they do produce a large quantity of lower grade heat (≈65°C). To be able to fulfill the high temperature heat demand, at steam quality, by the fuel cells there is a need for additional systems, like heat pumps.

Most heat pumps utilize the same process that refrigerators do but in reverse to bring heat from a lower temperature source to a higher temperature level. The principal flow and terms used are presented below:

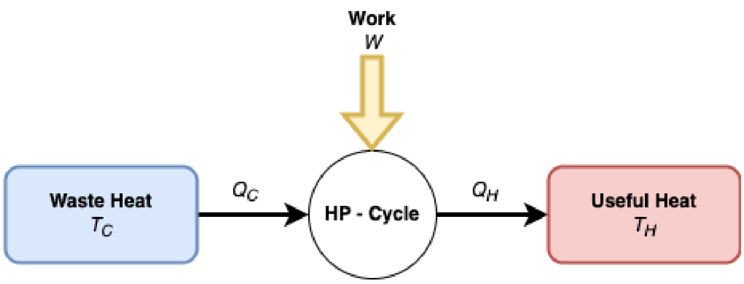


Figure 2.11: General principle of a heat pumps operation.

Heat is extracted at a low temperature level, then goes through the heat pump cycle. The low temperature heat is used in a evaporator where the heat transfer medium or refrigerant is evaporated at low pressure. Vapor is then compressed by a compressor that require work (usually done via electric motors), then condensed at higher pressure by a condenser, where heat is expelled at a high temperature as *Useful heat* side of the system. The liquid is then expanded, thus cooled, and begins the cycle again (Trzebiński 2019). The temperature range that these systems can be used in is effected by the choice of refrigerant and design of the system, and can be suited to a wide variety of applications.

2.2.3.2 Hydrogen Vaporization & Cooling from LH_2 Storage (CER)

One of the larger consumers of electricity onboard is the HVAC compressor (See further detail in subsubsection 2.2.1.5). As hydrogen is liquid below -253°C (20K) (Depken et al. 2022), and the FCs require a hydrogen feed temperature at or above

0°C to avoid freezing conditions inside the FC stack, a substantial amount of heat needs to be supplied to the hydrogen between the storage tank and the fuel inlet of the FCs.

The heating medium that heats the hydrogen can be of many different qualities. Sea-water can and has been used to evaporate LNG at harbour based LNG fuel terminals (Schreiner, Riemer, and Wachsmuth 2022), hence should be suitable for hydrogen vaporization. The heat required for vaporization can also come from waste heat produced onboard (Dahl 2023). While using sea-water heat to evaporate a cryo-cooled gas might seem like the most efficient option it should add complexity to the system with varying temperature and added number and area of heat exchangers.

The heat required for hydrogen vaporization can also be used as a cooling source, as has been used as such in at least one instance where a RO-PAX ferry utilized LNG as fuel (Dahl 2023), where the liquid temperatures of LNG are higher at 111K (Depken et al. 2022). In this case the "Cold energy" recovered from the LNG vaporization and conditioning was utilized for cooling of interior areas of the ship.

2.2.3.3 Hydrogen Fueled Boiler

As with the studied ship, there is often a need for a separate boiler to add heat to the vessel's heat system, transferred in form of steam or hot water. Fuel oils and gaseous fuels have been extensively used to fire boiler. Hydrogen is not that well used as some other fuels, but many boilers today accept mixes of hydrogen and natural gas, and some modern residential size boilers are designed to run on pure hydrogen (McManan-Smith 2022).

2.2.3.4 Thermal Energy Storage

A Thermal Energy Storage (TES) system can receive heat from a heat system and release at a later time (Dall'Armi, Pivetta, and Taccani 2022), this in essence can decouple the heat production and consumption in the time domain. In this case a low temperature TES is considered, where the TES will be charged when there is excess LT heat in the system and discharged to the HT Heat Pump when the heat system is under heavy load.

2.3 System Alternatives & Case Setup

This section first describes the different system alternatives that are to be evaluated and definition of the basic modeling setup for these alternatives. The system alternatives are followed by the definition of the evaluation process, based on a series of 31 cases that are modeled to gain insight into their effect on the a future PEMFC powered cruise ship.

The list of system alternatives are divided into *Background* and *Foreground* systems, where the former represents modification to the demand profile of some or all the "case days", while the latter category handles the technical aspects, such as the number of FC stacks different methods to meet and handle the vessel's heat demand.

2.3.1 Background Systems

Water production (Water prod.): Increased electricity demand to provide continues fresh-water for a fully laden ship (1800 passengers + 155 Crew) by an RO plant (for further details see subsubsection 2.2.1.6 where the technical data is presented). The energy demand profile is continuous, requiring the same amount of power for all time-steps. This assumes that the ships fresh-water tanks are large enough to accommodate the over and under -production that a changing water demand over the full day is meet by a continuous feed rate.

Reduced Fuel heating High Temperature Heat Demand (Red. HTH_{Fuel}) reduction of HTH demand for all times as per percentage values in Table 2.3 of the total power demand over the full year (weighted by the number of days of each "case day" in section 2.1), split up on the number time-steps in the model. Fuel heating demand is assumed to be constant in the model.

Reduced Galley High Temperature Heat Demand (Red. HTH_{Galley}) by reducing the total HTH heat demand of the ship for certain times of the day based on the total power demand presented in subsubsection 2.2.1.6 (in a similar way to above case), and weighted by the Galley heat demand presented in Figure 2.12 to bring higher loads during certain times of the day. The same weight is used for all "case days". The HTH demand is replaced with either electricity or LTH in a 1:1 relationship, and moved in time as per Hot Water Heating Demand in Figure 2.12. Both cases are tested as the Galley heat demand is somewhat unclear, see more details in subsubsection 2.2.1.4.

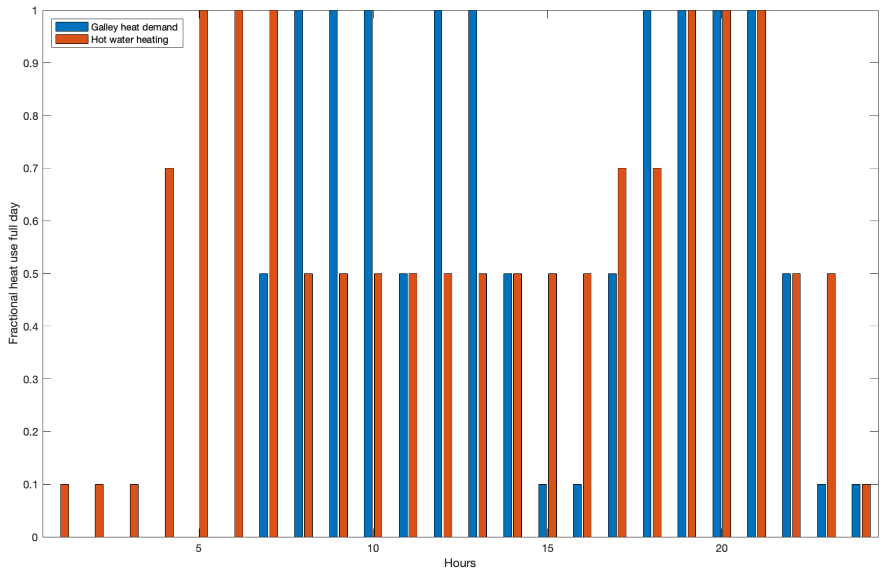


Figure 2.12: Distribution of galley and hot water heating heat demand over a full day. Values from Baldi, Ahlgren, et al. 2018.

Reduced Space Heating High Temperature Heat Demand (Red. HTH_{SpaceH}) is handled in a very similar way to Fuel heat demand, based on Table 2.3, but the demand is moved to LT heat instead of being removed altogether.

2.3.2 Foreground Systems

Number of fuel cell stacks (η_{FC}) obviously the number of fuel cell stacks needed to match the maximum energy demand for the case that is run, but there is the option to over size the number of stacks and is thus tested. The model setup have three different ways of deciding the number of FC stacks; MP (Maximum power), where the FC system is dimensioned to match the current rated power of the ship (rated power for Main and Auxiliary engines), or set to match maximum demand (MD), where the FC system is dimensioned to match the maximum propulsion and electricity demand for the ship for all five "case days". The third option is Variable size (Var.) where the system is dimensioned for the maximum demand per case day. The third option is somewhat unrealistic for the studied case ship, but can be helpful in understanding how the maximum demand changes over the year.

Boiler (Boil.) is the option to supply the full HTH demand for the ship by the use of hydrogen fueled boilers (see subsubsection 2.2.3.3).

Assuming a boiler is run on pure hydrogen, calculating the fuel need is straightforward, dividing the heat need by the lower heating value of hydrogen (presented in Table 2.5) and by the first-law efficiency of the boiler, in this case assumed to be 0.85 (Baldi, Moret, et al. 2020), resulting in Equation 2.21 when P_{need} is given in kWh:

$$Hydrogen\ use = P_{need,LT} \cdot \frac{1}{LHV_{H_2} \cdot 0.85} kg \tag{2.21}$$

For the case where a heat pump is utilized, the heat pump presents a more energy efficient way of creating steam from the LT heat network than using a boiler as per Equation 2.22. In this case the boiler would only provide heat to a liquid the above calculation is valid.

$$HHV_{H_2} \cdot \eta_{FC} \cdot COP_{HP} \geq HHV_{H_2} \cdot \frac{1.0273}{0.85} \qquad \forall \eta_{FC} \geq 38.6\% \tag{2.22}$$

In the case where the boiler is providing HT heat, or steam, a factor of 2.73% is added to the fuel consumption as the heat below condensation is assumed to be of no use, resulting in Equation 2.23 below:

$$Hydrogen\ use = P_{need,HT} \cdot \frac{1.0273}{LHV_{H_2} \cdot 0.85} kg \tag{2.23}$$

Heat Pump + Boiler (HP + Boil.) is a combination of subsubsection 2.2.3.3 and subsubsection 2.2.3.1 where a high temperature heat pump supplies the HTH, and the boiler is used to supply additional heat when the LT heat system is lacking heat.

Modeling the heat pump is based on one primary input value, the Coefficient Of Performance (COP), an important metric for heat pumps that characterize its efficiency. COP is the ratio between produced heat or cooling to the work input. With reference to Figure 2.11 the COP for a heat pump that produces heat is defined as:

$$COP_{HP} = \frac{|\Delta Q|}{W} = \frac{Q_H - Q_C}{W} \tag{2.24}$$

According to one heat pump manufacturer their steam generating heat pump has a COP of 3.5, 2.8 and 2.5 at waste-water temperature 80, 70 and 60°C respectively while producing steam at 120°C (Fuji Electric Co. n.d.). For a more typical heat pump that works below steam temperatures a typical COP can be above 4.5 (Kanchiralla et al. 2022).

As the required HT heat need is known, along with the COP_{HP}, there are two unknown in Q_C and W, calculated as below:

$$W = \frac{Q_H}{COP_{HP}} \rightarrow \Big\{W = Q_H - Q_C\Big\} \rightarrow Q_C = Q_H\Big(1 - \frac{1}{COP_{HP}}\Big) \tag{2.25}$$

Giving the electrical power W needed to drive a heat pump system for a specific HT heat need, and the required heat taken from the LT heat system Q_C. Assuming that the effluent water temperature from the PEMFC system the COP_{HP} is set to be 2.65 for Q_C=65°C (as mentioned in subsubsection 2.2.2.4).

Above calculations are used in conjunction with the boiler calculations for this alternative.

Heat Pump + Thermal Energy Storage (HP+TES) similarly to above but the overproduction in LT heat is stored for use for times when the LT heat is lacking heat.

The TES's state of charge is the only parameter used to model the TES in this case, with a maximum value representing its size and heat is simply added when there is an excess and discharged if there is a deficit. This is a slight simplification of the real case, where density change and $\Delta_{T,min}$ should be considered, however with the FC output temperature being higher than the defined heat interval of the LTH system the simplified calculation should give a representable picture of its use.

The Heat Pump is modeled as described in the Heat Pump + Boiler case.

Cold energy Recovery (CER) utilizes the hydrogen evap. stage to reduce the power needing to be supplied to the HVAC compressor for cooling during the hotter months of the year (Summer and Mid-season hot) and reduces the heat need to be supplied for hydrogen vaporization. This case does include the heat supply from below hydrogen evap. case.

LTH Hydrogen Vaporization (LTHH_2 Vap.) represents a system where no CER is used, instead the full heat need for hydrogen evap. is supplied by the LTH system, based on the description in subsubsection 2.2.3.2.

Calculating the heat needed for the vaporization of LH_2 as described in Equation 2.26:

$$Q_{H_2} = C_{p,L}(T_{vap} - T_L) + \Delta H_{Vap} + C_{p,G}(T_{Req} - T_L) \tag{2.26}$$

Where T_L is the liquefied hydrogen storage temp, T_{Vap} is the temperature of evaporation for a certain pressure and T_{req} is the temperature of the hydrogen gas feed to the FCs. $C_{p,L}$ and $C_{p,G}$ is the liquid and vapor heat capacity. At boiling point the values are at $9.8 kJ/kg \cdot K$ for liquid and 12.2 $kJ/kg \cdot K$ for vapor at boiling point and $14.32 kJ/kg \cdot K$ at STP. ΔH_{Vap} is heat of vaporization at 447 kJ/kg (Schreiner, Riemer, and Wachsmuth 2022, Klell 2010). Assuming the hydrogen is stored at 15K and needs to be heated to 273K (STP), the Q_{H_2} is 3868.1 kJ/kg if $C_{p,V}$ assumed linear between 15K and 273K.

Water Recovery (WR) is where water produced by the FC system is recovered and used to lower the water production rate. This option is only evaluated when onboard water production is considered (see subsection 2.3.1 for more details on water production). Water recovery rate is based on the hydrogen use per Equation 2.15 and Equation 2.17, i.e. the molar mass difference between water and hydrogen. The paper *Recovery and quality of water produced by commercial fuel cells* (Tibaquirá et al. 2011) highlights that while water in their tests were only recovered at a 8% rate there are measures that can be put in place to increase this number substantially. The results are provided for 8%, whereas 50% recovery is discussed.

2.3.3 Case Setup

To evaluate different aspects of the onboard energy systems a series of cases are defined for evaluation. Table 2.6 presents 31 different runs, where investigated system alternatives (on the X-axis) are divided into the two main groups of *Foreground* and *Background* systems presented previously in section 2.3. The cases are divided into categories based on the main area investigated, first the *Baseline & Verification* where the model is tested with varying numbers of installed FC stacks, to investigate the effect the installed power has on the fuel consumption and average load factor for the three main "case days" tested. One addition is the *Ref.* cases where the *Reference Model* is used on the same case days to verify that the *System Model* produces reasonable results for different days and number of installed FCs. The case where a varied amount of fuel cells are used depending on the "case day" ($Var.$) is not necessarily interesting from a practical standpoint for the studied ship, but it highlights the effect on fuel consumption that a system minimized in installed power for a very constant load has, i.e. where there is a very low degree of excess power in most cases.

The next category, *Heat Supply* investigates different modifiers to the heat system, both in demand (*Background*) and the the heat system (*Foreground*). The sole hydrogen boiler is used to test the different demand modifiers while the remaining heat system cases are tested for both full list of, and none, of the modifiers. All cases are tested in the winter "case day", as it presents the highest total heat demand thus puts the greatest load on heat system components.

The next category handles the Hydrogen Vaporization cases, where the foreground systems of $LTHH_2Vap.$ and CER is tested to gauge their impact. This is tested for the summer "case day", as the HVAC power demand is significantly higher in that case, thus allowing for a comparison between the system layouts. More details on the $H_2Vap.$ case can be found in subsubsection 2.2.3.2.

The last section investigates the case of onboard water production (WP), for different seasons, to see the impact that the additional load would bring to the energy use of the ship.

Table 2.6: Overview of tested cases divided into categories. Different case days provides the baseline demand for heat and power. HPD stands for High Propulsion Demand, one of the case days characterized by high propulsion demand. η_{FC} is the number of installed FC stacks, MP: sized to match rated power of the existing ship, MD: dimensioned for the max demand of the case setup for all case days, Var.: dimensioned for the current case day. Background and foreground systems are explained below.
*: *Case where heat demand of the galley is met with electricity instead of LT Heat*

			Background				**Foreground**						
	Case #	**Case day**	Water Prod.	Red. HTH_{Fuel}	Red. HTH_{Galley}	Red. HTH_{SpaceH}	η_{FC}	Boil.	HP+Boil.	HP+TES	CER	$LTH_{H_2Vap.}$	WR
Baseline & Validation	1	Winter					MP						
	2	HPD					MP						
	3	Summer					MP						
	4	Winter					MD						
	5	HPD					MD						
	6	Summer					MD						
	7	Winter					Var.						
	8	HPD					Var.						
	9	Summer					Var.						
	10	Winter					Ref.						
	11	HPD					Ref.						
	12	Summer					Ref.						
Heat Supply	13	Winter					MD	•				•	
	14	Winter		•			MD	•				•	
	15	Winter			•		MD	•				•	
	16	Winter			•*		MD	•				•	
	17	Winter				•	MD	•				•	
	18	Winter					MD		•			•	
	19	Winter					MD			•		•	
	20	Winter					MD	•			•	•	
	21	Winter		•	•	•	MD	•				•	
	22	Winter		•	•	•	MD		•			•	
	23	Winter		•	•	•	MD			•		•	
	24	Winter		•	•	•	MD	•			•	•	
H_2 Vap.	25	Summer					MD		•			•	
	26	Summer					MD		•		•	•	
	27	Summer		•	•	•	MD		•			•	
	28	Summer		•	•	•	MD		•		•	•	
WP	29	Winter	•				MD	•					•
	30	HPD	•				MD	•					•
	31	Summer	•				MD	•					•

2.4 Modeling

Primary modeling takes place in MATLAB (The MathWorks Inc. 2021). Main functional units are kW, where demand is set for a certain time-period, and the model works to meet this demand with a specified system setup, for both heat and power demand. Changes to demand and system properties are varied and results are produced from the calculations results.

How the demands are varied and the system properties are defined in previous section, no other parameters are changed between the model runs.

There is in essence two different models that are used, the main *System Model* that is the more advanced model developed to represent "real" fuel cells and includes a selection of the studied systems and operational aspects (based on the case setup), and the simpler *Reference Model*, that is based on the same data as the *System Model* when it comes to basic power demand, but does not consider heat management or other studied aspects, and instead calculates fuel use from the equations in subsubsection 2.2.2.7 and is used to validate the *System Model* for the basic fuel use to meet the electricity and propulsion demand.

2.4.1 System Model

The purpose of the model is to calculate power levels for each FC stack in a system for every minute for several different scenarios, or "case days". The model is written in the MATLAB software, starting with several inputs in .CSV format. The "case day" data is a table that contains the 15min average energy need for electrical, propulsion, HT heat and LT heat for the 5 different case days. Hence the table contains 20x96 data points, and handled in the model as separate tables per case. The 2_{nd} input is the 200kW FC performance data, containing 9 different load conditions, presenting hydrogen flow, load factor, net and gross power, net thermal rejection, efficiency, voltage and current for the different load conditions (PowerCell AB 2022). Another data-set presents the ramp-rate for the same load conditions. There are additional inputs that describe efficiency's for heat pumps, boilers, or other sub-components.

The model can run different amounts of FCs in the system, based either on the maximum power demand per case, maximum for all cases, or matching the power output of the case ship. Power need is defined by the case vessels momentary propulsion demand and electricity demand divided by an efficiency factor, set to 95% to accommodate losses for the FC external supporting systems, losses in power distribution and conversion efficiency for the drive-train.

Matching power demand is based on a series of loops and if/elseif statements. The model loops over all cases j and time-steps t, and in some cases the number of FCs η_{FC}. The power demand data is converted from 96 time-steps (24h*4) at 15min resolution to minute data (1440 time-steps), and then smoothed to get some ramping for the power level changes.

Modifications to the systems, defined as the system alternatives, such as changed demand for some heat consumers or systems such as boiler and/or heat pumps is handled before or after the main loop that sets the operation of the individual fuel cells, changing demand or modeling how a certain heat deficit for certain times are fulfilled. Demand profile for heat demand in galley/hot water (Figure 2.12) is added in the beginning of the model.

The main goal of the model is to run as many FC stacks as possible at all time, as this is where the greatest efficiency is reached, assuming the net power output of the individual FCs do not fall below a set value for continuous operation, where the FC starts a shut-down process until once again required. The model considers 4 separate cases;

- Power demand is above the lower limit for all stacks and all stacks are at or above minimum power for the earlier time-step:
  $\textit{Power needed} \geq \textit{Minimum power for each stack} \cdot \textit{Number of installed FCs}$
  For previous time-step: $\textit{Stack power} \geq \textit{Minimum power for each stack}$
  where the FCs provide equal share of the power need.

- Power demand is below the lower limit for all stacks running;
  Power need ≤ Minimum power for each stack · Number of installed FCs
  Where as many as possible stacks run at minimum power, and remaining stacks start a 4 minute ramp-down to zero linearly from minimum power.
- Power demand is above the lower limit for all stacks and some stacks are below minimum power for the earlier time-step:
  The cells below minimum power for the previous time-step is set to min power, the ones previously running is set to run at minimum power to provide the required power.

The main result produced from the main loop described above is a table of power levels for each individual fuel cell for all time-steps, this is then converted using the FC performance data as a lookup table producing the results such as hydrogen flow, load factor, net and gross power, net thermal rejection, efficiency and ramp rate. Further details of the system model can be found in Appendix A and full MATLAB code in Appendix B.

2.4.2 Reference Model

The reference model is based on the same power demand data as the *system model*, and uses the same basic efficiency and power demand calculation considering the electricity and mechanical power combined power need. Hydrogen use, air use, heat rejection and water production is calculated from Equation 2.15, Equation 2.11, Equation 2.19 and Equation 2.16 respectively, instead of using performance values of a real fuel cell. These values are used as reference to test the validity of the values produced by the *system model*. The reference model does not represent the change in efficiency at different power levels, and does not consider different FC stacks, instead calculated as a single "stack", not considering the dynamics of starting and stopping individual fuel cells. The efficiency of the fuel cell is set by the value V_c at 0.65V, as said to be a good reference value (Dicks and Rand 2013).

2.4.3 Cost Implications

To aid in discussion and conclusions the results of the defined cases, some cost data is added to analysis. The cost data is collected during the literature search and utilized to forecast some cost implications of the results. This aims to put the different system alternatives into context on how large of a difference they make to costs involved for the owner/operator of a future, fuel cell powered, cruise ship.

This section aims to first summarize economic data for the applicable components followed by some economic implications that different system layouts imposes.

The calculations are on simple side, CAPEX and OPEX are calculated based on Table 2.7, where O&M costs are percentages of CAPEX for the specific type of equipment. Many components are omitted in this chapter, only the main differentiators between cases presented in the previous chapter are included, and efficiency by calculating costs for yearly fuel expenses, then added to the OPEX. Lifetime is set as 25 years, where equipment with a lower lifetime is simply multiplied by a factor to bring the OPEX up to a level to cover operation of the full ship lifetime.

Table 2.7: Cost parameters for major components. Cost year 2021.

Component	**LT [yr]**	**Specific CAPEX**	**O&M**	**Source**
PEMFC	8	1100€/kW	2%	Kanchiralla et al. 2022
H_2 liquefaction	25	2100€$/kgLH_2/day$	4%	Kanchiralla et al. 2022
H_2 Tank	25	1.71€$/kWh$	2%	Kanchiralla et al. 2022
Heat Pump	25	1000€$/kW$	2%	Kanchiralla et al. 2022
Boiler	25	180€$/kW$	5.3%	Putriastuti et al. 2021
H_2 Fuel	*N/A*	3€/kg	*N/A*	European Commission 2021

The fuel system is scaled to match the maximum demand for a case setup, so for any technical setup the fuel storage capacity is set for the HPD demand. The number of fuel cells are set as per the cases presented previously, and total yearly fuel demand is calculated for all days of the year, i.e. a mix of all "Case days".

3

Results

This chapter presents the data that is produced by the 31 cases defined in the previous chapter, divided into the three main categories, and adds some additional results on specific issues such as response rate and cost implications. The main data point used in the evaluation is total fuel use over the specified day. As the each "case day" is well defined, the total fuel use gives an indication on the efficiency of the full system. Under each section information are added to gain insight into the dynamics presented for a specific set of cases.

3.1 Baseline and Verification

Table 3.1 shows the total hydrogen consumption, average load of the FC system and number of installed FCs for cases 1-12 (see Table 2.6 for further details). Note that N/A comes from the *Reference model* that does not consider the number of FCs, thus is not able to calculate the average load of the system.

Table 3.1: Results from cases 1-12, Baseline & Validation, investigating the impact of different amounts of FC stacks and verifying with the Reference model (Case 10-12). All cases tested for Winter, HPD and Summer day. Case setup is presented in Table 2.6.

Case	**Total H_2 Consumption** $[tonne/day]$	**Avr. Load**	η_{FC}
1	6.4	18.2	173
2	14.2	34.3	173
3	9.1	23.8	173
4	6.5	27.9	97
5	16.4	57.6	97
6	10.0	38.4	97
7	7.5	62.5	42
8	16.4	57.6	97
9	10.1	41.3	90
10	7.1	N/A	N/A
11	15.2	N/A	N/A
12	10.0	N/A	N/A

Taking the data from Table 3.1 into context; Figure 3.1 shows the relative difference between the cases. Note the relatively large difference between "case days", with a smaller difference depending on the model used. The cases where the number of FCs are varied for each case day (Var.) matches the closest to the *reference model*, also the case for the HPD "case day" where the MD case matches similarly to the Var. and Ref. case, as expected per the setup where MD is sized according to the maximum demand that is expected to be found in the HPD case. One can also note that the trend that higher installed capacity lowers the fuel consumption, where the MP case has the highest number of FCs, MD has slightly less and Var. the lowest for most cases, except the HPD where Var. and MD has the same system size.

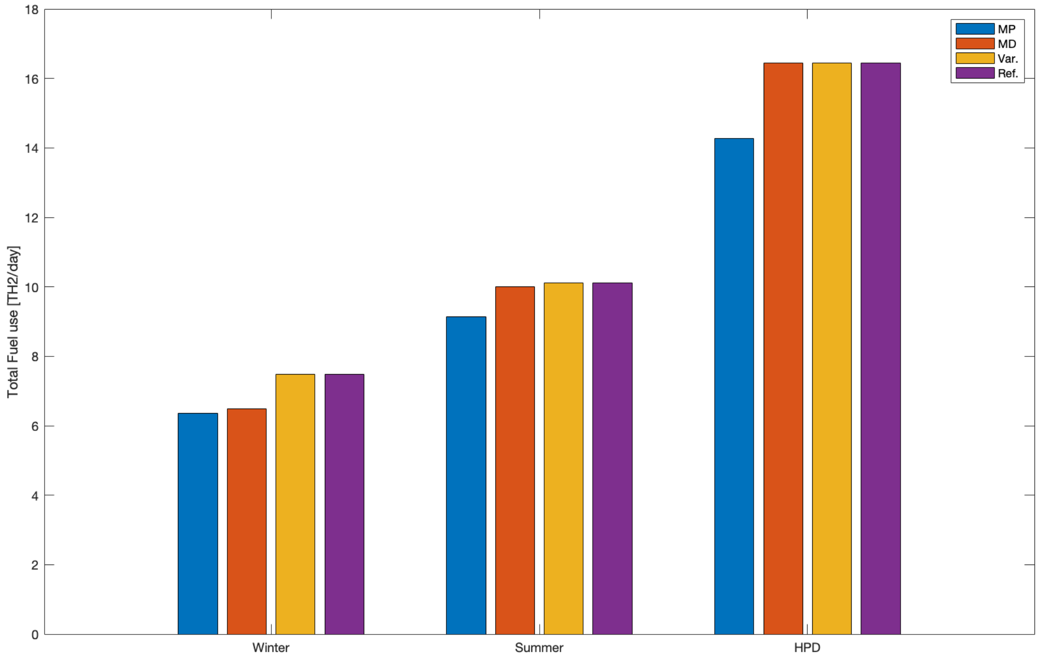
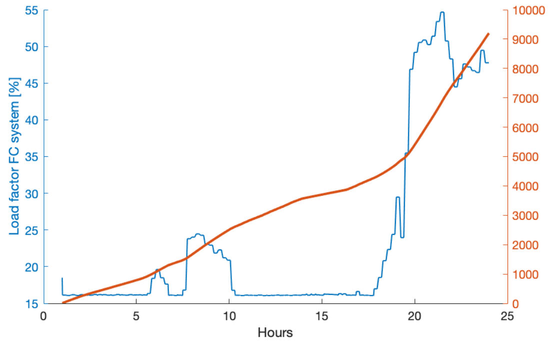


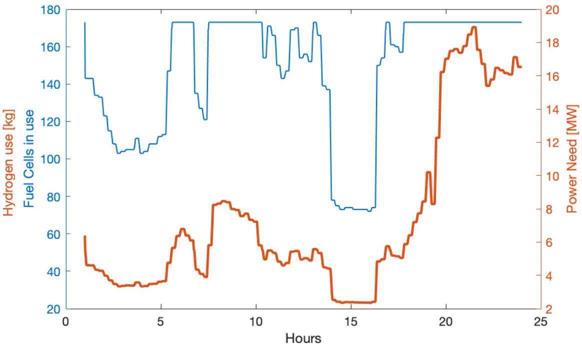
Figure 3.1: Total fuel consumption per day (tonnes LH_2/day) grouped into "case day" categories showing grouped values based on the model runs for cases 1-12.

The difference in installed capacity, i.e. the number of FCs in the system and how the operate to meet the demand is further visualized in Figure 3.2 where case 3 and 6 are expanded upon, showing two plots for each case where fuel use is compared to the system load-factor and the number of FCs in operation together with the power demand of ship for the summer "case day". Figure 3.2b and 3.2d shows the number of fuel cells in operation for each time-step in blue, note the difference in maximum value for each, with the first representing the MP case 3 where the installed number of FCs are 173 (from Table 3.1), and the latter with a max number of FCs in operation of 97.

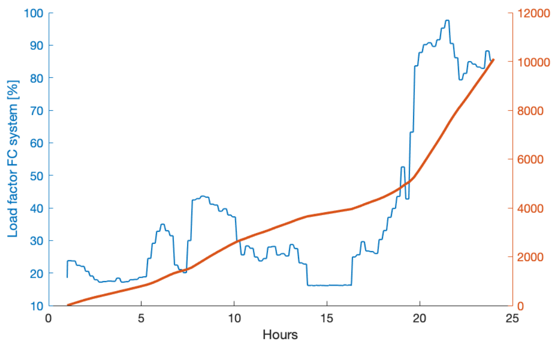
The difference in operation is clearly seen, where 3.2d have all stacks active for most of the time-period, which is not the case in 3.2b. This is reflected in 3.2a and 3.2c where the load factor is smaller for the MP case over the whole time-period due to the higher installed capacity, and only goes above the minimum power level



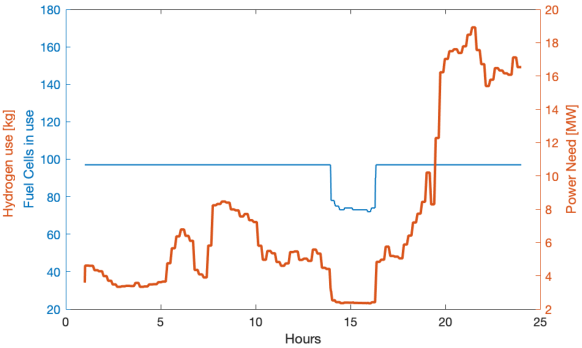
(a) Cumulative Fuel Use / FC Load Factor full Summer day for MP case (3).



(b) Number of fuel cells in use / Total Power Demand full Summer day for MP case (3).



(c) Cumulative Fuel Use / FC Load Factor full Summer day for MD case (6).



(d) Number of fuel cells in use / Total Power Demand full Summer day for MD case (6).

Figure 3.2: Series of figures showing how the differing numbers of fuel cells in the system are utilized to meet the same demand profile. Note the different scales of the Y-axis's in the set of figures.

when all FCs are running. For the MD case the load factor is above minimum level for nearly all time-periods, where all FCs are running, and is only at minimum level for the relatively short time-period around hour 15 where the power demand is low enough that some FCs are shut down. The effect is seen in the cumulative fuel use represented in the orange line in 3.2a and 3.2c where the slope correlates with the load factor, leading to a lower total fuel consumption for MP case. The dynamic of higher fuel efficiency with lower loads are further explained in subsubsection 2.2.2.8.

3.2 Heat Supply

The heat supply system presents some unique challenges due to the varying amounts and qualities required for different periods of the year. Table 3.2 shows the total hydrogen consumption, average load of the FC system and number of installed FCs for case 13-24 (see Table 2.6 for further details). Case 13-24 are all running the winter "case day" and the MD number of fuel cells, sized after the HPD day at 97 fuel cell stacks for all cases.

Table 3.2: Results from cases 13-24 for Heat management impact on Winter case day. Case setup is presented in Table 2.6.

Case	**Total H_2 Consumption** $[tonne/day]$	**Avr. Load**	η_{FC}
13	6.7	27.0	97
14	6.6	27.0	97
15	6.6	27.0	97
16	6.8	27.2	97
17	6.7	27.0	97
18	6.7	27.9	97
19	6.5	27.9	97
20	6.7	27.0	97
21	6.4	27.0	97
22	6.5	27.4	97
23	6.3	27.4	97
24	6.4	27.0	97

The results on total fuel use presented in Table 3.2 are also presented in Figure 3.3 where the case 4 is added as the baseline reference for a winter day with a total of 97 FC stacks.

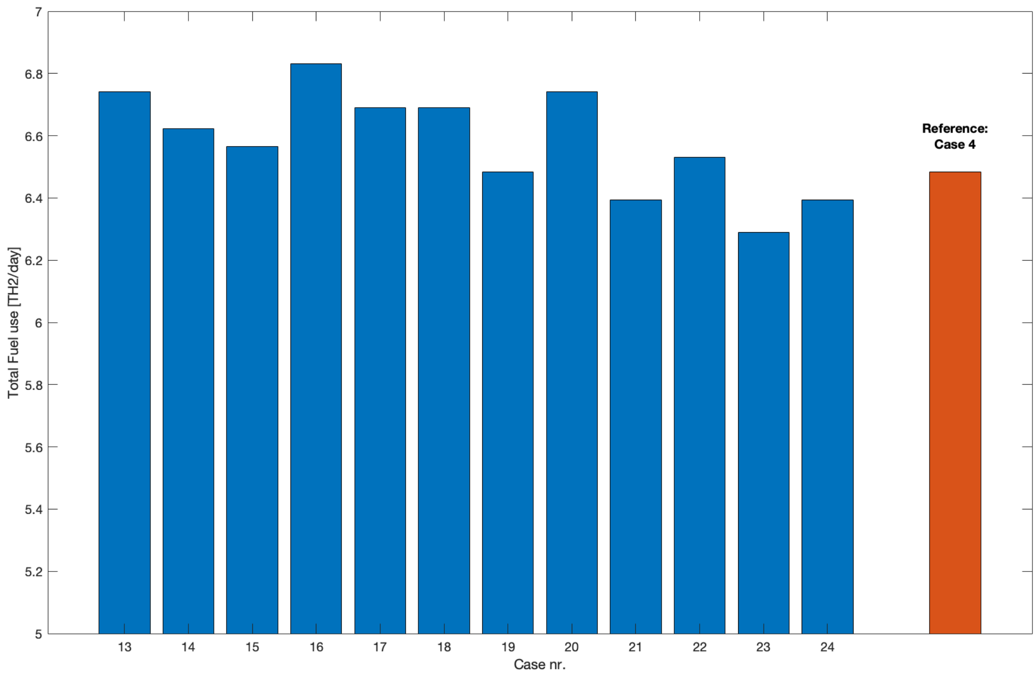


Figure 3.3: Total fuel consumption per day (Tonnes LH_2/day) for cases 13-24 and 4 as a reference to the baseline figures (note the truncated Y-axis).

Figure 3.3 shows a spread of results both above and below the reference +5.11% / -3.1% (+349kg/-195kg), this is expected as the reference does not take heat management into consideration at all. Cases 13-17 investigates the demand side of the system, where case 13 shows the system without any background system modifiers, only the boiler to satisfy HT heat demand and heat for H_2 vaporization, being one of the least fuel efficient options. Case 13 can be compared to case 20 where the CER case is added, showing no difference in the results as expected due to the CER only being active during the summer "case day". Both reduction in fuel heating and Galley HT heat demand shows notable reductions in the overall fuel consumption by 1.78% / 2.63% respectively (120 and 177kg/day), while for case 16 galley HTH demand is replaced with electricity instead shows a notable increase in fuel consumption. Case 17 shows a moderate decrease in total fuel consumption with reduction of the HTH space heating demand in favor of LT heat.

Looking at cases 18-19 where the foreground systems are further investigates, namely the heat supply systems, where HP+boiler and HP+TES is tested, and should be compared to case 13. There is a slight reduction in fuel demand for the HP+boiler option at -0.77% (-52kg/day) and larger reduction for HP+TES option at -3.84% (-259kg/day) compared to case 13.

Cases 18 and 19 share many similarities, where the FC system supplies most of the LT heat and the HP supplies the HT heat. They differ in how a deficiency of LT heat is supplied for the winter "case day". For other days there is no difference, only during the winter days does the heat system need additional heat apart from what the FC system supplies. The winter day is presented in Figure 3.4 where some hours lack sufficient amounts of heat (hours 3-6, 8, 16-17). For case 18 this heat is supplied with a boiler providing LT heat to support the system in these relatively few hours.

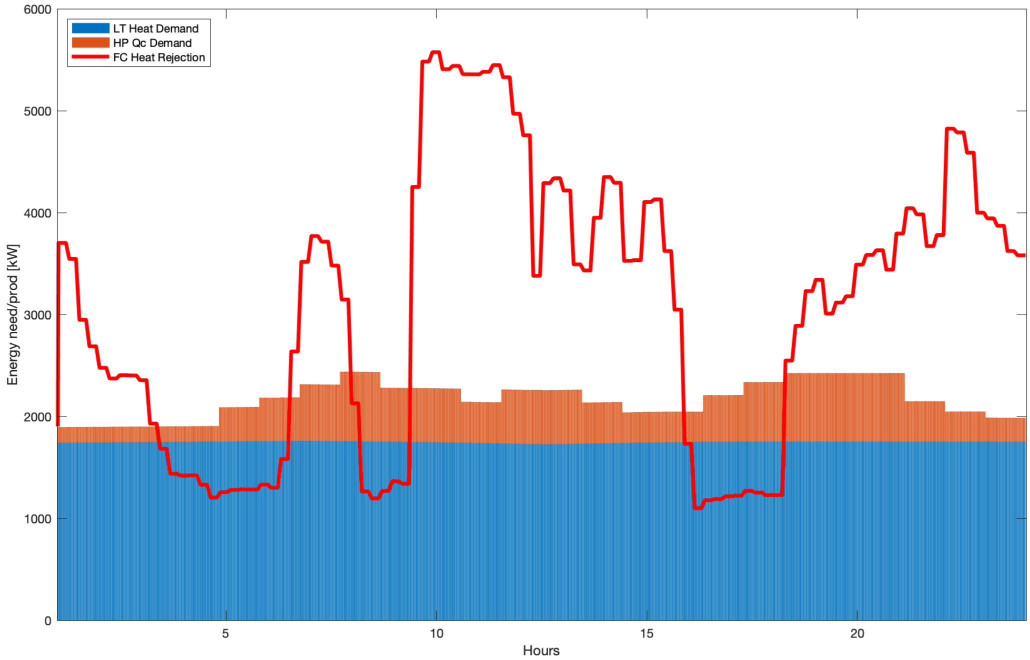


Figure 3.4: LT heat demand for ship systems and heat pump over the full day, with overlay of the Fuel cell system heat rejection. Applicable for cases 18 and 19.

For case 19, the lack of heat for the winter case is instead of a boiler supplied by a thermal energy storage that is charged by the excess heat available at other time-steps. The state of charge of the TES and in-and-out flows of energy is presented in Figure 3.5. In this case the hydrogen consumption is minimized as non of it is utilized for additional heat, instead a new system needs to be added. For the studied case the thermal energy storage capacity is 2408 kWh.

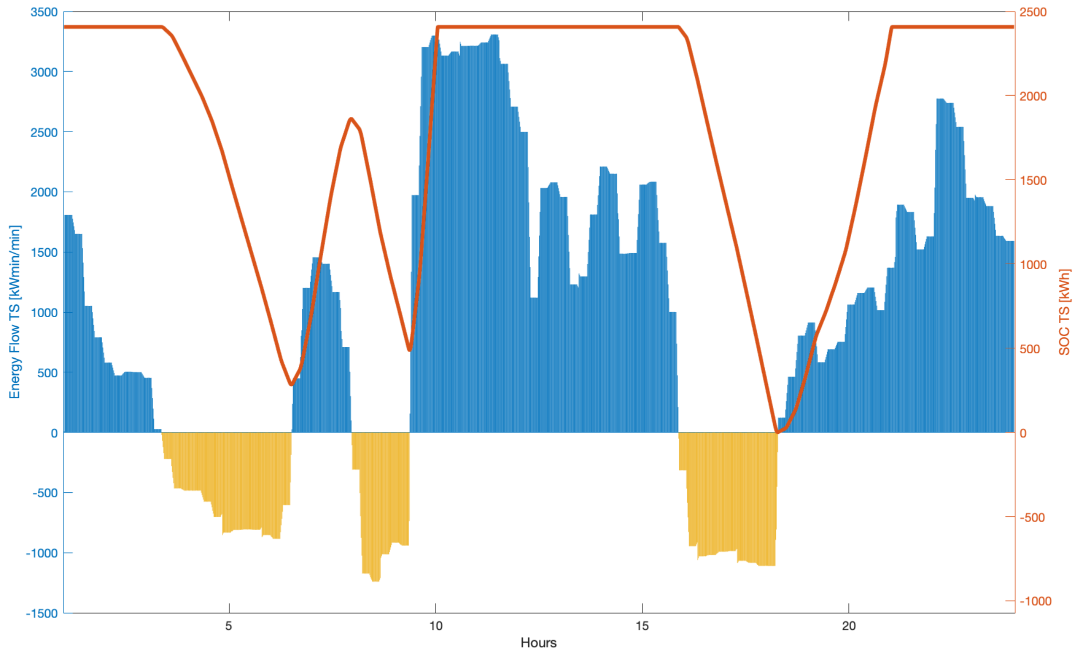
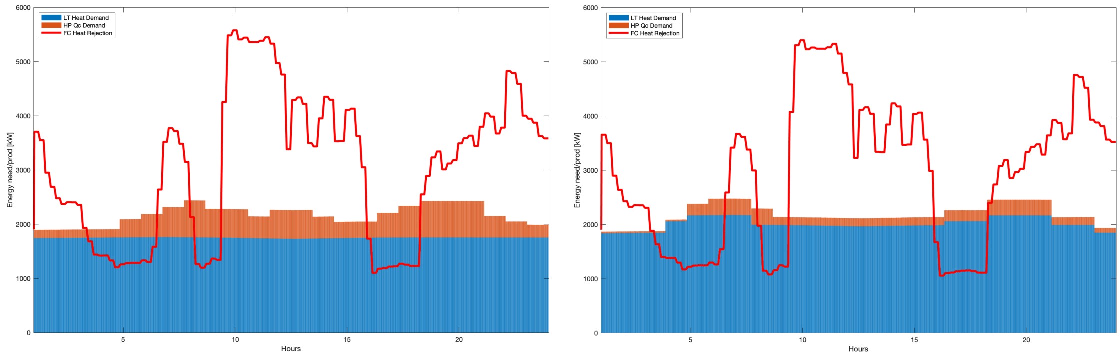


Figure 3.5: Energy flow to and from the TES on left side, with state of charge (SOC) for the TES on the right for case 19.

For cases 21-24 the same foreground systems are tested as in cases 13 & 18-19, but with use of some background system modifications, the reduced HTH demand. Case 21 shows the expected reduction in total fuel consummation as the demand side has been correspondingly reduced for the boiler case. The same is true for case 23 where HP+TES is used, reduction in the demand leads to a reduced fuel need. Case 22, utilizing boiler+HP shows an increase compared to the sole boiler case (21), which does not correspond to the reduction seen between cases 13 & 18. Figure 3.6 highlights the change in demand, where the galley heat demand is shifted to LT heat from HT. The change between case **(a)** and **(b)** is the LT heat need over the day, increased where the galley is requiring heat, thus lowering the available waste heat for the HP. In case 22 there would be an efficiency gain in using the FC system to provide more electricity to galley needs instead of using LT heat, as the limit is reached for heat provided by the fuel cell system.



(a) Case 18. **(b)** Case 22.

Figure 3.6: LT heat demand for ship systems and heat pump over the full day, with overlay of the Fuel cell system heat rejection.

Cases 21 and 24 present the same data as would be expected in similarity to cases 13 and 20 where CER does not effect the winter case.

3.3 Hydrogen Vaporization

Hydrogen vaporization is investigated in cases 25-28, where the impact of heat needed for hydrogen vaporization and recovery of some of this energy is evaluated. All cases are tested for the summer "case day". Cases 25 & 26 test the difference with or without CER when no demand reduction is applied from the background systems, while cases 27 & 28 evaluates with or without CER with all demand reductions (background systems). For all cases the HTH is supplied with Boiler+HP to maximize the load on the LT heat system. Results are presented in Table 3.3 and fuel consumption comparison presented in Figure 3.7.

Table 3.3: Results from cases 25-28 for Hydrogen Vaporization impact on the summer case day. Case setup is presented in Table 2.6.

Case	**Total H_2 Consumption** $[tonne/day]$	**Avr. Load**	η_{FC}
25	10.0	38.4	97
26	9.6	37	97
27	10.0	38.4	97
28	9.6	37	97

Notably there is no difference in the total fuel consumption between 25 & 27, 26 & 28, but there is a difference between the CER and non-CER cases. The reduction in fuel demand for the CER case compared to the non-CER case amounts to a reduction of 4.3% (426kg/day) of daily demand. The lack of difference between the background system modifications comes down to relatively small heat demand in the first place for the summer day (see Figure 2.3 for typical base energy demand), and the efficiency of the HP in providing HT heat, and no boiler operation thanks to the excess in LT heat.

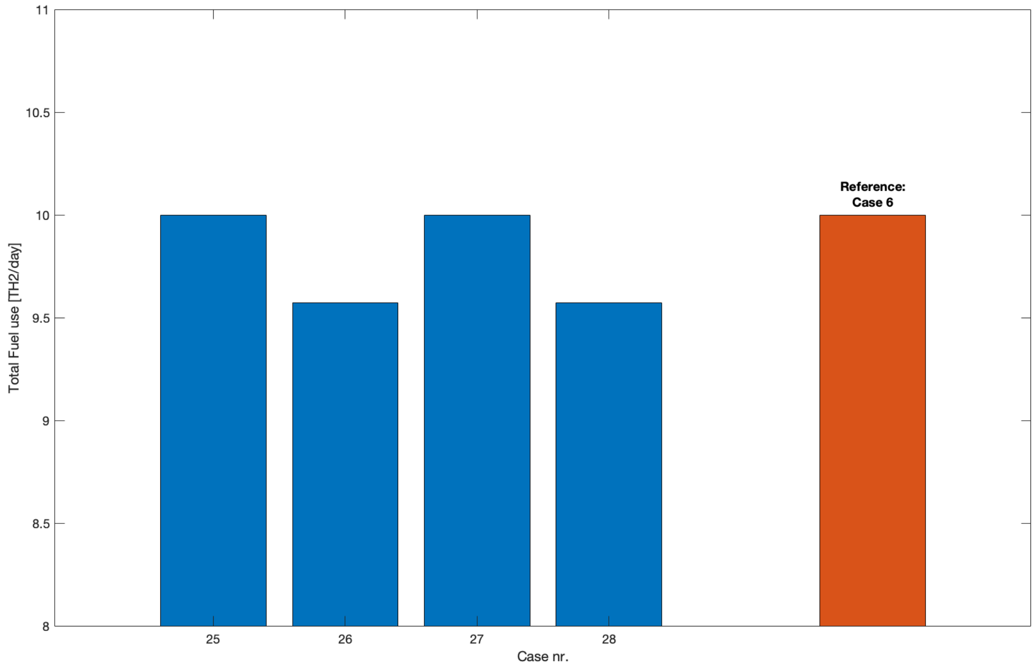


Figure 3.7: Total fuel consumption per day (Tonnes LH_2/day) for cases 25-28 and 6 as a reference (note the truncated Y-axis).

Reference case 6 is also noted to have the same fuel demand as cases 25 & 27, even when the hydrogen vap. heat is used in the later cases, this, once again, comes down to the excess of LT heat in the summer cases.

3.4 Water Production

Cases 29-31 test the what impact of onboard water production. Here the main addition to the system is a RO plant to supply the ship with enough water for a full passenger and crew load with the associated electrical power load that the RO plant entails. These cases are further explained in subsubsection 2.2.1.6 and subsection 2.3.1. Table 3.4 presents the hydrogen consumption for a full day of operation and average load, along with the number of installed FCs in the system based on the maximum demand over all days. A difference can be seen in this case, where the number of FCs has changed from 97 in many of the previous results (Table 3.2, Table 3.3), to 98 required FCs when water production is used (Table 3.4).

Table 3.4: Results from cases 29-31 for Water Production impact on Winter, HPD and summer case days. Case setup is presented in Table 2.6.

Case	Total H_2 Consumption $[tonne/day]$	Avr. Load	η_{FC}
29	6.6	28.0	98
30	16.5	57.3	98
31	10.1	38.4	98

Figure 3.8 shows the total fuel consumption numbers in relation to cases 4-6, highlighting a relatively small difference in total fuel consumption for water production. A fully laden ship requires around $400m^3/24h$, or $0.257m^3/min$ if water production rate is equal over the whole period. This equates to an additional load of 77kW over the all time-steps, the reason for one extra 200kW FC stack.

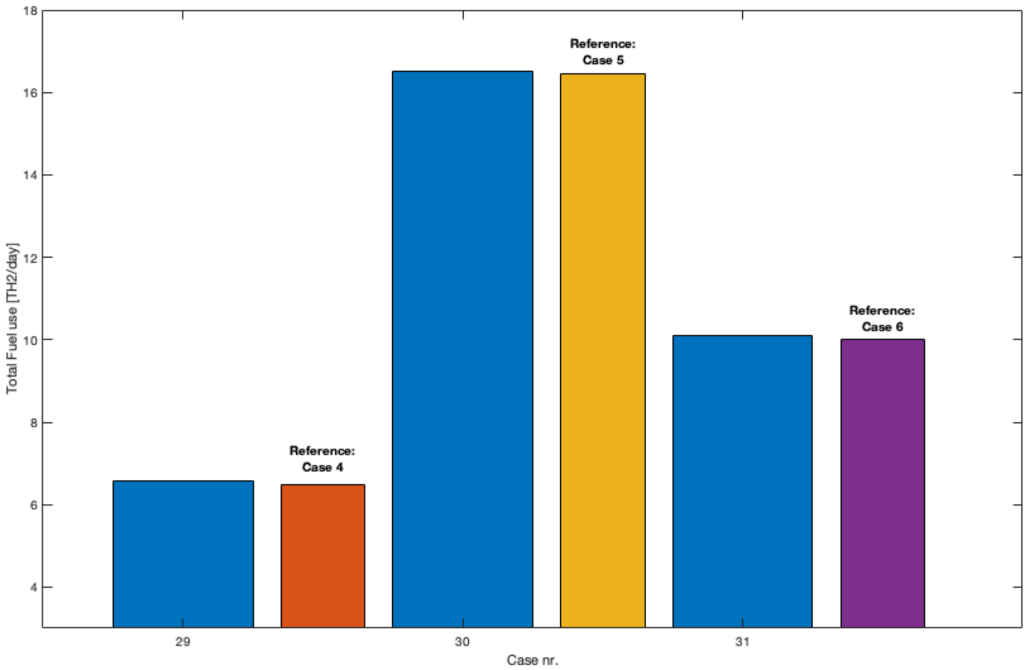
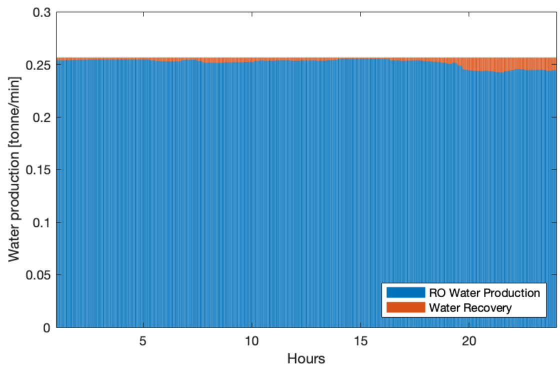


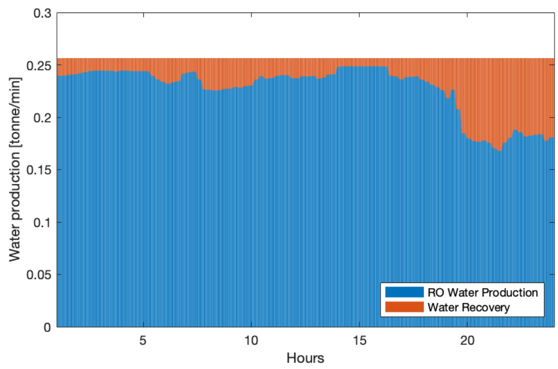
Figure 3.8: Total fuel consumption per day (Tonnes LH_2/day) for case 29-31 and case 4-6 as a reference to the baseline figures (Once again note the truncated Y-axis).

Water recovery impact on the system is relatively small with a large number of persons onboard. For the studied cases at 8% recovery (see subsection 2.3.2 for further details) is assumed. This is shown in Figure 3.9, where **(a)** is the case used in the results above (specifically Case 31). The water recovery is providing 1.8% of the daily fresh-water need.

If a recovery factor of 50% could be attained, the corresponding results would be as **(b)**, where 11.5% of the daily water need is covered by the water recovery for the specific day. These values change correspondingly with fuel consumption, so for a winter day where fuel consumption is slightly lower, thus water recovery potential is smaller.



(a)



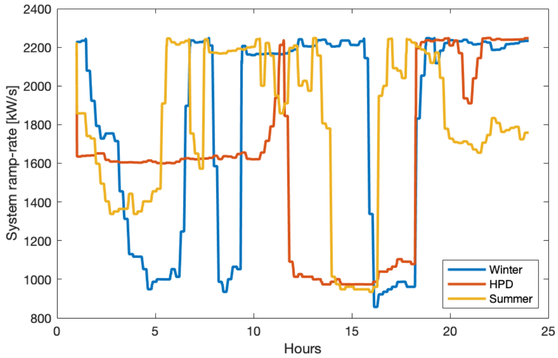
(b)

Figure 3.9: Share of water production between RO and Water Recovery from fuel cells over a full day. **(a)** is summer "case day" with 8% Water Recovery (as tested) and **(b)** is summer "case day" with 50% Water Recovery.

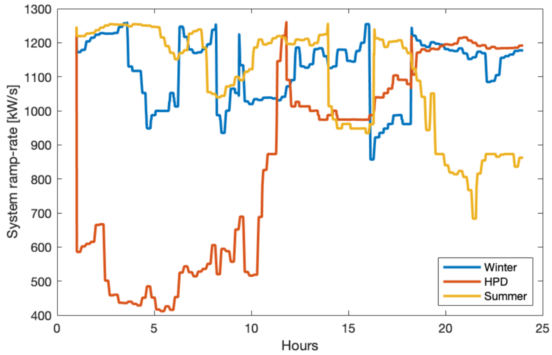
3.5 Response Rate

The models used in this all cases, and reflected in all previous results in chapter 3 have been focusing on meeting a demand for energy, and little regard has been given to the instantaneous available power (minute or sub-minute scale). It is important for the FC system to meet demand shifts instantly when it arises, otherwise other load shifting systems has to be included.

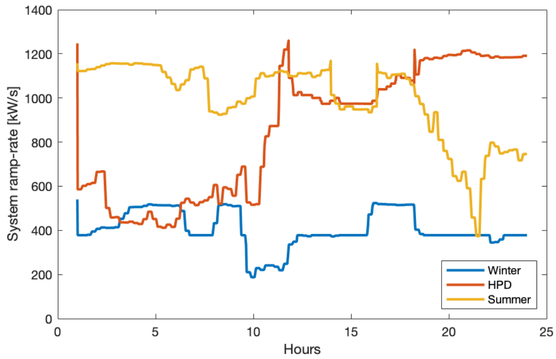
Plotting out response rates in kW/s is given in Figure 3.10, for 9 different cases. Figure **(a)** shows the response rate for the three MP cases (173 FCs), the setup where the lowest average load factor is found for the system, giving the highest available response rate of the studied cases. Figure (b) shows a steady high response rate for the summer and winter "case day", while the HPD "case day" goes as far down as in figure **(c)**, where the installed capacity is the same for HPD but differs for summer and winter.
One additional characteristic is seen again in **(a)** and **(b)**, similar to Figure 3.2, where cases 1-3 and 4-6 act in similar way when the load goes low enough that the number of active FCs are similar between the cases, independent of the installed number of FCs per case. This is seen in **(a)** and **(b)** in the HPD "case day" where hours 1-10 have the same shape but very different number where the largest load is on the system, while for hours 12-17, where the load is the lowest the system shows similar response rate between the cases.



(a) Cases 1-3.



(b) Cases 4-6.



(c) Cases 7-9.

Figure 3.10: Plots of Response Rates in 9 cases, given as kW/s for the different cases (note the differing scales on the Y-axis).

3.6 Number of Fuel Cells

Assuming the price of of PEMFCs at 1100€/kW, giving a per stack price of 220,000€ for 200kW of capacity, we can put some numbers on the different amounts of stacks installed in the tested cases, and calculate the total fuel demand and fuel storage costs. Assigning CAPEX to the first point, then adding OPEX+fuel cost for each year up to the 25 year lifetime is presented in Figure 3.11. Note that CAPEX is not anuitized, instead only added to the first point in the plot, representing a simplification to many other cost evaluations.

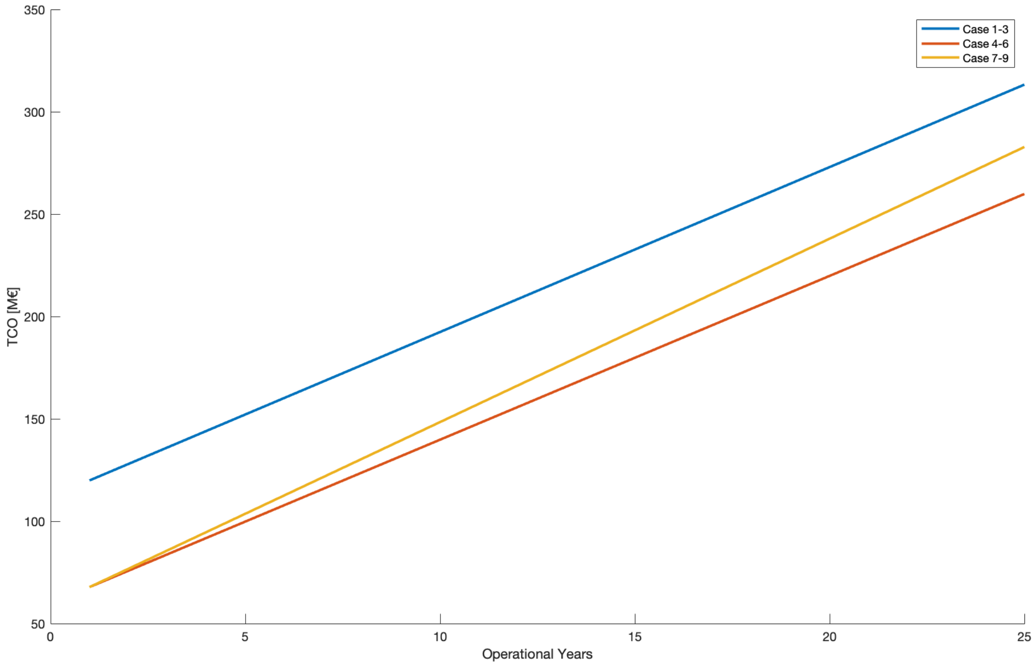


Figure 3.11: CAPEX and OPEX plotted for 25 years, cases 1-9. Total Cost of Ownership (TCO) is presented in million € on the Y-axis.

Note that cases 1-3 and 4-6 share a very similar slope, thus a similar OPEX, indicating that the fuel savings that cases 1-3 have compared to 4-6 is relatively insignificant of the total cost of operating the vessel. For cases 7-9 however, the increased fuel cost with the relatively small amounts of installed power does lead to significantly higher OPEX approaching that of cases 1-3 after 25 year of operation.

Assuming that the ship is re-fueled every day, the boil off is not included in the analysis. If the vessel was to transit longer distances, this is a factor that needs to be included, and a re-liquefaction plant needs to be included.

3.7 Heat System

For the heat system there is an interest in comparing the costs between the cases. Cases 13-24 are in many ways similar, all handling the heat flows and designed around the same amount of installed FCs, simplifying there comparison. Figure 3.12 shows a comparison between the cases in CAPEX, excluding the PEMFC costs that is 66,687,500€ for case 13-24.

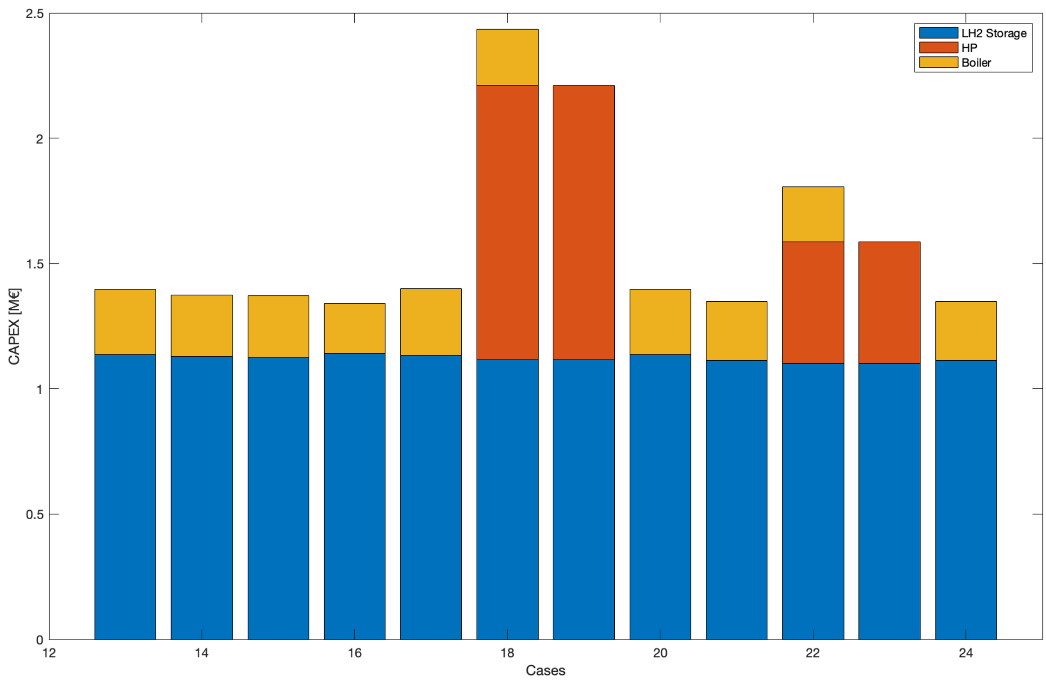


Figure 3.12: CAPEX for cases 13-24 showing the costs for the Boiler, Heat Pump and Hydrogen Storage, excluding the PEMFC cost (same for all cases).

Notably the boiler CAPEX, closely linked to installed capacity remains similar for all cases except cases 19 and 23 where TES takes the place to supply extra LT heat for winter days. The cases utilizing heat pumps show a significantly higher CAPEX due to the higher cost per power unit. Hydrogen storage does in all cases represent the majority of the CAPEX apart from the FCs.

Figure 3.13 presents the OPEX data for the same cases, with inclusion of the fuel cells. The heat pumps have smaller share of the OPEX than CAPEX, due to the lower O&M factor. Clearly the FC system presents the largest share of the OPEX due to the significant part of CAPEX.

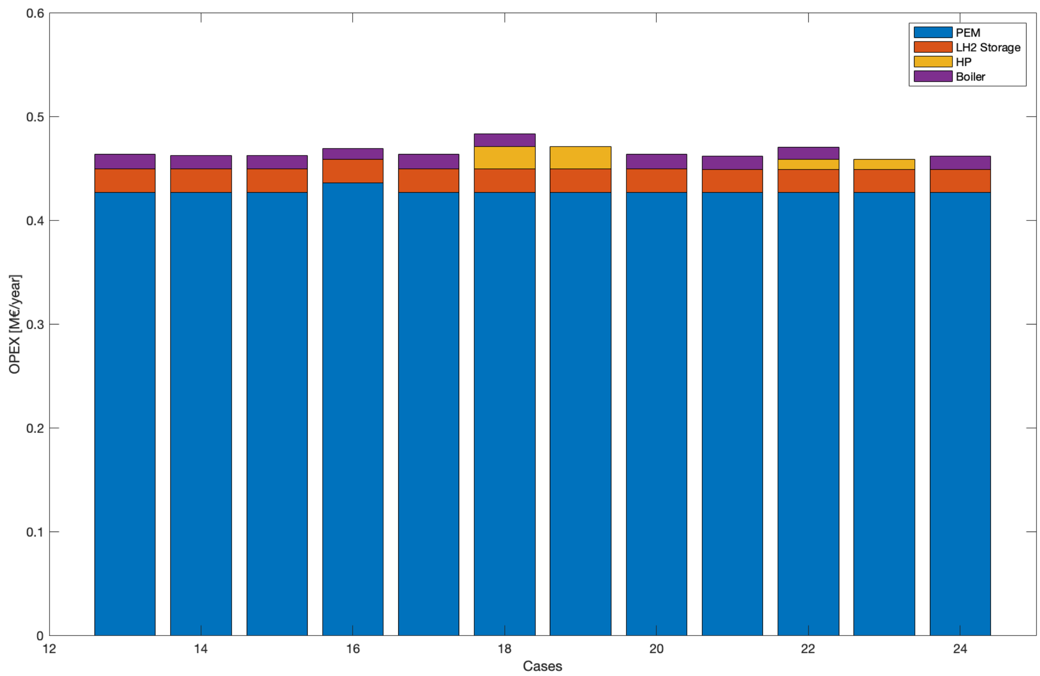


Figure 3.13: OPEX for cases 13-24 showing the yearly costs for the PEM fuel cells, Boiler, Heat Pump and Hydrogen Storage.

Figure 3.14 presents the fuel cost for one year of operation for case 13-24. Similarly to the results in section 3.2, with relatively small differences between cases. The results are further smoothed out as the yearly fuel need does include other "case days" apart from just the winter day where the heat system has it's greatest impact.

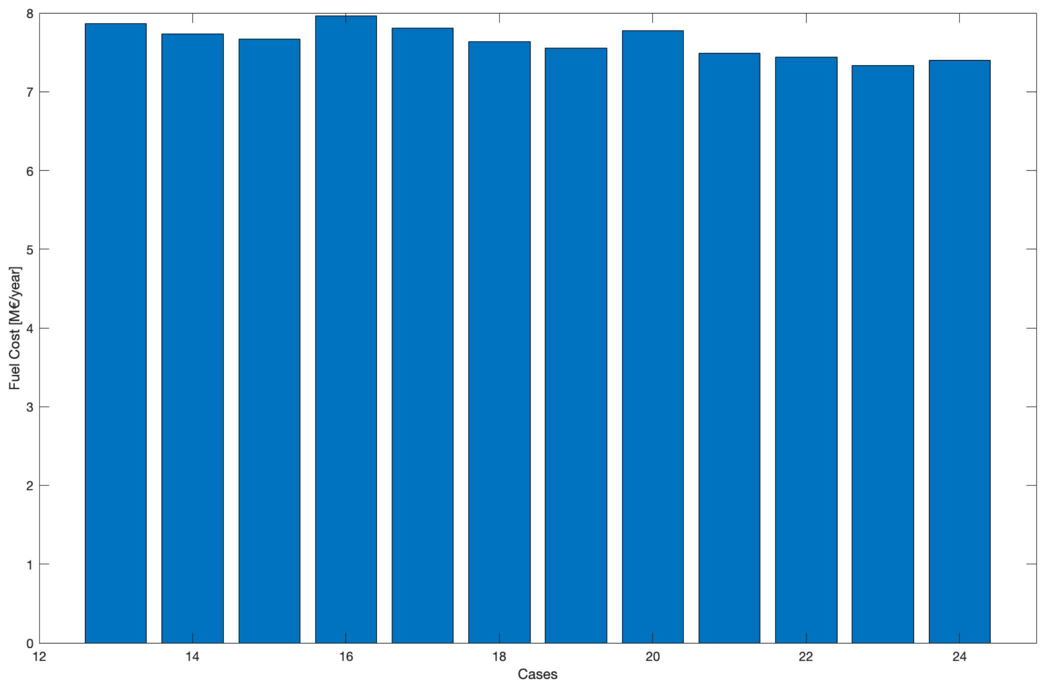


Figure 3.14: Fuel costs in M€/year for cases 13-24.

We can note that case 16 presents the highest yearly fuel cost, where the galley heat demand is met with electricity instead of HT heat. We can also note that the cases utilizing heat pumps do equate to a lower yearly fuel consumption compared to the solely boiler heated options.

3.8 Hydrogen Vaporization & Water Production

Gauging the impact of CER vs. the case without (28 and 27 respectively) via a Total Cost of Ownership (TCO) plot presented as Figure 3.15. Case 31 is also added to see the lifetime cost of powering onboard water production, the cost of the water production plant is however not included. The TCO plot shares its setup with Figure 3.11, where the CAPEX is plotted as the first point on the X axis, with added OPEX for each year of 25 year lifetime.

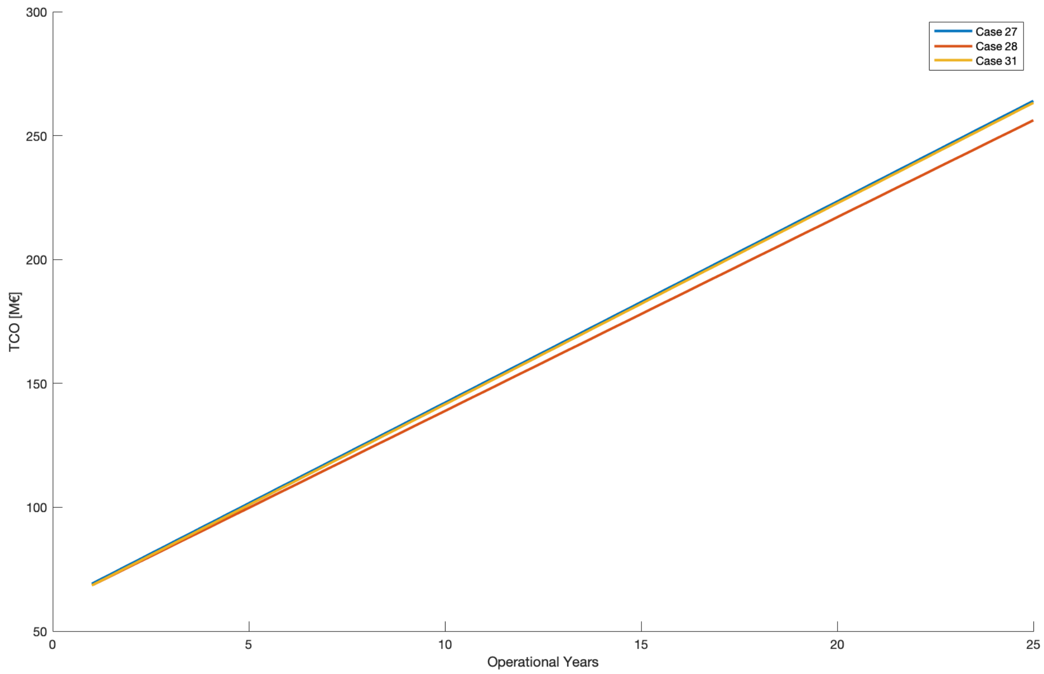


Figure 3.15: CAPEX and OPEX plotted for 25 years, cases 27, 28 and 31. Total Cost of Ownership (TCO) is presented in million € for the full 25 year lifetime on the Y-axis.

Note a very slight difference between cases 27 and 31, highlighting the relatively small extra load that water production puts on the system. A more notable difference comes between 27 and 28, where CER is used. Being applied only to the summer and MSH "case day" it still presents savings that are notable on the lifetime of the vessel.

4

Discussion

4.1 Technical Feasibility

The first question that should be answered is that of feasibility, is it possible or practical to utilize fuel cells for large passenger ships? Section 2.2 notes that the fuel cell systems in themselves do not present a large issue, as the systems are designed to be combined for MW scale installations. The question is how this fits with the ships systems and requirements. The same chapter goes through the ship's systems; while the case vessel is equipped with direct shaft drives, there has been an alternative around for some time, the diesel electric architecture. This enables the generators and propellers to be decoupled, such that the system becomes less dependent on the type of system generating power. This in combination with a modern electrical system layout as the proposed HVDC system, seems to provide an architecture that can fulfill the electric power and propulsion demand of a large ship when combined with only fuel cells or a hybrid setup. The next issue is how to fulfill the heat demand.

4.2 Change in Heat Flows & Low Temperature Waste Heat

The heat flow of the heat system when fuel cells are introduced are in many ways very similar to the original setup of the studied ship (see Figure 2.4), where waste heat is utilized to fulfill most of the demands of the ship, and a boiler can be used to assist when the waste heat is insufficient. The original heat system setup can be seen with fuel heating, where waste heat was utilized for fuel pre-heating. Looking closer there are, however, some differences that are inherent to the PEMFC. First the steam use for fuel tank and fuel heating is removed, providing a substantial reduction of the steam need. The original system provides both low temperature heat and steam quality high temperature waste heat from the HTHRS and EGB respectively. The original system seems to tend towards use of steam for heating that does not strictly require the high temperature such as galley heat need, tank heating and space heating.

The large heat demand for the ship provides a system where the low temperature waste heat of the fuel cells can be utilized. The temperature is in a range where it should be able to directly feed the low temperature system, reaching some degree of utilization, and when a HP and/or TES systems are installed for its utilization can be increased, or even maximized. Interestingly in comparison to the existing ship there is a fuel heating system in the FC case, to vaporize the liquid hydrogen, that utilizes the low temperature heat even further. The main change in energy flow is the reduction in high temp. heat use in favor for low temp. heat, a natural design change to better utilize the heat produced by the fuel cells.

4.3 Efficiency Factors

Fuel use has been the major parameter used in this work to indicate efficiency, it should be said however that it's not exactly an indicator that can be used to compare all the 31 cases used when it comes to *FC system efficiency*. The changes in demand that the "backround" system modification represents, and the hydrogen vaporization options, are changes to the services a certain system provides, thus should fuel efficiency only be used to compare efficiency when these options are the same, such that the system provides the same services. On the contrary, it can be said that the *total efficiency* of the vessel improves if some demands such as the existing ships fuel heat system is removed, space heating demand is changed from the HT circuit to LT or CER is utilized.

When it comes to the *FC system efficiency* the main takeaway is the importance of individual load factor of the different fuel cells, as the higher efficiencies are reached at minimum load. Two takeaways can be identified from this, either the system is "oversized" so that there are an abundance of fuel cells that can run at lower load for more hours over the day, or the operational profile of the ship is changed so that the ship utilizes the fuel cell system more efficiently, for example, running at lower speeds to reduce the propulsion load.

For the *total efficiency* other factors are at play, but still very connected to the *FC system efficiency*, in that a lower demand from the ship will reduce the fuel demand if the number of installed fuel cells are the same, so reducing the heat need when propulsion power is high would be worthwhile to reduce the total FC load factor. Only using extra power when there are individual fuel cells when they are not in use for example, keeping the *FC system efficiency* as high while supplying more energy. A word of caution should however be raised, as when the fuel cells are running at lower load factors, less heat is produced compared to electricity. This could in some cases result in a lack of LT heat that would require the use of boilers to supply this heat, which should be avoided due to the lower efficiency when it comes to hydrogen use.

4.4 Water Recovery

The water produced by the fuel cells, even at such scale that is discussed in this work, would provide quite a marginal amount of water compared to the scale of water use onboard, thus has not shown to be of significance. It could be the case that for other vessel types with large installed power capacity, that water recovery could for example satisfy the crew's fresh-water demand, and other similar qualities of water. At 8% recovery the system produces on average slightly over 1200l/h of water, which could satisfy quite a large crew and technical-water need if not carrying passengers. Carrying passengers will increase the water use drastically and thus require a separate systems that provide fresh-water to the ship.

4.5 Fuel Storage

Handling fuel in the form of liquid hydrogen has in parts been omitted from this report, where handling and storing the fuel is a complex matter. While hydrogen is characterized with a very high energy density to weight, this ratio is not that favorable when it comes to volume (Table 2.5). Reducing the stored volume while keeping the energy content comes from compressing or liquefying hydrogen. Liquid hydrogen contains around 2.36kWh/L (Biert et al. 2016), or 59.45 kg/m^3 of liquid hydrogen.

The studied vessel might be one of the better candidates for hydrogen fuel cell propulsion systems, as the vessel travels relatively short distances and docks two times per day (for reference see for example Figure 2.2). While the base value for the results section are in tonne hydrogen per day, it could be argued that even that the values presented will overestimate the fuel volume that must be stored onboard. If assuming that the storage volume needs be sufficient for one full day this would entail between 6 and 17 tonne LH_2 capacity (Cases 23 and 30 respectively), or 104.8 and 275.4m^3 LH_2, this would work with only one re-fueling per day (depending on the case). If the ship can be refueled at both stops these volumes could be greatly reduced by about 50%. This would however greatly reduce the range of the vessel or capacity to handle unforeseen events that would require re-routing, staying at sea due to search and rescue operations or re-positioning events like changing routs or going to a shipyard for maintenance. In reality the stored fuel volumes would likely be greater to accommodate such events.

On the subject of onboard fuel handling the safety aspect is highly relevant, where the complex rules and regulation around hydrogen is a current issue limiting the near term potential of the technology. Keeping hydrogen storage safe onboard might change the design of the ship, if tanks needs to placed such that the area can be well ventilated if large amounts of gas needs to be evacuated in a safe manner. This might impact the layout of the ship if tanks would need placing on weather deck.

4.6 Economic Considerations

The hydrogen cost used in Table 2.7 is set to be 3€/kg, this number is in the higher end of the stated values by the source European Commission 2021 of 1.5-3.5€/kg production cost for hydrogen. As stated by the report and as would be the case in reality, the production cost would in most cases not be the same as the fuel cost when fueling the ship. Depending on where and by what means, even at what time of the day the hydrogen is produced, might greatly impact the price. Adding to this the hydrogen handling, and in our case, liquefaction. This is in-itself an energy demanding process that should increase the final price of the commodity.

The analysis method itself has been simplified and parts omitted that would be expected in a more classical "Techno-economic assessment", as the "cutoff" has been made too aggressively to be argued to make a full analysis. The calculations can however show some interesting aspects. In general terms, the results show that the most impactful part of CAPEX and OPEX are the fuel cells. Both in the term of installed capacity, since that cost vary greatly with the number of installed fuel cells, and the sensitivity to the cost parameters that are presented for the PEMFC. The sensitivity to cost parameters makes the total numbers presented in this work even less applicable, it does however tie into another aspect of the fuel cell technologies. While some projects have been shown to work for marine applications, the fuel cell sector can be said to be a developing market, thus putting general numbers on the costs associated or estimated lifetime are subject to change in the future.

Costs associated with heat production are relatively small. Using heat pumps in combination with a hydrogen fueled boiler, or a sole boiler to full-fill the full demand there is a relatively small difference in fuel demand, while lower with the heat pump option the installation and maintenance costs are slightly higher. What is the better option is sensitive to the cost data, but with the current setup the HP should be cost efficient with the yearly fuel saving covering the higher CAPEX within a few years. This is however once again sensitive to the area of operation of the vessel, considering a cruise vessel that would cruise less in cold climates this might not be the case. The heat system is also sensitive to the demand, considering the cases where HT heat demand is reduced or powered by other system the CAPEX is greatly reduced for the HP, but the effect of heat system efficiency is similarly reduced.

Thermal energy storage, TES, where tested in a few cases, and shows a reduction in investment cost by the magnitude of the boiler investment cost for the similar cases using HP+Boiler. This comes from the exclusion of any investment or O&M cost for the heat storage system. These systems do provide the best economical performance when it comes to OPEX, if the maintenance costs can be kept below the level where the added fuel consumption of the boiler is. Considering the thermal capacity that the TES needs to work with the system, and the low temperature difference in the system, it would be expected that the TES does need to be of considerable size, and might impact the design of the vessel. If it could be effectively integrated to the ship structure, and complexity kept to a low level (considering the relatively high cycling rate the efficiency demands can be kept lower) it might show economical benefits.

While costs for onboard water production can be seen to be relatively insignificant, due to the simple adding electricity demand, there is no data accounting for the investment cost of the water production plant, this would however be a cost associated with both a diesel fueled power-train and a hydrogen FC system. A greater impact is seen with the CER system, that does show a notable decrease of costs over the ship's lifetime, greatly reducing the electricity demand over the warmer months of the year.

4.7 Potential Benefits of TES

Going back to the TES system, there might be other benefits apart from potential fuel savings. While the studied ship is modeled to support its own power need when in harbor, there are more and more harbors utilizing shore power to power ships while tied up alongside their docks. This could be a solution for the studied vessel as well, to avoid using precious hydrogen when the more efficient solution would be to take power from the shore side energy system. While this would fulfill the electricity demand, the issue would be the heat system. If a HP is installed this could provide HT heat, but still needs available low temperature heat normally supplied by the FC system. While utilizing the boiler system for this need it would handle the full LT heat load in these situations, it could potentially increasing its size. TES could in this case provide another service, storing heat from when the ship is running to feed the heat system in harbor. This would increase its utilization to the full year, instead of the relatively few times per year where the LT heat supplied from the FC system does not fulfill the ship's demand. Another added benefit would be while starting and ramping up the FC system, where the hydrogen flow increases before the increased heat output from the FC system reaches the hydrogen vaporization system, the TES system would be supporting the LT system shifting heat demand and heat production in time.

4.8 Other Work

There has been a series of works that investigate the application of fuel cells in the marine sector over the last few years. One of the more broad pictures that has been shown regarding fuel cells in a marine application is *Study on the use of fuel cells in shipping* by the European Maritime Safety Agency in 2017 (Biert et al. 2016), where a summary of fuel cell projects are described to gauge the feasibility of such propulsion systems, and the main fuel cell types are described and ranked. The PEMFC is given one of the higher potentials as it is seen as one of the more mature types, although noting its sensitivity to fuel impurities and relatively low lifetime and the low temperature waste heat. The SOFC fuel cell type is also given a high future potential, noting that the type can run on different fuels, gain higher efficiency and provides a high temperature waste heat, although not as developed at the time as the PEMFC.

While this work focuses on the PEMFC, as noted above there is also a potential for the SOFC, which has been described further in the paper *The role of solid oxide fuel cells in future ship energy systems* (Baldi, Moret, et al. 2020) highlighting a good potential of the SOFC, especially when run on natural gas as is an option for the SOFC compared to the PEMFC. Regarding the application the paper notes a more cost efficient application on cruise ships compared to tanker vessels, and highlights additional advantages for cruise ships when it comes to reduced noise and vibration levels that the system provide compared to a normal combustion engine power-train, a benefit that is shared with PEMFC.

Another paper taking once again a broader prospective is *A review of fuel cell systems for maritime applications* (Tronstad et al. 2017), where the authors note that a hydrogen fueled PEMFC can provide a power dense solution, for endurance up to 100h, and above that the natural gas fueled SOFC provides a more cost effective solutions as the fuel volumes increase, in line with the previous paper.

Looking more in detail on the PEMFC system is the paper *On optimal integration of PEMFC and low temperature waste heat recovery in a cruise ship energy system* (Dall'Armi, Pivetta, and Taccani 2022), highlighting the promise of hydrogen fueled PEMFC as a decarbonizing strategies, that can be suitable for cruise ships navigating coastal areas. The paper looks further into the heat recovery, setting up a more complex model of the heat recovery and heat pumps than in this work, noting the challenge of low temperature heat recovery but also the possibility of improvements in the area.

The choice between SOFC and PEMFC is a well discussed question from the above papers, and there seems to be an trend towards SOFC when long range operation is required, well above the ranges that the studied ship in this is supposed to navigate. The challenge of heat recovery is also highlighted in all above papers, and is said to be one of major benefits of the SOFC, but the last example shows that a high degree of recovery is also possible for the PEMFC case, just as this thesis shows. In comparison to the last paper this thesis looks from a wider perspective on the heat side, but with less detail in the analysis.

4.9 Limitations & Future Work

While the case data used in this work has been highly valuable and has in most cases provided a solid base for the work, there has been uncertainties when it comes to certain areas. The demand modifiers described in subsection 2.3.1 do share some uncertainty in how they can be applied. The reduction is based on total yearly power demand for all cases except water production, and does bring up the question exactly when and how these consumers use their defined amount of heat.

There are a series of other uncertainties in the analysis, stemming from the relatively large amount of systems evaluated, for example the parameters that the model is based upon are in many ways simplifications and rough estimates of future technologies. For example the boiler models that have been simplified having a single overall efficiency, or the heat pump's COP is based on one single manufacturer's estimate. The heat system has been modeled as simply a kW_{in}/kW_{out}. This can represent the heat balance to an extent, but is limited in reflecting the actual heat transfer system that would involve losses over long distances, minimum ΔT values for heat exchanger areas and pump losses to transfer the heat transfer medium to different locations in the vessel. Cooling systems has also been simplified, assuming that any excess heat can be cooled off to sea-water. While the sea provides an excellent heat sink, it does require energy and equipment to be able to transfer the heat.

There are a series of areas that have come up during this work that would be interesting to look further into, and may be of interest for future work. One of these is the demand response. In this work the data is compiled from 15 minute average power need, this gives a good insight in the amount of energy that is recovered, but limits the insight into how a fuel cell system might act in a shorter time-frame to meet the instantaneous power ramping that can occur when large consumers are started or stopped, an example would be bow-thrusters. Studying how the ramp-rate (presented in Figure 3.10) would meet the instantaneous demand could highlight if other supporting system would be required, like batteries to assist in rapid load shifts over short time-frames (sub second to minute scale).

Boilers to assist the heat demand of the ship has been well discussed in this work, leading to a sort of hybrid heat system. It would be interesting to look further into the same sort of hybridization of the power generating system, for example the implementation of hydrogen fueled gas-turbines, that could support the system while at high loads and if an exhaust gas boiler was installed in conjunction, support the heat system.

The supporting systems for the fuel cells or balance of plant equipment, has briefly been mentioned in subsubsection 2.2.2.1 and is not further handled in detail in this work, it would however be interesting to look into how the compressors, filters, and other equipment supporting the fuel cells would work and how the energy consumption would effect the efficiency of operation, which in this work is only represented by an overall efficiency figure (see subsection 2.4.1).

5
Conclusions

Utilizing fuel cells to power a modern cruise ship seems highly feasible in the near future. Implementing this new power generating system requires careful consideration to fully utilize the efficiency increase that fuel cells promises. The number of installed fuel cells is shown to have a large impact on the total efficiency of the power generating system. This indicates that the system should be oversized to a degree, but the result also points to the large cost associated with the fuel cells, and extra costs for an oversized system. Over-sizing the system leads to a lower load factor of each individual cell, where the highest efficiency is seen. Minimizing the load factor of most operation, however, leads to several points of operation where a number of fuel cells are switched off, reducing their utilization. Potential for increased system efficiency can also be said to be dependent on a future lower price of fuel cell system installations to have a noticeable gain of the increase in system efficiency, if hydrogen costs remain high.

Adjusting the heat demand of the vessel can simplify the system and reduce the fuel consumption in total, focusing on utilizing the low temperature heat that the PEM fuel cells produces. Heat pumps seem like a promising way of producing the higher temperature heats required, like steam. It can also be supplied by hydrogen powered boilers with lower upfront costs but at lower efficiency. Thermal energy storage also shows promise, but might face problems due to the size required to store sufficient energy in some cases due to the low temperature in the system. The major change to the onboard heat flows is that the only readily available source in the low temp heat and that additional energy is spent on delivering high temperature heat. Heat is still needed for fuel heating, but for the PEM case the heat is provided from LT heat. Additional efficiency increasing measures can be implemented, like CER, to gain work from the fuel heating process by replacing HVAC compressor work.

The focus on LT heat for the heat system when properly designed should to quite a high degree utilize the waste heat of the PEMFC. Utilization of the produced water from the PEMFC faces challenges when it comes to large cruise ships as the amount of water is limited in comparison to the required volumes, thus requiring additional equipment to fulfill the fresh-water demand of the vessel.

Looking at other work in the area, the mentioned papers do highlight the interest for fuel cells in the marine industry, and also show some feasibility for such systems. The fact that fuel cells have been tested on smaller scale previously in a marine setting, and the flexible power generation options that a modern diesel-electric HVDC system provides in combination with integrated heat systems does point to a promising future for hydrogen fuel cells within the marine industry.

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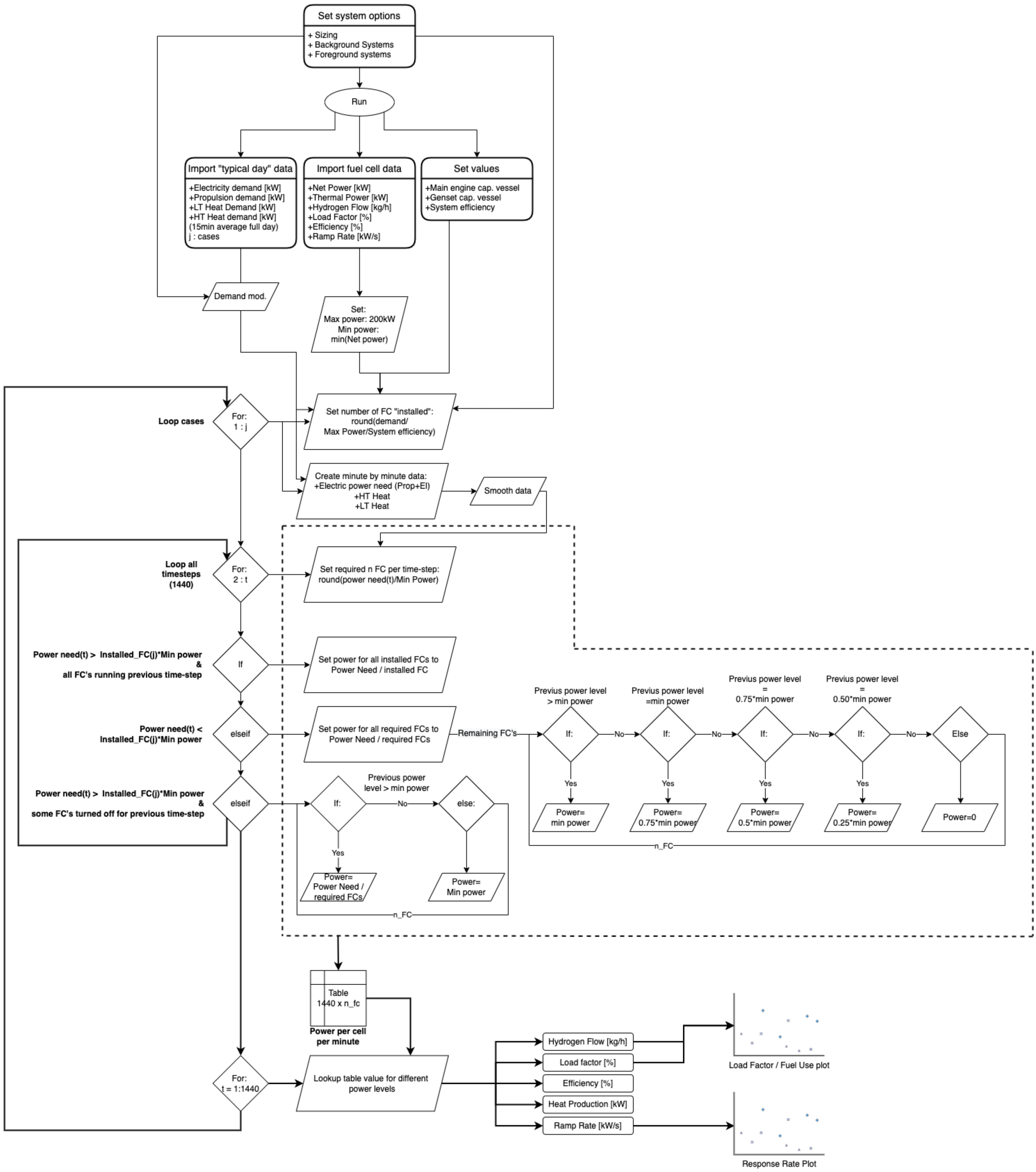
A

Appendix I - Model line diagram

The line diagram describing the main operations of the *System model* is presented on the next page.


Set system options
+ Sizing
+ Background Systems
+ Foreground systems
Run
Import "typical day" data
+Electricity demand [kW]
+Propulsion demand [kW]
+LT Heat Demand [kW]
+HT Heat demand [kW]
(15min average full day)
j : cases
Import fuel cell data
+Net Power [kW]
+Thermal Power [kW]
+Hydrogen Flow [kg/h]
+Load Factor [%]
+Efficiency [%]
+Ramp Rate [kW/s]
Set values
+Main engine cap. vessel
+Genset cap. vessel
+System efficiency
Demand mod.
Set:
Max power: 200kW
Min power:
min(Net power)
Loop cases
For:
1 : j
Set number of FC "installed":
round(demand/
Max Power/System efficiency)
Create minute by minute data:
+Electric power need (Prop+El)
+HT Heat
+LT Heat
Smooth data
Loop all
timesteps
(1440)
For:
2 : t
Set required n FC per time-step:
round(power need(t)/Min Power)
Power need(t) > Installed_FC(j)*Min power
&
all FC's running previous time-step
If
Set power for all installed FCs to
Power Need / installed FC
Power need(t) <
Installed_FC(j)*Min power
elseif
Set power for all required FCs to
Power Need / required FCs
Remaining FC's
Previus power level
> min power
Previus power level
=min power
Previus power level
=
0.75*min power
Previus power level
=
0.50*min power
If:
No
Else
Yes
Power=
min power
Power=
0.75*min power
Power=
0.5*min power
Power=
0.25*min power
Power=0
n_FC
Power need(t) > Installed_FC(j)*Min power
&
some FC's turned off for previous time-step
elseif
Previous power
level > min power
If:
No
else:
Yes
Power=
Power Need /
required FCs
Power=
Min power
n_FC
Table
1440 x n_fc
Power per cell
per minute
For:
t = 1:1440
Lookup table value for different
power levels
Hydrogen Flow [kg/h]
Load factor [%]
Efficiency [%]
Heat Production [kW]
Ramp Rate [kW/s]
Load Factor / Fuel Use plot
Response Rate Plot

B

Appendix II - MATLAB Code

```
%%% "System Model" for masters thesis System efficiency
   of heat integrated H2-fueled PEMFC power generation on
    cruise ships%%%
%%% By Jesper Lidqvist (jesper.lidqvist@student.chalmers.
   se) %%%
%%% Chalmers university of technology, 2023 %%%


% Vessel Data
clear
clc
imp_data=csvread("energies-351769-
   supplementary_TypicalDay.csv",2,0);
imp_MS200=csvread("MS200_data.csv",1,0);

%TD1: Mid-season (Hot)
%TD2: Winter
%TD3: High propulsion demand
%TD4: Summer
%TD5: Mid-season (Cold)
% Propulsion demand for different days
Eprop(1,:) = imp_data(:,2)';
Eprop(2,:) = imp_data(:,7)';
Eprop(3,:) = imp_data(:,12)';
Eprop(4,:) = imp_data(:,17)';
Eprop(5,:) = imp_data(:,22)';
% Electricity demand for different days
Eelec(1,:) = imp_data(:,1)';
Eelec(2,:) = imp_data(:,6)';
Eelec(3,:) = imp_data(:,11)';
Eelec(4,:) = imp_data(:,16)';
Eelec(5,:) = imp_data(:,21)';
% High temp. heat demand for different days
EheatH(1,:) = imp_data(:,4)';
EheatH(2,:) = imp_data(:,9)';
EheatH(3,:) = imp_data(:,14)';
```

```
EheatH(4,:) = imp_data(:,19)';
EheatH(5,:) = imp_data(:,24)';
% Low temp. heat demand for different days
EheatC(1,:) = imp_data(:,3)';
EheatC(2,:) = imp_data(:,8)';
EheatC(3,:) = imp_data(:,13)';
EheatC(4,:) = imp_data(:,18)';
EheatC(5,:) = imp_data(:,23)';

% Fuel cell preformance data
MS200BOL=imp_MS200(1:9,:); % MS200 BOL Preformance data
MS200EOL=imp_MS200(13:21,:);% MS200 EOL Preformance data
MS200RRBOL=imp_MS200(25:32,1:2); % MS200 BOL Ramp-rate vs
    net power output kW & kW/s
MS200RREOL=imp_MS200(25:32,3:4); % MS200 EOL Ramp-rate vs
    net power output kW & kW/s

% Overall eff.
O_Eff=0.95;
% Current prop
MaxMech=23400; %kW
MaxEl=11040; %kW
timestep = 3600/4;
% Fuel cell high/low power
Cutoff_low = 32; %kW
Cutoff_high = 200; %kW

close all


%%% Case modifications %%%
%Set option to 0(off) or 1(on) or otherwise specified
Opt(1)=0; % Water prod (Modify number of PAX below)
Opt(2)=0; % Fuel heat demand red.
Opt(3)=0;
% 1:Galley HT heat demand red. to elec
% 2:Galley HT heat demand red. to LT Heat
Opt(4)=0; % Space heating from HT to LT heat
Opt(5)=2; % Set n_fc:
% 0=Set n_fc per max demand
% 1=Varry n_fc per case
% 2=Set n_fc per max current power n=n_fc
Opt(6)=3; % HTH Options:
% 1=HP + Boiler supplies HTH
% 2=HP + TS supplies HTH
% 3=Boiler supplies HTH
```

```
Opt(7)=1; % Hydrogen Vap.
% 1: Hydrogen vap. from LT heat
% 2: Cold energy recovery


% Heat Pump preformance
COP_H=2.65;

% Relative heat demand
Galley_HD=[0 0 0 0 0 0 0.5 1 1 1 0.5 1 1 0.5 0.1 0.1 0.5
   1 1 1 1 0.5 0.1 0.1]; %Relative demand Energy and
   Exergy analysis Figure A6
HWH_HD =  [0.1 0.1 0.1 0.7 1 1 1 0.5 0.5 0.5 0.5 0.5 0.5
   0.5 0.5 0.5 0.7 0.7 1 1 1 0.5 0.5 0.1]; %Relative
   demand

for q=1:24 %Set as minute data
    Galley_HD15((q-1)*4+1:q*4) = Galley_HD(q);
    HWH_HD15((q-1)*4+1:q*4) = HWH_HD(q);
end


% Total yearly energy demand
Tot_energy=sum(((sum(EheatC(:,1:end),2)+sum(EheatH(:,1:
   end),2)+sum(Eprop(:,1:end),2)+sum(Eelec(:,1:end),2)))
   .*[112;31;9;41;172])/365/96; %total daily demand kWh
   /15min

% Water prod
% Max 1800 PAX, 155 Crew
if Opt(1)==1
    PAX=1800;
    Crew=155;
    Water_need=(0.2*PAX+0.06*Crew)/(1440); %Water need/
       min
    Pwr_water=Water_need*5*60; %kW
    Eelec=Eelec+Pwr_water; % RO 4-5.5 kWh/m^3
end

% Red Fuel HTH Demand Option
if Opt(2)==1
    for j=1:5
        EheatH(j,:)=EheatH(j,:)-Tot_energy*0.021;
    end
end
```

```
% Red Galley HTH Demand Option
if Opt(3)>0
    Galley_red=1; %Galley red. factor
    for j=1:5
        EheatH(j,:)=EheatH(j,:)-Tot_energy*96*0.031*
           Galley_red/sum(Galley_HD15)*Galley_HD15;
        if Opt(3) == 1
            Eelec(j,:)=Eelec(j,:)+Tot_energy*96*0.031*
               Galley_red/sum(HWH_HD15)*HWH_HD15;

        elseif Opt(3) == 2
            EheatC(j,:)=EheatC(j,:)+Tot_energy*96*0.031*
               Galley_red/sum(HWH_HD15)*HWH_HD15;
        else
            error('Wrong Galley heat param.')
        end
    end
end
% Red Space Heating HTH Demand Option
if Opt(4)==1
    for j=1:5
        EheatH(j,:)=EheatH(j,:)-Tot_energy*0.009;
        EheatC(j,:)=EheatC(j,:)+Tot_energy*0.009; %Moving
            the heat to the LT heating side
    end
end
% Red. HVAC demand from cooling by LH2 Option
if Opt(7) == 2
    CER_Case=[1 0 0 1 0]; % Summer and MSH
    for j=1:5
    Eelec(j,:)=(Eelec(j,:)-sum(Tot_energy)*0.009*2.3856*
       CER_Case(j)); % 2.3856 is the weight added to
       correspond to hot days
    end
end

for j=1:5 % Typical days

    for q=1:96 %Create minut-by-minute power need for
       1440 points (24h)
        P_need_EP((q-1)*15+1:q*15) = (Eprop(j,q)+Eelec(j
           ,q))/O_Eff; %Tempory variable
        HeatC_need((q-1)*15+1:q*15) = EheatC(j,q);
        HeatH_need((q-1)*15+1:q*15) = EheatH(j,q);
    end
```

```
    % Heat pump calc
    for t=1:1440
        P_need_HP(j,t) = HeatH_need(t)/COP_H;
        H_need_HP(j,t) = HeatH_need(t)*(1-1/COP_H);

        if Opt(6) < 3 % Cases where HP is used
            P_need(t) = P_need_EP(t)+P_need_HP(j,t); %
               Define power need total
        else
            P_need(t) = P_need_EP(t); % Define power need
                total
        end
        H_need_C(j,t) = HeatC_need(t); % Save data
        H_need_H(j,t) = HeatH_need(t);
    end

%%% Set number of fuel cells %%%
if Opt(5)==0
        n_fc(1:5)=ceil((max(Eprop(3,:)+Eelec(3,:)+EheatH
           (3,:)/COP_H))/Cutoff_high); %Set n_fc per max
           demand
    elseif Opt(5)==1
        n_fc(j) = ceil((max(Eprop(j,:)+Eelec(j,:)+EheatH(
           j,:)/COP_H))/Cutoff_high); % Varry n_fc per
           case
    elseif Opt(5)==2
        n_fc(1:5)=ceil((MaxMech+MaxEl)/Cutoff_high); %Set
            n_fc per max current power
    else
        n_fc(1:5)=Opt(5); %Set to a defined value
    end

%%% Set power levels per individual cells %%%
    P_need=smooth(P_need); %Gives the data some smoothnes
        in the ends
    clc
    close all
    P_cell=zeros(length(P_need),n_fc(j));
    P_cell(1:2,:)=Cutoff_low+5; % Assigne t=1:2 power
       level of all stacks
    for t=2:length(P_need)

        req_fc(t)=round(P_need(t)/Cutoff_low)-1; % Number
            of required fuel cells per timestep
        if (P_need(t) >= Cutoff_low*n_fc(j)) && all(
           P_cell(t-1,:)) > 0; % If all cells are running
```

```
        and power demand requires all cells
        P_cell(t,1:n_fc(j))=P_need(t)/n_fc(j);
    elseif P_need(t) < Cutoff_low*n_fc(j) % Ramp down
        & shutdown of some cells

        P_cell(t,1:req_fc(t))=P_need(t)/req_fc(t);
        for n=req_fc(t)+1:n_fc(j)
            if (P_cell(t-1,n)>Cutoff_low) % Min Power
                P_cell(t,n)=Cutoff_low;
            elseif (P_cell(t-1,n)==Cutoff_low) %
               shutdown min 1
                P_cell(t,n)=Cutoff_low*3/4;
            elseif P_cell(t-1,n)==Cutoff_low*3/4 %
               shutdown min 2
                P_cell(t,n)=Cutoff_low*1/2;
            elseif P_cell(t-1,n)==Cutoff_low*1/2 %
               shutdown min 3
                P_cell(t,n)=Cutoff_low*1/4;
            else  %shutdown min 4
                P_cell(t,n)=0; % Full shutdown
            end
        end
    elseif (P_need(t) >= Cutoff_low*n_fc(j)) && all(
       P_cell(t-1,:)) == 0; % Returning to all stack
       op.
        for m=1:n_fc(j)
            if (P_cell(t-1,m) < Cutoff_low)
                P_cell (t,m) = Cutoff_low;

            else
                P_cell(t,m) =P_need(t)/n_fc(j);
            end
        end
    elseif req_fc(t-1) < req_fc(t) && (P_need(t) <
       Cutoff_low*n_fc(j))% Some stacks returned to
       op.
        P_cell(t,1:req_fc(t))=P_need(t)/req_fc(t);
        for n=1:req_fc(t)
            if P_cell(t-1,n) < Cutoff_low
                P_cell (t,n) = Cutoff_low;

            else
                P_cell(t,n) = P_need(t)/req_fc;
            end

        end
```

```
    end
end

% Assigne values to operation point to plottable
   values
for t=1:1440 % Number of timesteps
    data_row(t,:)=0;
    data_row_RR(t,:)=0;
    H2_flow(t,:)=0;
    Load_F(t,:)=0;
    Eff(t,:)=0;
    Heat_prod(t,:)=0;
    Ramp_rate(t,:)=0;

    n_fc_op=nnz(P_cell(t,:)>(Cutoff_low));
    for n=1:n_fc_op
        data_row(t,n) = nnz(MS200BOL(:,6)<P_cell(t,n)
           );
        data_row_RR(t,n) = nnz(MS200RRBOL(:,1)<P_cell
           (t,n));
        H2_flow(t,n) = (MS200BOL(data_row(t,n),2)+(
           P_cell(t,n)-MS200BOL(data_row(t,n),6))/(
           MS200BOL(data_row(t,n)+1,6)-(MS200BOL(
           data_row(t,n),6)))*(MS200BOL(data_row(t,n)
           +1,2)-MS200BOL(data_row(t,n),2)))/60;
        Load_F(t,n) = MS200BOL(data_row(t,n),3)+(
           P_cell(t,n)-MS200BOL(data_row(t,n),6))/(
           MS200BOL(data_row(t,n)+1,6)-(MS200BOL(
           data_row(t,n),6)))*(MS200BOL(data_row(t,n)
           +1,3)-MS200BOL(data_row(t,n),3));
        Eff(t,n) = MS200BOL(data_row(t,n),8)+(P_cell(
           t,n)-MS200BOL(data_row(t,n),6))/(MS200BOL(
           data_row(t,n)+1,6)-(MS200BOL(data_row(t,n)
           ,6)))*(MS200BOL(data_row(t,n)+1,8)-
           MS200BOL(data_row(t,n),8));
        Heat_prod(t,n) = MS200BOL(data_row(t,n),7)+(
           P_cell(t,n)-MS200BOL(data_row(t,n),6))/(
           MS200BOL(data_row(t,n)+1,6)-(MS200BOL(
           data_row(t,n),6)))*(MS200BOL(data_row(t,n)
           +1,7)-MS200BOL(data_row(t,n),7));
        Ramp_rate(t,n) = (MS200RRBOL(data_row(t,n),2)
           +(P_cell(t,n)-MS200RRBOL(data_row(t,n),1))
           /(MS200RRBOL(data_row(t,n)+1,1)-(
           MS200RRBOL(data_row(t,n),1)))*(MS200RRBOL(
           data_row(t,n)+1,2)-MS200RRBOL(data_row(t,n
```

```
            ),2)));
        end
        mLoad_F(t,j)=mean(nonzeros(Load_F(t,:)));
        sH2_flow(t,j)=sum(H2_flow(t,:)); %kg
        sHeat_prod(t,j)=sum(Heat_prod(t,:)); %kW
        P_need_logg(t,j)=sum(sum(P_cell(t,:)));
        FC_use_logg(t,j)=n_fc_op;
        Total_RR(t,j)=sum(Ramp_rate(t,:));
        mEff(t,j)=mean(nonzeros(Eff(t,:)));
        water_prod(t,j)=sH2_flow(t,j)*9.34/1.05*0.08; % [
           kg/min] Molar mass difference and 8% recovery
           rate.
end

% Hydrogen vap. and CER
% Q_h: 3868.1 kJ/kgH2
% HVAC: 0.8% Total energy demand
H2_vap_E(:,j) = sH2_flow(:,j)/60*3868.1; %kW
if Opt(7) == 1 % H2 Vap.
    sHeat_prod(:,j) = sHeat_prod(:,j)-H2_vap_E(:,j);
end

if Opt(7) == 2 % CER
    sHeat_prod(:,j) = sHeat_prod(:,j)-H2_vap_E(:,j)+
       sum(Tot_energy)*0.009*2.3856*CER_Case(j);
end
% Heat demand systems (over var. j)
Boiler_op(j,:) = H_need_C(j,:)+H_need_HP(j,:)-
   sHeat_prod(:,j)'; %Sum of low temp. heat with HP
   heat need
if Opt(6) == 1 %HP + Boiler supplies HTH
    Boiler_op(Boiler_op<0) = 0; %Takes only the
       positive values (where heat is lacking)
    Boiler_H2(j,:) = Boiler_op(j,:)/60/33.6/0.85; %[
       kg/min] H_2 LHV 33.6 kWh/kg
elseif Opt(6) == 2 %HP + TS supplies HTH
    TS_Size=124000+2.0467*10^4; %kWmin
    TS_H(j,1)=TS_Size;
    for t=2:1440
        if Boiler_op(j,t)>0
            TS_H(j,t)=TS_H(j,t-1)-Boiler_op(j,t);
        elseif Boiler_op(j,t)<0 & -Boiler_op(j,t)<(
           TS_Size-TS_H(j,t-1))
            TS_H(j,t)=TS_H(j,t-1)-Boiler_op(j,t);
        else
            TS_H(j,t)=TS_Size;
```

```
            end
        end
        Boiler_H2 = [0;0;0;0;0];
    elseif Opt(6) == 3 %Boiler supplies HTH
        Boiler_H2(j,:) =  1.0273*H_need_H(j,:)
           /60/33.6/0.85; %[kg/min] H_2 LHV 33.6 kWh/kg
% assuming 2.73% heat loss while condensating steam
% Addera eff at 0.85
        H_need_HP(:,:)=zeros(size(H_need_HP));


    else
        %error('Heat pump option not compliant (Option 6)
           ')
    end
end

if Opt(6)==0
Boiler_H2 = [0;0;0;0;0];
end



%%% Print out some values, short %%%
fprintf('%f ',(sum(sH2_flow(:,2))+sum(Boiler_H2(2,:)))
   /10^3)
disp(' ')
fprintf('%f ',(sum(sH2_flow(:,3))+sum(Boiler_H2(3,:)))
   /10^3)
disp(' ')
fprintf('%f ',(sum(sH2_flow(:,4))+sum(Boiler_H2(4,:)))
   /10^3)
disp(' ')

fprintf('%f ',mean(mLoad_F(:,1)))
disp(' ')
fprintf('%f ',mean(mLoad_F(:,1)))
disp(' ')
fprintf('%f ',mean(mLoad_F(:,1)))
disp(' ')

fprintf('%d ',n_fc(2))
disp(' ')
fprintf('%d ',n_fc(3))
disp(' ')
fprintf('%d ',n_fc(4))
```

```
disp(' ')

% Boiler OP
fprintf('%d ',sum(Boiler_op(2,:)))
disp(' ')

%% Print out some values
% Print total fuel cons.
fprintf('MSH total Fuel Cons.: %f ',(sum(sH2_flow(:,1))+
   sum(Boiler_H2(1,:)))/10^3) %Total fuel cons in tonnes
   per day
disp(' ')
fprintf('Winter total Fuel Cons.: %f ',(sum(sH2_flow(:,2)
   )+sum(Boiler_H2(2,:)))/10^3)
disp(' ')
fprintf('HPD total Fuel Cons.: %f ',(sum(sH2_flow(:,3))+
   sum(Boiler_H2(3,:)))/10^3)
disp(' ')
fprintf('Summer total Fuel Cons.: %f ',(sum(sH2_flow(:,4)
   )+sum(Boiler_H2(4,:)))/10^3)
disp(' ')
fprintf('MSC total Fuel Cons.: %f ',(sum(sH2_flow(:,5))+
   sum(Boiler_H2(5,:)))/10^3)
disp(' ')
% Print mean load
fprintf('MSH Mean Load: %f ',mean(mLoad_F(:,1))) %Percent
    load of all running cells
disp(' ')
fprintf('Winter Mean Load: %f ',mean(mLoad_F(:,1)))
disp(' ')
fprintf('HPD Mean Load: %f ',mean(mLoad_F(:,1)))
disp(' ')
fprintf('Summer Mean Load: %f ',mean(mLoad_F(:,1)))
disp(' ')
fprintf('MSC Mean Load: %f ',mean(mLoad_F(:,1)))
disp(' ')
% Number of installed FC's
fprintf('MSH Number of installed FC: %d ',n_fc(1))
disp(' ')
fprintf('Winter Number of installed FC: %d ',n_fc(2))
disp(' ')
fprintf('HPD Number of installed FC: %d ',n_fc(3))
disp(' ')
fprintf('Summer Number of installed FC: %d ',n_fc(4))
disp(' ')
fprintf('MSC Number of installed FC: %d ',n_fc(5))
```

```
disp(' ')

%% Plot HW and galley demand
X=[Galley_HD' HWH_HD']
figure(6)
bar(linspace(1,24,24),X)
ylabel('Fractional heat use full day')
xlabel('Hours')
set(gcf, 'Position',  [100, 100, 1000, 600])
legend('Galley heat demand','Hot water heating','Location
   ','northwest')

%% Fuel use plot
figure(5);
hold on
j=4 %Typical day
FU=[sH2_flow(:,j) H2_flow(:,j)]
bar(linspace(1,24,1440),FU,'stacked')
%legend('Winter','High propulsion demand','Summer','
   location','northwest')
ylabel('Hydrogen use [kg]')
xlabel('Hours')
set(gcf, 'Position',  [100, 100, 1000, 600])

%% Response rate plot
close all
figure(1);
plot(linspace(1,24,1440),Total_RR(:,2),LineWidth=2)
hold on
plot(linspace(1,24,1440),Total_RR(:,3),LineWidth=2)
plot(linspace(1,24,1440),Total_RR(:,4),LineWidth=2)
legend('Winter','HPD','Summer','location','southeast')
ylabel('System ramp-rate [kW/s]')
xlabel('Hours')
set(gcf, 'Position',  [100, 100, 500, 300])
hold off

%% LF / Fuel Use plot
figure(2);
hold on
yyaxis left
plot(linspace(1,24,1440),mLoad_F(:,2))


ylabel('Load factor FC system [%]')
```

```
yyaxis right
plot(linspace(1,24,1440),cumsum(sH2_flow(:,2)+H2_flow
    (:,2)))

ylabel('Hydrogen use [kg]')
xlabel('Hours')
set(gcf, 'Position',  [100, 100, 500, 300])

%% Power use plot
j=4; % Pick case
figure(3);
BP1=[Eprop(j,:)' Eelec(j,:)' EheatH(j,:)'/COP_H];
bar(linspace(1,24,96),BP1,'stacked')
legend('Propulsion','Electricity','HT Heat Pump','
    location','northwest')
ylabel('Energy use [kW]')
xlabel('Hours')
set(gcf, 'Position',  [100, 100, 1000, 600])

%% Heat consumption/Prod plot
j=4; % Pick case
figure(4);
BP2=[H_need_C(j,:)' H_need_HP(j,:)'];
bar(linspace(1,24,1440),BP2,'stacked')
hold on
plot(linspace(1,24,1440),sHeat_prod(:,j),'LineWidth',3,'
    Color','r')
legend('LT Heat Demand','HP Qc Demand','FC Heat Rejection
    ','location','northwest')
ylabel('Energy need/prod [kW]')
xlabel('Hours')
set(gcf, 'Position', [100, 100, 1000, 600])

%% Thermal storage
close all
clc
figure(9)
j=2; % Pick case
x=(sHeat_prod(:,j)'-(H_need_C(j,:)+H_need_HP(j,:)));

yyaxis left

ylim([-1500 3500])
bar(linspace(1,24,1440),max(x,0),'FaceColor','#0072BD')
hold on
bar(linspace(1,24,1440),min(x,0),'FaceColor','#EDB120')
```

```
ylabel('Energy Flow TS [kWmin/min]')
xlabel('Hours')
yyaxis right
plot(linspace(1,24,1440),TS_H(j,:)/60,LineWidth=3)
ylabel('SOC TS [kWh]')
ylim([-1071.4 2500])
set(gcf, 'Position', [100, 100, 1000, 600])


fprintf('Sum heat production and use: %d MWh',sum(x)
   /10^3/1440)
disp(' ')
fprintf('Sum heat deficit: %d kWh',abs(sum(x(x<=0)/1440))
   )
disp(' ')




%% Number of FC use
%close all
figure(6)
j=4 %Case
yyaxis left
plot(linspace(1,24,1440),FC_use_logg(:,j),'LineWidth',1)
%plot(linspace(1,24,1440),sum(P_need_logg(:,j)~=0,2),'
   LineWidth',2)
ylabel('Fuel Cells in use')
ylim([20 180])
hold on
yyaxis right
plot(linspace(1,24,1440),P_need_logg(:,j)/10^3,'LineWidth
   ',2)
ylabel('Power Need [MW]')

xlabel('Hours')

set(gcf, 'Position', [100, 100, 500, 300])

%% Efficiency
figure(7)
j=4 %Case
plot(linspace(1,24,1440),mEff(:,j),'LineWidth',2)
ylabel('Mean Efficiency [%]')

xlabel('Hours')
```

```
set(gcf, 'Position', [100, 100, 500, 300])
%% Water prod
figure(8)
j=4
bar_WTR=[-water_prod(:,j)/1000+Water_need water_prod(:,j)
   /1000]
bar(linspace(1,24,1440),bar_WTR,'stacked')
legend('RO Water Production','Water Recovery', 'location'
   ,'southeast')
ylabel('Water production [tonne/min]')
xlabel('Hours')
set(gcf, 'Position', [100, 100, 500, 300])
sum(bar_WTR(:,2))/(sum(bar_WTR(:,2))+sum(bar_WTR(:,1)))
```