Tampereen yliopisto

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FUEL CELL WASTE HEAT RECOVERY IN MARINE APPLICATIONS

Master’s thesis
Faculty of Engineering and Natural Sciences
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June 2023

ABSTRACT

Eveliina Vehkala: Fuel Cell Waste Heat Recovery in Marine Applications
Master's thesis
Tampere University
Master's Programme in Environmental and Energy Engineering
June 2023

Drastic cuts to the greenhouse gas (GHG) emissions are urgently needed from every sector to combat the global warming. The maritime industry is estimated to produce around 7 % of global GHG emissions. Significant emission reduction targets are set for the coming decades by IMO and other regulatory bodies. Power production on ships is currently almost entirely based on oil-based fuels for both propulsion and auxiliary power, which means that the marine sector needs to find alternative ways for power production in order to fulfill the environmental goals.

Fuel cells (FCs) are electrochemical devices that convert chemical energy in fuel to direct electrical current. Their most notable advantages are high efficiency even on partial loads, modularity, quietness, and reliability. FCs produce exhaust gas that might be very hot depending on the cell type. If this waste heat can be utilized, it would make the system even more environmentally friendly since more output is gained from the same amount of fuel. Waste heat recovery (WHR) boilers, producing steam or hot water, can be used for this task. Ships, especially cruise vessels, have a heating need for e.g. space heating, kitchen and laundry facilities.

This thesis has been commissioned by Alfa Laval Aalborg Oy. The purpose of this thesis was to find out what the role of the FCs will be in the marine sector in the future. It was also investigated what are the typical temperature levels and mass flows of FC exhaust in different operating conditions. The limitations for applying finned tube boilers in FC WHR are considered.

Several types of FCs exist. Based on literature review, the most suitable FC types for marine applications are proton exchange membrane (PEM), solid oxide (SOFC) and molten carbonate (MCFC) fuel cells. SOFC and MCFC are high temperature (HT) FCs that operate on temperatures up to 1,000 °C. PEM operates usually around 65-85 °C but HT-PEMs can operate in temperatures as high as 220 °C. The most suitable fuel for all cell types is hydrogen, but the HT cells are able to internally reform other hydrogen-rich fuels such as methane, methanol and diesel. FC exhaust consist of H_2O, N_2, O_2 and H_2 when operating on pure hydrogen, added with CO_2, CO and remnants of hydrocarbons when operating on hydrocarbon fuels.

In the future, the fuels used in the marine sector will be more diverse. According to a literature review, the ship power production is expected to go thorough transition, with the first stage being less carbon-intensive fuels, such as LNG or methanol combusted in engines, becoming increasingly common. After this intermediate period, the goal is a transition to fully carbon-free means of power production. The timeline of this final turning point depends on the development of the technological maturity of the alternative fuels, and it is expected to be only after 2050. FCs with green hydrogen would be the environmentally ideal solution, but there are unsolved challenges especially in the availability of green hydrogen and the storage and bunkering infrastructure.

As a part of this thesis, a case study was carried out on covering the heat needs of a cruise ship with FC exhaust. Data of the electricity and heat consumption of a cruise vessel was utilized in the study, as well as experimental measurements of SOFC power production available in literature. The vessel was assumed to produce all the electricity with SOFC stacks. Constant air utilization and constant air mass flow partial load operation strategies were compared. Correlations were developed for the exhaust mass flow and temperature as a function of the electrical power production. The exhaust composition was also calculated. WHR boiler performance was evaluated as part of the system and the hot water and steam production were compared against consumption data. As a result, it was noticed that the steam and hot water demands could be fulfilled reasonably well, the coverage factors being over 90 % for all evaluated situations. The constant air mass flow operating strategy produces less variation in the exhaust mass flow but more variation in the cell temperature than constant air flow operating strategy.

Keywords: fuel cell, waste heat recovery, WHR boiler, cruise vessel

TIIVISTELMÄ

Eveliina Vehkala: Jätelämmön talteenotto polttokennoista laivasovelluksissa
Diplomityö
Tampereen yliopisto
Ympäristö- ja energiatekniikan DI-ohjelma
Kesäkuu 2023

Kasvihuonekaasupäästöjä on kiireellisesti vähennettävä kaikilla sektoreilla ilmaston lämpenemisen hillitsemiseksi. Merenkulkualan arvioidaan aiheuttavan n. 7 % maailman kasvihuonekaasupäästöistä, ja IMO sekä muut sääntelyelimet ovat asettaneet huomattavia päästövähennystavoitteita tuleville vuosikymmenille. Laivojen voimantuotto perustuu tällä hetkellä liki yksinomaan öljypohjaisiin polttoaineisiin, mikä tarkoittaa, että merenkulkualan tulee löytää vaihtoehtoisia tapoja energian tuottamiseen päästötavoitteiden saavuttamiseksi.

Polttokennot muuntavat polttoaineiden kemiallista energiaa sähkövirraksi. Polttokennoilla on korkea hyötysuhde erityisesti osakuormilla, ja ne ovat modulaarisia, luotettavia ja hiljaisia. Kennostot tuottavat pakokaasua, jonka lämpötila riippuu kennotyypistä. Lämmön talteenotto (LTO) kuumasta pakokaasusta kasvattaa järjestelmän kokonaishyötysuhdetta. LTO-kattiloita voidaan hyödyntää höyryn tai kuuman veden tuottamiseen polttokennojen pakokaasuista. Laivoilla, erityisesti risteilyaluksilla, on tarvetta lämmölle höyryn tai kuuman veden muodossa mm. tilojen lämmitykseen ja keittiön tarpeisiin.

Tämä diplomityö on tehty Alfa Laval Aalborg Oy:n toimeksiannosta. Työn tarkoitus oli selvittää, millainen rooli polttokennoilla on laivojen voimantuotannossa tulevaisuudessa. Työssä selvitetään myös, mitkä ovat tyypilliset polttokennojen pakokaasun massavirrat ja lämpötilatasot. Lisäksi pohditaan ripaputkikattiloihin liittyviä rajoitteita polttokennojen lämmöntalteenotossa.

Polttokennoja on useaa eri tyyppiä. Kirjallisuuskatsauksen perusteella laivasovelluksiin parhaiten soveltuvat kennotyypit ovat protoninvaihto-, kiinteäoksidi- ja sulakarbonaattikennot. Näistä kiinteäoksidi- ja sulakarbonaattikennot ovat ns. korkean lämpötilan kennoja, joiden toimintalämpötila voi olla jopa n. 1 000 °C. Protoninvaihtokennot toimivat useimmiten 65—85 °C lämpötiloissa, muuta ns. korkean lämpötilan protoninvaihtokenno voi toimia jopa 220 °C lämpötilatasolla. Kaikille kennotyypeille sopiva polttoaine on vety, mutta korkean lämpötilan kennot voivat käsitellä myös muita vetypitoisia polttoaineita kuten metaania, metanolia ja dieseliä. Kun polttoaineena käytetään vetyä, kennoston pakokaasu koostuu seuraavista yhdisteistä: H_2O, N_2, O_2 ja H_2. Hiilivetypolttoaineilla pakokaasu sisältää näiden lisäksi hiilidioksidia, hiilimonoksidia ja hiilivetyjen jäämiä.

Kirjallisuuskatsauksen perusteella merenkulun polttoaineissa tullaan kokemaan vaiheittainen siirtymä kohti nollapäästöjä: välivaihe dieselistä vähemmän päästöintensiivisiin polttoaineisiin, kuten nesteytettyyn maakaasuun, ja tämän jälkeen lähes täysin päästöttömiin polttoaineisiin kuten vihreään vetyyn. Siirtymän aikaikkuna riippuu vaihtoehtoisten polttoaineiden teknisestä kypsyydestä. Vihreällä vedyllä tankattavat polttokennot olisivat erittäin vähäpäästöinen ratkaisu, mutta erityisesti vedyn saatavuudessa ja jakeluinfrastruktuurissa on ratkaisemattomia ongelmia. Tällä hetkellä maailmassa on muutama polttokennoja käyttävä demonstraatioalus.

Tässä diplomityössä tarkastellaan case-esimerkin kautta, voidaanko risteilyaluksen kuuman veden ja höyryn tarve kattaa polttokennojen savukaasuilla. Laskennassa hyödynnettiin dataa aluksen lämmön- ja sähkönkulutuksesta, sekä mittaustuloksia polttokennoston tehontuotannosta. Esimerkissä oletettiin, että kaikki laivan sähköntarve tuotetaan kiinteäoksidikennostolla. Pakokaasun massavirralle ja lämpötilalle muodostettiin korrelaatiot saatavilla olevan datan pohjalta kahdella osakuorman ajotavalla. Myös pakokaasun koostumus selvitettiin. LTO-kattilan höryn ja kuuman veden tuotto laskettiin kullakin hetkellä pakokaasun massavirran ja lämpötilan pohjalta, ja tuotantopotentiaalia verrattiin kulutusdataan. Tulokseksi saatiin, että lämmöntarve voidaan kattaa polttokennojen hukkalämmöllä lähes kokonaan, kattavuuskertoimen ollessa yli 90 % kaikille tarkastelluille tilanteille.

Avainsanat: polttokenno, lämmön talteenotto, LTO-kattila, risteilyalus

PREFACE

I would like to thank Alfa Laval Aalborg Oy for commissioning this thesis and giving me the opportunity to immerse myself in an interesting topic. Especially, I want to thank Jere Kouvo for supervising the thesis process on behalf of the company and giving helpful comments.

This endeavor would not have been completed without my supervisor Henrik Tolvanen who was crucial in forming my vague ideas into a thesis. I am grateful not only for support with the thesis process, but also for excellent teaching during my studies in Tampere University. Thanks should also go to Aleksi Sivonen for being the second examiner.

My family and friends have continuously supported me during my studies and thesis project which I am grateful for. Lastly, thank you Jussi for proofreading and reminding me to take breaks.

Vaasa, 27th June 2023

Eveliina Vehkala

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LIST OF ABBREVIATIONS AND SYMBOLS

AC	Alternating current
AFC	Alkaline fuel cell
ALA	Alfa Laval Aalborg Oy
CCS	Carbon capture and storage
CH_2	Compressed hydrogen
CH_4	Methane
CII	Carbon Intensity Indicator
CO	Carbon monoxide
CO_2	Carbon dioxide
DC	Direct current
DMFC	Direct methanol fuel cell
EEDI	Energy Efficiency Design Index
EEXI	Energy Efficiency Index for Existing Ships
ETS	Emissions Trading System
EU	European Union
FC	Fuel cell
GHG	Greenhouse gases
GT	(1) Gross tonnage (2) Gas turbine
H_2	Hydrogen
H_2O	Water
HCCI	Homogenous charge compression ignition
HCl	Hydrogen chloride
HEX	Heat exchanger
HRSG	Heat recovery steam generator
HT	High temperature
ICE	Internal combustion engine
IEA	International Energy Association
IMO	International Maritime Organization
LH_2	Liquefied hydrogen
LNG	Liquefied natural gas
MCFC	Molten carbonate fuel cell
N_2	Nitrogen
NO_x	Nitrogen oxides
O_2	Oxygen
ORC	Organic Rankine cycle
PAFC	Phosphoric acid fuel cell
PEMFC	Proton exchange membrane fuel cell
SEEMP	Ship Energy Efficiency Plan
SO	Sulfur oxide
SOFC	Solid oxide fuel cell
WHR	Waste heat recovery

α_{rec}	Recirculation factor	-
A	Surface area	m^2
h	Enthalpy	J/kg
LMTD	Logarithmic mean temperature difference	K
$\dot{m}$	Mass flow	kg/s
$\dot{m}_a$	Air mass flow	kg/s
$\dot{m}_f$	Fuel mass flow	kg/s
P_{cell}	Electrical power output from a unit cell	W

T	Temperature	K, °C
U	Overall heat transfer coefficient	$W/m^2/K$
U_a	Air utilization factor	-
U_f	Fuel utilization factor	-
Q	Heat rate	W

1. INTRODUCTION

Climate change, which is caused and accelerated by emission of greenhouse gases (GHG) in the atmosphere, is a serious threat to the ecosystem and human life. Therefore, actions to cut down the GHG emissions are urgently needed from every sector. Marine shipping industry accounts for 7-8 % of global GHG emissions (Atilhan et al. 2021) which means that minimizing the emissions of marine sector would be significant in the global scale. Moreover, the limited nature of fossil fuels is an incentive for transition from traditional fossil fuels to cleaner power sources.

One way to produce energy with less GHG emissions are fuel cell (FC) systems. FCs are devices that convert the chemical energy of hydrogen to electricity virtually without greenhouse gas emissions from the electricity producing process itself. Fuel cells were invented as early as 1839 (Behling 2013), but their commercial breakthrough has been slow (Wang et al. 2018). However, nowadays there is more interest in fuel cell projects than ever (Olabi et al. 2020). The biggest interest has been to utilize fuel cells as the source of power for passenger vehicles, but FC technology for marine sector has also been developed and demonstrated (Xing et al. 2021b).

To further minimize the GHG emissions, attention should be paid to energy efficiency as well. FCs, depending on the cell type, produce hot exhaust gas (Behling 2013). If the waste heat can be captured and utilized, it means both economical savings as well as environmental benefits since more useful energy output is gained form the same amount of fuel. Therefore, a waste heat recovery (WHR) boiler could be utilized as a part of FC system. In scientific literature, FC-WHR systems in ships have been recently evaluated by Xing et al. (2021b), Evrin and Dincer (2019), Ouyang et al. (2020) and Wu et al. (2019).

This thesis is commissioned by Alfa Laval Aalborg Oy in Rauma, Finland. Alfa Laval Aalborg (ALA) designs waste heat recovery and fired boiler systems for cruise ships and ferries as well as land-based applications. The main purpose in this thesis is to map out how significant the FCs will be in marine sector in the future and what needs to be taken into account when designing WHR systems for this emerging technology. In this thesis, the following research questions are investigated by a literature study and calculations:

1. What types of fuel cells can be used in ships and what will be their role in the future?
2. What limitations there are for waste heat recovery from marine fuel cells?
3. What are the temperature and mass flow of the gas produced by FC system on partial loads?
4. What considerations arise regarding the examined FC WHR systems with considered finned tube boilers?

An example case for waste heat recovery from FCs is also analyzed as a part of this thesis. The case study considers an imaginary FC powered cruise vessel. Data about electricity and heat consumption in a cruise ship are combined with experimental results of FC fuel input and electrical power output. As a result, correlations for the FC exhaust mass flow and temperature as the function of FC power output are obtained. The steam and hot water production potential with a waste heat recovery boiler is calculated and compared to the steam and hot water consumption of the vessel. Relating to this, the following question is answered:

5. How suitable the studied FC WHR system is for the considered consumption profile?

In the next chapter, a general concept of FCs, most suitable FC types for ships and FC partial load operation are considered. In chapter 3, hydrogen economy in marine sector and the future role of FCs in marine is discussed. In the fourth chapter, the principles of FCs and waste heat recovery are introduced. In chapter 5, the materials and methods for the case study are presented. The results of the case study are illustrated and discussed in chapter 6. Finally, the most important findings of this thesis are summarized and suggestions for future studies are made in the final chapter.

2. FUEL CELLS IN MARINE APPLICATIONS

The term “hydrogen economy” refers to a situation where hydrogen is used as the major carrier of energy in the society (Hashem Nehrir & Wang 2015, Zornoza et al. 2013). Hydrogen economy is seen as an effective way to minimize GHG emissions since it has the unique ability to “’decarbonize difficult to abate sectors”, such as shipping (Dillman & Heinonen 2023). For this scenario to become reality, there needs to be an environmentally friendly way of producing the hydrogen as opposed to current fossil fuel -based economy. This would mean widespread use of FCs to produce electricity from hydrogen. (Hashem Nehrir & Wang 2015).

A fuel cell is defined as an electrochemical device that transforms energy of chemical reaction to electricity (Basu 2007). It differs from a battery so that a FC is not charged with electrical energy. Instead, it produces electrical energy from fuel, usually hydrogen. Various types of FCs exist, with unique pros and cons.

In this chapter, the currently used fuels and ways of power production in the marine sector are introduced. In the subchapter 2.2, it is briefly explained how fuel cells operate and what differences there are between FC types most commonly or potentially used in maritime applications. The partial load operation of FCs is considered in the subchapter 2.3. In this thesis, the focus in on passenger and cruise vessels but due to the availability of literature and data, most of the analysis also includes merchant vessels.

2.1 Current technologies in marine power production

Most merchant and cruise ships today utilize diesel engines as their main source of power, followed by gas turbines. The power can be utilized for propulsion either mechanically, or by converting the mechanical energy to electricity in generator. The electric propulsion was introduced to cruise ships in 1990s and nowadays all newbuild cruise vessels use it. (Sulligoi et al. 2016)

According to International Energy Association (IEA) report on international shipping (IEA 2022), fossil fuels derived from oil represent over 99 % of the total energy use for international shipping in the year 2021 and all previous recorder years. Biofuels, ammonia, hydrogen, and electricity are classified as low-carbon fuels which constitute less than 0.5 % of consumed marine fuels in 2021.

Vessels of 5,000 gross tonnage or higher are mandated to report their fuel consumption data to International Maritime Organization (IMO) since 2019. (IMO 2021) It is approximated that these ships represent about 85 % of the total GHG emissions from ships. (IMO n.d.-b) According to the latest available fuel consumption report at the time of writing, which is from the year 2020, the total fuel consumption in included vessels was approximately 200 Mt. Of this total amount, heavy fuel oil alone covers 50 %. As can be seen from figure 1, virtually all the fuels consumed in 2020 were fossil-based and alternative fuels, such as methanol, have negligibly small shares. (IMO 2021)

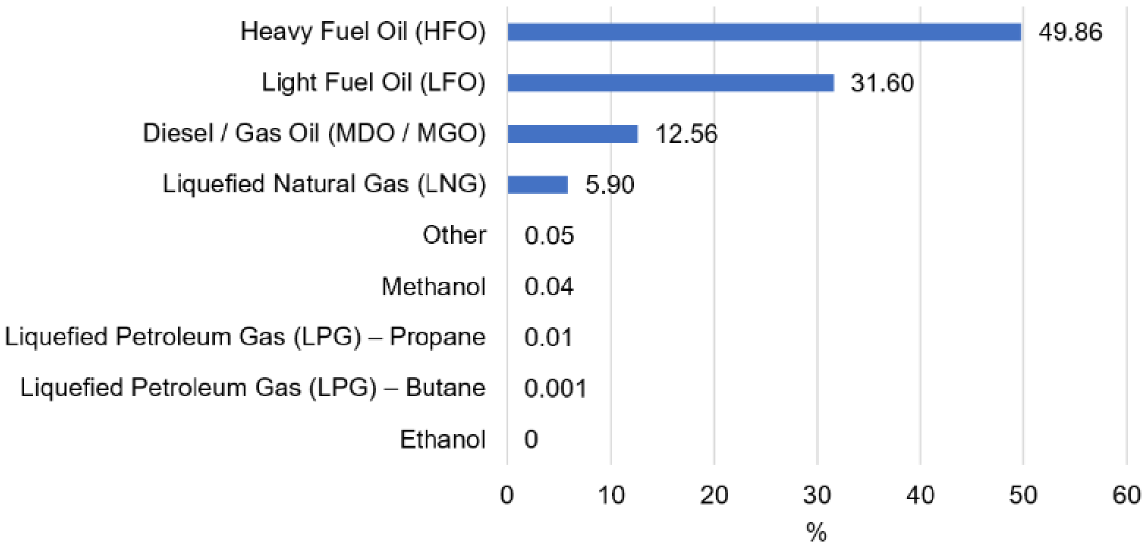

Figure 1. Consumed fuels by mass in ships over 5,000 GT in 2020 (IMO 2021).

The size of non-military FC powered fleet currently in use is limited to few demonstration vessels. It is worth pointing out that some FC systems include hydrogen reforming unit, meaning that they can make hydrogen onboard out of primary energy carriers such as diesel, LNG, or methanol. (Xing et al. 2021b) These would be listed under corresponding primary fuel in the statistics, meaning that the development of FCs will not necessarily show as hydrogen consumption in fuel statistics.

2.2 Fuel cell types in ships

Fuel cells were invented as early as 1800s by William Grove (Behling 2013). The first use for FCs in maritime sector were as early as in the 1960s for military submarines. FCs in civilian ships were seen first time in the 2000s. From 2000 to 2021, there has been only around 20 noticeable FC ship projects. Most of the demonstration ships have been some kind of passenger vessels, such as tourist boats or car ferries. (Xing et al. 2021b)

Fuel cells consist of anode and cathode plate, and an electrolyte membrane between them as is depicted in Figure 2. Next, the working principle of simplified FC is considered.

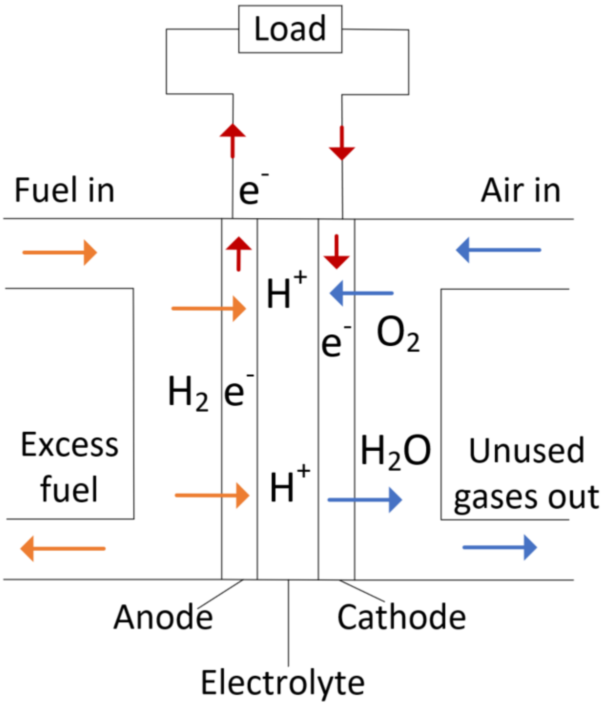

Figure 2. Simplified FC (adapted from EG&G Technical Services, Inc. (2004)).

The fuel, in this example pure hydrogen gas, is directed to the anode plate. An oxidation reaction, which yields free electrons, happens on the catalyst surface of anode. Since the electrolyte membrane does not let electrons pass thorough, the electrons are forced to go to cathode via external circuit thus producing electrical current. On cathode, the reduction reaction is taking place. Usually, the reduced media is oxygen from air that is fed to the cathode plate. (Basu 2007)

Since the reacting elements in FC are in most typical cases hydrogen and oxygen, the FC produces water. The nonsignificant to very low emissions of GHGs or other harmful compounds make FCs a very attractive way of producing electricity. Since there is no combustion happening, no NO_x will be created. Moreover, no SO is also formed since FCs are sensitive to sulfur and it is removed before the fuel enters fuel cell. (Basu 2007) However, the reality of emissions is determined by the whole process including the production and treating of the fuel. The fuel reforming methods will be looked at more closely later in this thesis.

One so-called unit cell can produce approximately 1 V voltage, in practice even less. Therefore, unit cells are connected parallel and stacked to produce desired voltage level. The current that a cell produces is determined by the surface area. These cell stacks have no moving parts which makes them very reliable and also do not produce noise.

Since FCs are modular by nature, it is simple to scale the system for different power needs. (Basu 2007)

FCs are generally more efficient than ICEs, especially on partial loads. Since FCs are not thermal machines, they are not bound by the Carnot efficiency. They also have fast response times to load changes. (Basu 2007) However, they require rather lot of space: Nerheim et al. (2021) estimate that complete FC system, including space reserved for fuel storage, has taken twice the volume of conventional ICE system in recent FC ship demonstration projects.

Xing et al. (2021b) names three FC types to be most promising for marine applications: proton exchange membrane (PEM), molten carbonate (MC) and solid oxide (SO) FCs. These FC types are evaluated further below in order to understand what opportunities and limitations they have regarding WHR.

The main FC types that are left outside of this evaluation are direct methanol (DM), alkaline (A) phosphoric acid (PA) FCs. DMFC, which is categorized as a type of PEMFC in some sources (EG&G Technical Services, Inc. 2004), utilizes methanol as fuel without reforming process. (Basu 2007) Methanol is already used as a fuel in small number of vessels (IEA 2022), so this FC type would be fitting option for auxiliary power production for those vessels. However, since DMFCs have the lowest operating temperatures of all FC types, approximately in range 0–60 °C, they do not offer significant WHR potential. (Basu 2007) AFC and PAFC mostly have specialized applications in e.g. space technology and also comparatively low operating temperatures (60–200 °C). (Basu 2007)

To the year 2021, the most popular FC type in noticeable marine demonstration projects has been PEM, including high temperature (HT) PEM. It is followed by MCFC and SOFC. Most of the installed PEM marine auxiliary power systems have been small, in the vicinity of tens of kilowatts. Most MC and SOFC projects have had capacity over hundred kilowatts, the biggest being 625 kW MCFC unit. (Xing et al. 2021b)

The FC system includes also other components than just the FC stack to produce usable electrical power. A schematic of FC system and its auxiliaries is presented in the figure 3.

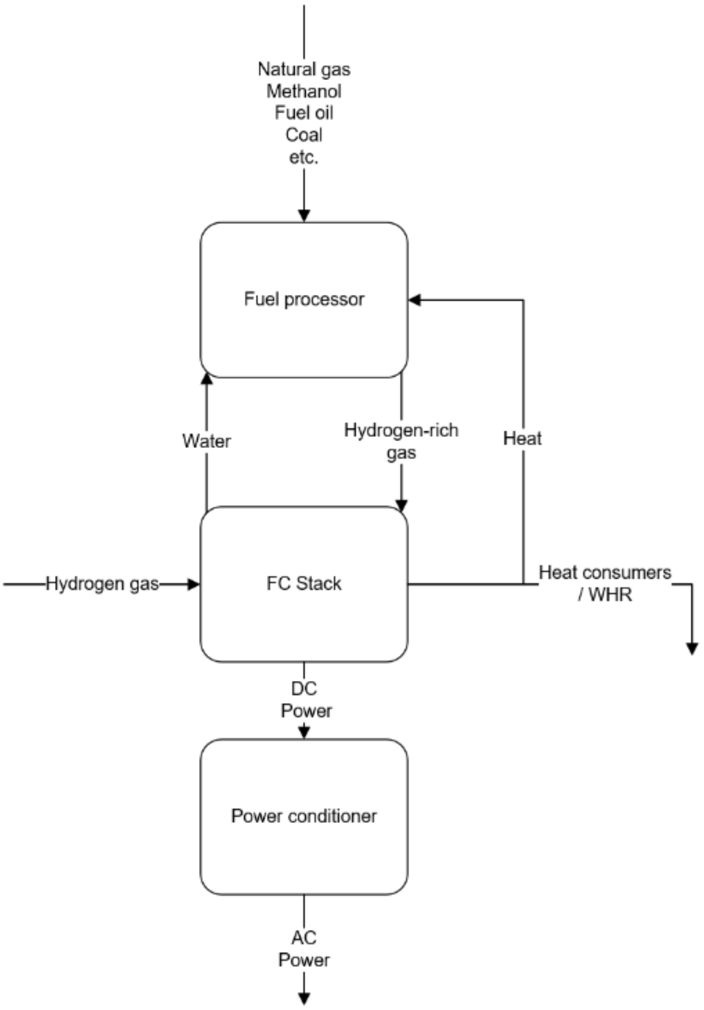

Figure 3. Simplified FC power system with auxiliaries (adapted from EG&G Technical Services, Inc. (2004))

The system is fueled either with pure hydrogen or some other hydrogen-rich fuel. Fuel pretreating might be needed depending on FC type and quality of the fuel. Some examples of these pretreating processes are removal of harmful compound (such as sulfur), fuel conversion to hydrogen and removal of carbon monoxide by the water-gas shift reaction. The byproducts from FC stack can be utilized in these fuel treatment processes, such as steam for the water-gas shift reaction or heat for fuel reforming. (EG&G Technical Services, Inc. 2004)

The energy in hot exhaust gas of the cell can be captured by e.g. waste heat recovery boiler and used for the fuel pretreatment process or other processes. The FC WHR is considered in more detail in the chapter 4. The FC system might also include a burner in the FC exhaust duct for combustion of unreacted fuel in the exhaust gas. (EG&G Technical Services, Inc. 2004)

Finally, it is noted that FCs produce direct current in comparatively low voltage level. Since most of the power systems both in ships and land-based installations use alternating current, the FC system needs to be supplemented with DC/DC converter for raising the voltage level and DC/AC inverter for conversion to alternating current. (EG&G Technical Services, Inc. 2004)

Proton exchange membrane fuel cell

PEMFCs are the most common and researched FC type. PEM is particularly well suited to mobile applications since it has high energy density, no corrosive fluid hazard and it is not sensitive to orientation (EG&G Technical Services 2004). They are most suitable FC type for vehicles, especially small ones such as passenger cars (Basu 2007), but also for maritime use (Xing et al. 2021b).

PEMFCs have a fast start capability due to relatively low operating temperature. The response to load changes is also rapid. (EG&G Technical Services 2004) The most notable drawback of PEMFC is their relatively high price compared to other cell types. This is mostly due to expensive platinum catalyst that PEMFCs require. (Basu 2007)

The operating temperature of PEMFC is usually 65–85 °C, but for HT-PEMFC up to 160–220 °C. Most of the completed marine demonstration projects have been HT-PEMFC systems. Lower temperature level PEMFCs do not offer notable potential for WHR, but with HT-PEMFC it is possible to utilize a heat exchanger or WHR boiler with steam turbine for WHR. (Xing et al. 2021b) As an example, according to work of Gao et al. (2012), 1 kW HT-PEM stack produces exhaust with mass flow of 12.61 g/s, temperature of 148.2 °C and relative humidity of approximately 0.02.

PEMFCs are not able to internally reform fuel like high-temperature FCs. This limits the usable fuels to pure hydrogen, which has low energy density and challenging to store, or externally reformed hydrocarbons. Moreover, PEMFCs are very intolerant for carbon monoxide, meaning that even a small amount of CO in the fuel will cause the cell reactions to stop. If fuel produced from hydrocarbons is used, there needs to be an additional mechanism for reducing CO in the fuel gas. However, since PEMFCs require clean fuel, it generates very little emissions. (Basu 2007)

The usual range for PEM operating pressure is atmospheric at the lowest and is up to 6-10 bar depending on author (Basu 2007, Zhang & Zhang 2013). In marine environment, it needs to be considered that salty air will cause degradation of polymer layer (Xing et al. 2021b).

Both temperature and pressure increase also increase the cell voltage. The improvement in performance due to increased pressure comes with the cost of pressurizing the reactant gases. The design of HT-PEM system depends strongly on if pure hydrogen or hydrocarbon is used as fuel. PEMFCs and to lesser extent HT-PEMFCs require having control on fuel and air temperature, cleanliness, and humidity. (EG&G Technical Services 2004)

Solid oxide fuel cell

From WHR point of view, especially interesting FC types are MCFC and SOFC since these have high operating temperatures, meaning that the exhaust gas produced is hot. These FC types are evaluated further below to understand what opportunities and limitations they have regarding WHR. These FC types are also especially interesting since they are able to perform internal reforming, meaning that there is enough heat for steam reforming reaction to produce hydrogen out of methane. This means that these FCs can be fueled directly with hydrocarbons such as natural gas. (Basu 2007)

If SOFC is fueled with pure hydrogen, reaction in the anode is:

$$H_2 + O^{2-} \rightarrow H_2O + 2e^- \tag{1}$$

and cathode:

$$\frac{1}{2}O_2 + 2e^- \rightarrow O^{2-} \tag{2}$$

Combining these equations makes the overall reaction:

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O \tag{3}$$

If the fuel contains carbon monoxide or hydrocarbons such as CH_4, a steam reforming reaction happens:

$$CH_4 + H_2O \rightarrow 3H_2 + CO \tag{4}$$

and also water-gas shift reaction:

$$CO + H_2O \rightarrow H_2 + CO_2. \tag{5}$$

The H_2 produced in these reactions will be further oxidized at the anode. SOFCs performance increases with increasing cell pressure. (EG&G Technical Services 2004)

In SOFC, the anode and cathode are made of porous ceramic material. The electrolyte is made of solid metal oxides, usually zirconium dioxide stabilized with yttrium. This material conducts ions in temperature range of 700–1,000 °C, which explains why SOFC operating temperatures are so high. (Basu 2007) On the other hand, Xing et al. (2021b) suggest that the lowest temperature for SOFC operation is 500 °C. Waste heat recovery from SOFC is worthwhile with heat exchanger, gas or steam turbine system. (Xing et al. 2021b)

SOFC is able to operate with pure hydrogen fuel, or it can internally reform hydrocarbons, such as methane in natural gas (Xing et al. 2021b, Basu 2007). Thermal cracking of ammonia is also possible (Xing et al. 2021b). In the case of fuel containing carbon, hydrocarbon, and water form carbon monoxide (CO). CO and water can further react to hydrogen gas and carbon dioxide, which reaction can also happen in reverse. Therefore, when supplying SOFC with hydrocarbons, small amounts of CO and CO_2 are emitted. (Basu 2007)

Molten carbonate fuel cell

Of discussed FC types, MCFC was developed latest, first commercial applications being in the first decade of 2000s. It is very similar to SOFC, the difference is that in MCFC liquid molten carbonate is contained in ceramic anode and cathode. Carbonate ions are formed on the cathode and transported thorough carbon electrolyte to the anode. CO_2 needed to produce the carbonate ion is taken form recirculated anode gas. MCFC and SOFC contain nickel as their catalyst, which makes these cell types more affordable than PEM with platinum catalyst. (Basu 2007)

To achieve conductivity of the carbonate electrolyte and to be able to use affordable metal catalyst, a high operating temperature is needed (EG&G Technical Services 2004). The operating temperature of MCFC is in the range of 550-700 °C (Xing et al 2021b, Basu 2007). It is able to utilize a wide range of fuels, such as natural gas, methanol, diesel and propane (Basu 2007). MCFC operating pressure is usually 3-4 bar (Xing et al. 2021b).

The chemical rection on MCFC anode with carbonate ion is:

$$H_2 + CO_3^{2-} \rightarrow H_2O + CO_2 + 2e^- \qquad (6)$$

and the cathode reaction:

$$\frac{1}{2}O_2 + CO_2 + 2e^- \rightarrow CO_3^{2-} \qquad (7)$$

The overall reaction is thus like reaction 3:

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O \qquad (8)$$

Gases are usually recirculated between anode and cathode, and therefore CO_2 just circulates in the process and big amounts of CO_2 are not emitted. The electrolyte of MCFC slowly evaporates which limits the operating life of the cell. (EG&G Technical Services 2004)

Increase of the operating pressure leads to increased cell voltage since mass transport rates rise as pressure increases. However, increasing the pressure also has undesired side effects such as carbon deposition on cell surfaces and methane formation in cell. The carbon deposition is detrimental to the cell performance since it blocks the catalyst surface. The formation of methane in the cell worsens the cell performance since it consumes H_2 molecules which makes smaller amount of fuel available. (EG&G Technical Services 2004)

Increasing the operating temperature of MCFC cell also enhances the performance of the cell. However, the more the temperature is increased the smaller the performance gain becomes. The exact change in the cell performance depends on the composition of gases feed into the cell and the operating conditions. (EG&G Technical Services 2004) In the table below, a summary of the properties of discusses FC types is presented.

Table 1. Summary of FC types

	Temperature *[°C]*	Pressure *[bar]*	Fuels	Typical composition of flue gas	Typical efficiency *[%]* (Nerheim et al. 2021)
HT-FPEM	160-220	1-10	H_2	H_2O, O_2, N_2, H_2	40-60
SOFC	500-1,000	1-8 (Nerheim et al. 2021)	H_2, diesel, natural gas, ammonia etc.	all of above + CO_2 and CO if fuel containing carbon	45-55
MCFC	550-700	3-4	same as SOFC	same as SOFC	45-60

2.3 Partial load operation of fuel cells

If maximum amount of electricity is not needed, FCs can be operated on partial loads. In maritime environment this situation might occur at startups and when vessel is docked and connected to shore-based electricity network. As previously mentioned, one of the major advantages of FCs is that their efficiency does not significantly drop on partial loads. (Basu 2007) Most of the literature on FCs partial load operation is not specifically for marine environment but stationary applications but can be applied to other operating situations.

There are two main strategies for operating a FC stack on partial load: bypassing some of the unit cells in the stack and operating the remaining cells at full load, or lowering the current density of the cell stack, meaning that the same surface area produces lower electrical current. (Campanari 2000) Bypassing some of the cells is in a way the simplest solution for FC partial load operation since the ratio of air and fuel inputs, the operating cell current density and the exhaust composition and temperature stay constant. However, this strategy requires that the FC stack is specifically built for bypassing.

Part-load operation by lowering the current density of all unit cells in the stack has been investigated by several researchers (Campanari 2000, Calise et al. 2006, Campanari 2001, Thorud et al. 2004, Lemański and Badur 2004), especially in the context of combined SOFC-gas turbine (GT) systems. The findings on FC operation can be generalized from these studies to other applications as well. Campanari (2000) presents two techniques for adjusting the current density: constant air flow rate and constant air utilization rate $U_{a.}$ U_a means the ratio of air that is utilized in the cell reactions to the total amount of air feed into the cell. Of course, the fuel flow needs also be adjusted to matching level, as Calise et al. (2006) states. Campanari (2000) points out that the variation in U_a will lead to variation in exhaust temperature. Since the cell heat generation is mainly discharged to the air flow, lowering U_a will reduce exhaust temperature. The exhaust temperature of the FC is a function of air and fuel inlet temperatures, air and fuel utilization factors, cell voltage, and efficiency.

According to Campanari (2000), part-load operating FC on constant air flow means that the U_a will be lowered. This leads to the cell voltage increase and a gain in the cell total efficiency. The exhaust temperature is reduced as lesser amount of heat is transferred to the same amount of air. Operating the cell on constant air utilization U_a means that the total mass flow of air is lowered, and the exhaust temperature of the cell stays relatively constant compared to full-load operation.

Calise et al. (2006) points out that in internal reforming FCs the steam needed for the reforming reaction is often generated by recovering the waste heat of the outlet stream and in start-up situation this heat source is unavailable so an alternative source for the steam is needed. This needs to be taken into account in a vessel by producing steam with e.g. auxiliary fired boiler. Calise et al. (2006) also states that it is not possible to arbitrarily vary all FC operating parameters since this might lead to unfeasible operating conditions. Campanari (2001) and Thorud et al. (2004) produced maps of the effect on output and exhaust temperature of varying SOFC operating parameters. Lemański and Badur (2004) created a mathematical model for SOFC and investigated the cell parameters as function of fuel mass flow and U_a.

Nerat (2017) investigated the rapid load change response on SOFC system. Author also points out the problem of local fuel starvation which means that some regions of the FC anode are undersupplied of fuel. This causes local reoxidation of the anode plate. Therefore, author advises that operation of FC with U_a close to 1 is best avoided. It was found that a steep change of voltage causes a temporary peak in the cell current density.

Since the operating temperature of SOFC is high, the cell requires preheating before startup. The electrical load can be connected only after the preheating has been performed. Barzi et al. (2009) investigated startup phenomena for SOFC system regarding to both thermal and electrical parameters. The electrical response time was found to be about 50 min and thermal 130 min. This means that SOFC and other high-temperature cell types are not suitable for applications where the power need is intermittent. However, Yang et al. (2017) states that "the load-following capability of an SOFC system is not severely limited by thermal responses". The thermal response time gives the air control system time to adjust the air flow rate. SOFC is also always operated with sufficient amount of excess air, so the air starvation phenomenon is not a problem, unlike in PEM cells. For SOFC, the fuel starvation is a bigger challenge. (Yang et al. 2017)

Khan et al. (2019) studied the effects of varying the current of 1.2 kW PEMFC system. The temperature transition happened approximately linearly after the load change and the response times were in the order of 3 min to get back to steady state. Kim et al. (2015) state that when the pressure of the PEMFC was increased while keeping the current density constant, the cell output voltage raised, meaning that the cell total output was increased. However, the authors point out the delay in the pressure change to the desired level. Also, the performance increase comes with the cost for compressing the fuel and inlet air. Regarding a stepwise load change, the FC performance was found to be dependent on the amount of liquid water in the cell. Fuel starvation occurred in some parts of the cell, especially on higher operating pressures.

3. REFORM OF POWER GENERATION IN MARINE APPLICATIONS

As previously noted, there is a need for transition towards less carbon-intensive ways of power production in the marine sector. In this chapter, the most notable agreements for cutting down the GHG emissions in the marine sector are briefly reviewed in order to give background for the scale and timeline of the transition towards cleaner power sources. The pros and cons of hydrogen as a marine fuel are evaluated based on the scientific literature. The feasibility of hydrogen as a widespread marine fuel is also considered from the point of view of necessary infrastructure for refueling. Lastly, the various professional forecasts of marine fuels in the future are compared and analyzed with the interest in FC systems in mind.

3.1 Regulations and agreements towards cleaner fuels

The regulations concerning emission limits will have a significant effect on the transition away from fossil fuels to FCs and other environmentally friendly solutions both in the marine sector and in general society. In this chapter, the most notable agreements for cleaner fuels in the marine sector are reviewed to understand the timeframe when FCs might become more common.

International Maritime Organization (IMO) is a specialized agency of the United Nations. It sets international standards in shipping for safety, security, and pollution control. (IMO n.d.-a) IMO also carries out extensive GHG studies every fifth year to gain understanding about the environmental impact of international shipping for emission control decision-making. Beginning of 2013, IMO entered into force environmental regulations for ships of 400 gross tonnage and above, stating that “These measures are the first ever mandatory global GHG reduction regime for an entire industry sector”. The regulations consist of the Energy Efficiency Design Index (EEDI) for newbuild vessels and the Ship Energy Efficiency Plan (SEEMP) for new and existing ships. (IMO n.d.-b) Certain ratings on Energy Efficiency Index for Existing Ships (EEXI) and Carbon Intensity Indicator (CII) will be required for existing vessels above 400 and 5,000 gross tonnage respectively starting in 2024. (IMO n.d. -c)

The IMO has set emission reduction goals for both carbon intensity (i.e., CO_2 emissions per transport work) and total GHG emissions form ships. The baseline year against which these emissions are compared is chosen to be 2008. For CO_2 emission intensity, IMO’s goals are to reduce it by 40 % by 2030 and to make an effort to reduce emissions further, by 70 % by 2050. For the total GHG emissions, IMO intends to reach the peak emissions as soon as possible and reduce total annual emissions by 50 % by 2050. The IMO has ambition towards phasing out all GHG emissions, which is consistent with Paris Agreement temperature rise goals. (IMO 2018) Liu et al. (2023) points out that IMO has been called out to make GHG emissions reduction regulations in faster pace.

The European Union has also placed regulations on maritime emissions. Already in 2013, the EU commission introduced a strategy for mitigating GHG emissions from shipping. The European Commission adopted a so-called "Fit for 55" legislation package in July 2021. These laws are aimed at cutting Europe's total GHG emissions by minimum 55% by 2030 against 1990 baseline and climate neutrality in 2050. Regulations for maritime transport were a part of this package. The EU's maritime emissions goals and reduction measures are more stringent than IMO's. (European commission 2022)

Maritime CO_2 emissions from ships over 5,000 gross tonnage will be included in EU Emissions Trading System (ETS), which previously covered industry, energy production and aviation sectors. In ETS there is a shared emission cap for all sectors and this set amount of emission rights is traded among participants. Maritime sector will join the emission trade gradually starting from 2024, meaning that in the first years only part of the emissions will need emission allowances. In 2027, all CO_2 emissions from intra-EU shipping and 50% of emissions of voyages from or to EU will be subject to trading. The increasing price for emitted CO_2-ton will make alternative fuels, such as hydrogen, more economically viable alternative. (European commission 2022)

As a part of the "Fit for 55" regulation package, Fuel EU Maritime law sets a limit for GHG intensity in marine fuels and supports alternative fuel infrastructure in ports. This legislation has not yet been adopted but the proposal sets targets for cuts in carbon intensity of energy used in ships. A notable aspect of this proposal is that carbon intensity is calculated on well-to-wake basis, meaning that the emissions form producing the fuel are also considered. The carbon intensity targets are compared against 2020 energy intensity baseline and the cuts are proposed to be 20% by 2035 and 80% by 2050 with several intermediate target levels. A target of 2% renewable fuels of non-biological origin is also proposed by 2030. (Soone 2023)

"Fit for 55" also includes the Renewable Energy Directive which sets a target of renewables in all energy consumption in EU, also in marine sector. Some fuel taxation exemptions in marine transport have also been dismantled as a measure to make shipowners seek more environmentally friendly fuels. (European commission 2022)

3.2 Hydrogen as a marine fuel

Hydrogen has a high energy density with respect to its mass, but since it is light gas in atmospheric temperature and pressure, it is difficult to store onboard. The space allocation for existing FC systems in ships, including fuel storage, is approximately twice as big as for conventional ICE. Both liquefied (LH_2) and compressed hydrogen (CH_2) have been used in demonstration FC vessels running on hydrogen. (Nerheim et al. 2021)

Nerheim et al. 2021 compared hydrogen and liquefied natural gas (LNG) as maritime fuels. Both LH_2 and LNG are cryogenic liquids, meaning that they have to be cooled to very low temperatures so that they stay in liquid state. However, LH_2 requires even lower storage temperature than LNG. The small molecular size of hydrogen causes it to leak through connections and valves more easily than any other fuel. It also has a wide flammable mixing range with air and comparatively low ignition energy, which causes additional safety concerns. (Nerheim et al. 2021)

H_2 can be not only consumed in FC, but also burned in ICE (Aakko-Saksa et al. 2023). Burning H_2 in engine makes the system more flexible as several types of fuels can be combusted in ICE. However, H_2 ICE technology is less mature that FC and has not been demonstrated in large-scale maritime application. It is forecasted (DNV 2022) that 4-stroke H_2 combustion engine for ships will not be commercially available until 2028.

Sürer and Arat (2022) discuss the hydrogen production methods most relevant for maritime sector. Currently the most common and affordable is grey hydrogen, which is produced by steam reforming methane or coal gasification. This way of production consumes fossil fuels – either natural gas or coal – and produces CO_2 emissions. As long as grey hydrogen is the most economical option, using hydrogen as a fuel does not bring any environmental benefits.

Blue hydrogen is produced like the grey hydrogen, with the difference that carbon capture and storage (CCS) system is used. This means that 85-95% of CO_2 emissions to the atmosphere are avoided. However, this H_2 production method still consumes limited fossil fuels. (Sürer & Arat 2022) Blue hydrogen is currently not being produced in a meaningful scale, and there are challenges in storing the captured CO_2. It is considered as a shot-term transition technology from traditional grey H_2 to green hydrogen (Sürer & Arat 2022).

A novel form of hydrogen production is producing hydrogen form methane with a pyrolysis process. This process turns the carbon in methane into solid form, thus the emission to air is avoided. H_2 produced with this method is called turquoise hydrogen. Turquoise

H_2 is comparable to blue with the difference that solid carbon is easier to store. (Sürer & Arat 2022)

The long-term goal for hydrogen production is called green hydrogen. It is produced by electrolyzing water into hydrogen and oxygen gases. The electricity required for the process comes from renewable sources such as wind or solar, making green hydrogen practically free of GHG emissions. (Sürer & Arat 2022) Widespread production of green hydrogen is the prerequisite of environmentally sustainable hydrogen economy. Right now, still 96% of H_2 production comes from fossil fuels. The electrolyzer technology for green hydrogen is not expected to be mature until after 2030. (Nerheim et al. 2021)

Rivarolo et al. (2020) discussed hydrogen storage on FC powered ship. Compressed H_2 stored in high-pressure tanks in one option, but to achieve a realistic energy density 350-700 bar pressure is required. On the other hand, liquid H_2 storage needs cryogenic temperature around 20 K. Liquid storage may be more advantageous than compressed regarding energy density, but the cooling of the H_2 is very energy-intensive and H_2 boil-off is an issue. Storing H_2 within metal hydrides is one storage option, but they are expensive and have low mass density. The advantages are high volumetric storage density and reasonable storage pressure (less than 40 bar).

In addition to H_2 production, there are also challenges related to hydrogen transport and distribution infrastructure in ports for refueling H_2 vessels. In 2022, there was H_2 bunkering station at only two ports worldwide. It has also been proposed that the H_2 vessels could be refueled directly from LH_2 carrier tankers, which could assist in the transition period when there are some LH_2 powered vessels but not many H_2 bunkering stations. (Ustolin et al. 2022) Especially problematic link in the refueling infrastructure are large LH_2 storage tanks, since due to the small size of H_2 molecule it can leak out of apparently solid walls and welded seams. (Chen et al. 2023)

3.3 Future predictions

According to the fourth IMO GHG inventory (IMO 2020), in “business as usual” -scenarios the CO_2 emissions from ships will increase 0-50% by 2050 compared to 2018 emissions. This corresponds to 90-130% increase compared to emissions in 2008, which is the baseline year for IMO emissions reduction goals. “Business as usual” has here been defined to “no adoption of new regulations that have an impact on energy efficiency or carbon intensity” in the shipping sector. Comparing this to IMO’s emissions reduction targets introduced in preceding chapter, it is clear that drastic changes are needed.

In addition to the “business as usual” -scenario, the fourth IMO GHG inventory also outlines the possible emission reduction measures that are necessary to achieve the climate targets. According to the inventory, the most influential measure in reduction of GHG emissions is the use of alternative fuels. This is further divided into two categories: use of alternative fuel with or without carbons. The alternative fuels with carbon in them are named to be LNG, methanol, and ethanol. Given examples of fuels without carbon are hydrogen and ammonia.

In the GHG Study, the penetration rates of emission reduction technologies are estimated. Penetration rate is defined as the percent of ships that have applied the named technology. IMO estimated these penetration rates for two scenarios: Scenario 1 presumes theoretically maximized CO_2 emission reduction. This means that “Each abatement technology is expected to be fully adopted by all newly built ships after 2019” (IMO 2020 p. 230). Scenario 2 assumes that the emission mitigation technologies have higher implementation barriers, which means that they are adopted more slowly than in scenario 1.

An excerpt of these rates is given in table 2 for the use of alternative fuels and waste heat recovery. It is noted that the waste heat recovery is not limited to certain fuels, but it can be utilized with any fuel.

Table 2. Penetration rates of selected emission reduction technologies (IMO 2020 p. 231)

Penetration rates of technologies (% of ship fleet over 100 GT)		**Reference**	**Scenario 1**		**Scenario 2**	
		2018	2030	2050	2030	2050
Use of alternative fuel with carbons	LNG + ICE	1 %	55 %	0 %	1.5%	20 %
	LNG+FC, Methanol + ICE, Ethanol + ICE	0 %	54 %		0.05%	
Use of alternative fuels without carbons	Hydrogen, ammonia, etc.	0 %	0.1%	100 %	0.05%	20 %
Waste heat recovery	Waste heat recovery	12.5%	66.5%	100 %	17.5%	42.5 %

It is noted that especially the first scenario is overly optimistic, since surely not every newbuild vessel has utilized all of the numerous emission reduction technologies since 2019. The purpose of including this scenario has probably been to highlight the need for immediate measures for emission reduction by showing the best-case results. Moreover, it is unclear on exactly what basis the penetration rates for scenario 2 were determined. It seems likely from the context that these scenarios were created by thinking backwards from the set emission goals for 2030 and 2050 to outline measures that need to be taken to achieve these goals. Therefore, these numbers should not be treated as a forecast of the future but rather a guide for IMO decision makers.

Despite mentioned shortcomings, some conclusions can be made from the estimated penetration rates. It is expected that the transition from conventional oil-based fuels to fully carbon-free fuels (and thus zero CO_2 emissions) is expected to happen via alternative fuels that contain some carbon. It is noted that LNG is classified as an alternative fuel even though it is fossil-based. Moreover, the way to utilize the fuel is not estimated as hydrogen can be used in ICE or FC.

The IMO GHG study (IMO 2020) suggests emissions reduction targets for 2030 and 2050 can be achieved if all of the suggested emission mitigation methods are used in all newbuild vessels starting from 2025. Moreover, approximately 64% of the CO_2 reduction is achieved by the use of alternative fuels without carbons. Therefore, it can be anticipated that there will be IMO regulations encouraging or mandating the alternative fuels in this decade since that is the single most effective way of reducing the CO_2 emissions.

International Energy Agency (IEA) report on international shipping (IEA 2022) outlines a prediction of marine fuels consumption in 2030. According to this prediction, the share of so-called low-carbon fuels will be 15 %. Biofuels (approx. 7 % of total) and ammonia (approx. 6 % of total) are the most notable emerging fuels. Hydrogen is expected to constitute only 1 % of the marine fuel consumption in 2030. The consumption of electricity will be negligible according to this prediction. The remaining portion of 85 % is expected to still be covered by fossil fuels according to IEA.

In the report it is pointed out that the lifetime of a marine vessel is long and thus the transition away from oil-based fuels is going to be slow. As of 2021, maritime industry is not on track for the Net Zero Scenario goal for 2030 according to IEA prediction. To achieve the Net Zero Scenario, IEA says that quicky adoptable innovations in zero-emission technology are needed.

A maritime classification society DNV has also published its forecast for future of marine fuels (DNV 2022). DNV has evaluated numerous future scenarios for fuel mix based on the development of fuel prices. Similar fuels were categorized into three broad groups in order to more realistically evaluate the future scenarios. These groups are fossil fuels, biofuels and electrofuels. DNV also investigated the maturity levels of different fuel technologies and forecasts when those will be widely commercially available. This helps to create the picture that the path to more environmentally friendly marine fuels will not be a single switch but a gradual transition with various competing technologies.

In the DNV study, it is notable that the pure hydrogen is not evaluated as a fuel. This is to point out that hydrogen is not a primary energy source but an energy carrier. Hydrogen can be produced out of primary energy sources, such as natural gas. The fuel cell technology is also not investigated further in the study. It can be concluded that the DNV experts do not expect fuel cells to be a significant part of the production of propulsion power. The idea of hydrogen economy is not fully abandoned by DNV, but they foresee that other primary energy sources will be used in the production of cleaner fuels. However, the production of power for auxiliary equipment such as pumps was not considered in the report.

Herdzik (2021) sees that hydrogen will be the main fuel for shipping in the future after a transition period. The author suggests that bio-based fuels, ammonia, alcohols (such as methanol), and gaseous fuels will be used during the transition away from liquid oil-based marine fuels. It is pointed out that all of these alternative fuels come with a set of problems, such as toxicity of methanol, low heating value of ammonia and methane slip with LNG. The author sees hydrogen as a long-term solution to those problems and forecasts that “The use of hydrogen in thermal engines is an intermediate solution”, whereas the use of hydrogen in fuel cells will be the ultimate goal. The reason for the growth of fuel cell ships is suggested to be higher efficiency of FCs compared to ICEs as FCs are not bound by the theoretical upper limit of Carnot efficiency.

Herdzik (2021) stresses that the selection of marine fuel has always happened based on the fuel price. Since alternative fuels are very likely to stay more expensive than fuel oil, “the IMO regulations will have a decisive impact” on future shipping fuel mix. The author estimates that hydrogen will be a significant marine fuel in 2050s, although some (DNV 2021) forecast this to happen already after 2040. According to this timeline estimate, it looks like most of the studies consider too short timescale (up to 2050) to see the breakthrough of FCs.

In the DNV report “Rising to the challenge of hydrogen fuel” (DNV 2021), which discusses the prospects of hydrogen economy not only in marine sector but also in the whole society, the challenges for hydrogen utilization are pointed out. If the whole maritime sector would be powered with hydrogen, all of the carbon-neutral electricity currently produced in the world would not be enough to cover the process of making hydrogen. When the already existing use of hydrogen in industry and the aims to considerably utilize hydrogen in other sectors, e.g. road transport, is considered, it is unlikely that hydrogen alone will be the answer to decarbonizing shipping.

Korberg et al. (2021) analyzed the total costs of various alternative fuels. Article introduces the factors that will be crucial for choosing the propulsion system between FC and ICE. These are fuel cost, efficiency, time spent at sea and naturally the cost of propulsion system. It is pointed out that the better efficiency of FC might justify the higher fuel price. Also, more time spent at sea favors the FC system. FC investment costs are seen to remain high in the coming years.

In a joint report (Baresic et al. 2022) between United Nations Climate Change High Level Champions and maritime consulting agency UMAS, a goal is set that scalable zero emissions fuels would make 5% of the fuel mix of global shipping in 2030. Scalable zero emission fuels are defined to include hydrogen, methanol, biofuels, liquefied biogas, ammonia, batteries, and wind propulsion. This goal is perceived to be a critical step in the journey to fully carbon-free shipping by 2050 as it is forecasted that alternative fuel solutions will take up quickly after the first large-scale commercial projects have been proven successful. According to the report, the shipping industry is not on track for this overall goal, one of the main reasons for this being the lack of availability of alternative fuels. However, the sub-goal for FC technologies development was seen as being on track since there already are demonstration vessels operating with FCs.

All of the forecasts discussed above seem to point to the situation where marine fuels in the future will be a mix of various fuel types, contrasting the current situation. There is a difference of opinion on what fuel will be the most popular, but the authors agree that there will be a transition period with less-carbon intensive fuels on the journey to fully (or near) carbon-free shipping. Authors highlight the urgent need for innovative technological solutions. Liu et al. (2023) state that since the average operating lifetime of a vessel is around 20 years, the year 2030 will be a turning point when the alternative fuels and other emission reduction technologies should be widely used in newbuild ships to fulfill the IMO emissions goals.

Since renewable fuels are more expensive and require significant investments, it is expected that the transition is not going to happen organically but rather enforced by regulations and sanctions. On the other hand, Liu and others (2023) suggest a reward mechanism for advancing the marine sector environmental reform in order to not place a disproportionate burden on the shipping sector.

The aforementioned authors expect that hydrogen will have at least some kind of share in the fuel mix after 2050, but it is not announced whether it will be consumed in FCs or combusted. Therefore, as a conclusion, it looks like the in next decades FCs will not be very significant in the main power production in ships. However, there is very little forecasts about utilizing FCs in auxiliary power production. Aakko-Saksa et al. (2023) points out that the space demands of FCs make them considered for auxiliary power production and smaller vessels.

Rivarolo et al. (2020) studied PEMFCs as a power source option for a tourist boat. The study concludes that the PEM system could not compete with ICE system economically. Moreover, the space required for H_2 storage was considered too large. The authors state that PEMFCs – and also FCs in general – will not be techno-economically viable option, unless carbon emissions are taxed, or zero-emissions water areas are established.

Latapí et al. (2023) investigated the main drives and barriers for using fuel cells in shipping in Nordic countries by interviewing experts in the field. The most notable barriers that interviewees mentioned were economic in nature. High costs of FC systems and the lack of supply for green hydrogen were the most important ones, along with lack of hydrogen refueling infrastructure and regulations. Other types of barriers than economic were also identified, such as lack of knowledge and trained staff and the inertia of change.

According to Latapí et al. (2023), the main external driver for adopting FC systems in Nordic shipping industry is external legislation and regulations which almost all interviewed experts mentioned. Almost as important are internal environmental commitments. Focusing on FC projects is also viewed as a way to achieve access to external funding and to fulfill customer expectations.

4. FUEL CELL WASTE HEAT RECOVERY AND UTILIZATION IN SHIPS

FCs produce exhaust gas, which temperature and composition varies according to FC type, fuel, and operating conditions. The energy in hot flue gas can be captured and utilized, thus making the FC system efficiency higher as more useful energy is gained from the same amount of fuel. The principles of waste heat recovery and how it has been applied to marine FCs are introduced below in the subchapters.

Salonen (2020) developed a method for mapping out the opportunities for utlizing waste heat which is illustrated in the figure 4. In the first phase, the source for waste heat is recognized and the possible users for the waster heat are identified. If there are no users for the waste heat, the heat recovery will naturally not be worthwile.

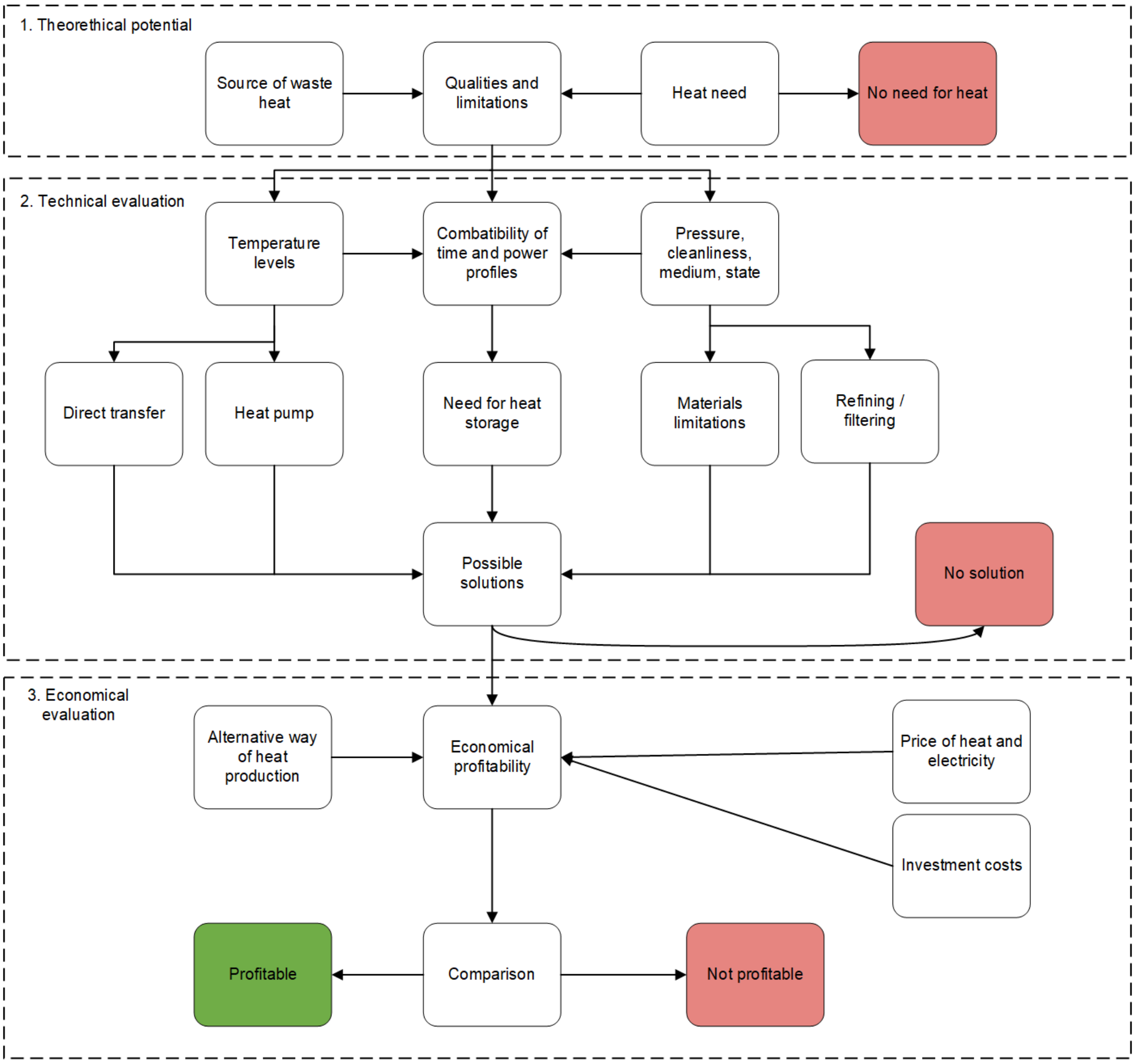

Figure 4. Waste heat recovery evaluation process (Salonen 2020, adapted)

Technical evaluation for WHR is carried out as the next step. The temperature level of the heat source is evaluated against if it is high enough to utilize as is or if there is a need to raise the temperature level with a heat pump. The time and power profiles of the produced heat are considered regarding the user's need for heat. If there is a mismatch in the timing of heat production and need, the system might need a heat storage. Moreover, the properties such as pressure, composition and cleanliness of waste heat carrying steam are evaluated. These factors might set limits for the materials of WHR system or set a need for pretreating (e.g., filtering) the hot stream. Based on these evaluations, possible technical solutions can be drafted.

Lastly, the economic factors are evaluated to find out if the WHR is financially profitable. The investment and operating costs are compared to purchasing heat from an outside party or to the costs from producing heat in alternative ways. Based on these three main steps, the technoeconomic potential for WHR can be evaluated.

4.1 Waste heat recovery in ships

The nominal efficiency of marine diesel engine is usually around 50% which means that the hot engine exhaust gas carries a significant amount of energy. Waste heat recovery from exhaust gases is a standard practice in ships and increasingly strict energy efficiency requirements from IMO make energy efficiency even more important consideration for both newbuild and existing ships. (Latarche 2021)

Waste heat boilers, often fire-tube type, are used to produce steam or hot water to use in the ship (Latarche 2021). Water-tube WHR boilers are also used (Behrendt & Szczepanek, 2022). The waste heat boiler can act as an economizer preheating water for oil-fired auxiliary boiler or, if the amount of steam is large enough, to produce electricity in steam turbine. The steam or hot water can be also used directly for heating. Other heating mediums than water, like thermal oils, are also sometimes used. (Latarche 2021)

The water tube WHR boiler onboard on the ship consists of the heat transfer surface tube bundles. There is also a steam drum for collecting the steam and separating it from water if the system produces steam as opposed to hot water. The feedwater is pumped to the boiler with feedwater pumps. The feedwater pumps suction water from a hotwell tank to which condensate returns from circulation. The temperature of the tank is maintained high since it lessens the amount of dissolved oxygen which causes corrosion in the boiler. (Morton 2020)

The WHR boiler can be modeled in a simplified manner by utilizing the logarithmic mean temperature difference (LMTD) method, which is based on the following equations:

$$Q = UA\Delta T_m \tag{9}$$

where Q is the heat rate (W), U is the overall heat transfer coefficient (W/m^2/K), A is the boiler heat surface area (m^2) and ΔT_m is the logarithmic mean temperature difference. This temperature difference is defined as follows:

$$\Delta T_m = \frac{\Delta T_1 - \Delta T_2}{\ln{(\Delta T_1/\Delta T_2)}} \tag{10}$$

where $\Delta T_1$and ΔT_2 describe the temperature differences at the inlet and outlet of the exhaust gas and heated fluid. (Incropera & DeWitt 2001)

Based on the heat rate, the mass flows for steam and heated water can be found form the following equation:

$$Q = \dot{m}\,\Delta h \tag{11}$$

where $\dot{m}$ is the mass flow (kg/s) and Δh is the enthalpy change (J/kg). (Incropera & DeWitt 2001)

As the fuels and sources of power in shipping get more diverse as described in the chapter 2, it can be expected that various types of WHR systems are also going to emerge. The ship environment sets some special considerations for the WHR system, such as limited space, stringent safety regulations and ability to tolerate tilting.

4.2 Waste heat consumers in ships

The steam consumers vary according to the type of the vessel. In cargo ships it can be used for cargo heating or steam-powered cargo pumps in tankers. (Latarche 2021) In passenger ships, waste heat can be used for heating of the cabins and kitchen. In cruise ships, there are additional needs for steam in laundry facilities and swimming pool heating.

The heat demand depends strongly on the weather conditions and ambient temperature on the vessel's route. Cao et al. (2016) investigated heat needs in a container ship hauling refrigerating cargo from Pusan, Korea to Karachi, Pakistan. The power consumption per category is presented in table 3. The refrigeration is the largest heat consumer, demanding over 60 % of the total heat load. The category auxiliaries includes pump and fan power consumption. Since the considered vessel sails in warm climate area, there is no demand for space heating.

Table 3. Refrigerated cargo ship heat consumption (Cao et al. 2016)

Heat consumer	Power consumption (GJ)	Share of power consumption (%)
Water heating	22.69	3.7
Space cooling	127.33	21
Refrigeration	390.28	64.3
Space heating	0	0
Auxiliary	66.21	10.9
Total	606.51	99.9

Brækken investigated in his thesis (2021) power consumption in various passenger ships. In the passenger ferry operating between Mariehamn and Stockholm, propulsion was the biggest power consumer at 51 % as can be seen form table 4. Cabin heating was the biggest heat consumer at 18 % share with the cabin cooling being the smallest individual consumer. The yearly power consumption is given allocated per passenger. The total passenger capacity of the considered vessel was 1,800 persons, which means that the total yearly heat consumption was 51 GWh.

Table 4. Passenger ship power consumption (Brækken 2021)

Power consumer	Share of yearly power consumption (%)	Yearly power consumption (kWh/passenger/year)
Propulsion	51.3	14,449
Accommodation heating	17.7	4,994
Fuel/tank heating	3.8	1,068
Galley	3.5	974
Hot water heating	5.4	1,508
Accommodation cooling	0.9	251
Other	17.4	4,900*
Total	100	28,144

*average of high and low estimate by the original author

The power and heat consumption for a large-scale cruise ship was also considered by Brækken (2021). Propulsion is the biggest power consumer also in this case. The “Other” category includes heating consumers such as kitchen, laundry and swimming pool heating. The total passenger capacity for the large cruise ship is 5,230 persons, which means the yearly total power consumption of 240 GWh.

Table 5. Cruise ship power consumption (Brækken 2021)

Power consumer	Share of yearly power consumption (%)	Yearly power consumption (kWh/passenger/year)
Propulsion	48	21,989
Accommodation cooling	7.6	3,499
HVAC auxiliary	10	4,576
Other	34.4	15,774.5
Total	100	45,837.5

*average of high and low estimate by the original author

As can be seen from these estimates, the electricity and heat consumption vary greatly depending on the size of ship, onboard amenities, and weather conditions. Gnes et al. (2020) name the heat consumers and the respective temperature levels on a large cruise ship presented in the table 6. Both steam and hot water are needed for the ship's functions. Steam is produced for the AC heating, kitchen, and laundry use. Hot water is needed at two temperature levels: around 90°C and 60°C. A notable hot water user is desalinated water production, which is done with thermal evaporators.

Table 6. Cruise ship heating consumers (Gnes et al. 2020)

Steam consumers	Properties
Air conditioning heating	180°C, 10 bar(a) (sat.)
Galley	180°C, 10 bar(a) (sat.)
Laundry	180°C, 10 bar(a) (sat.)
Hot water consumers	
Hotel hot water	60°C
Non-hotel hot water (swimming pools, laundry)	90°C
Engine room heat users	90°C
Tank heating (thermal treatment of fuel and sludge)	50°C
Desalinated water production	90°C

Heat can be transferred from source to consumers either directly or with a heat pump. Heat pumps are utilized when there is a need to transfer heat from lower to higher temperature, i.e. the heat source is in cooler temperature than the heat consumer. Direct transfer has lower investment costs, but the heat source is required to constantly be warmer than the needed consumer temperature. Heat pumps provide more flexibility to the system since the quality of waste heat can be increased by increasing the usable temperature. Adding a heat storage in the direct heat transfer system helps to lessen the effect of fluctuating heat source temperatures. (Salonen 2020)

The heat transfer to heat pump cooling or heating system in a waste heat recovery context can be either direct or indirect. For direct system, the heat exchange device extracting heat from the hot engine exhaust gas provides thermal capacity directly to the heat consumer. This configuration has a risk that the possibly toxic or fire-hazardous working fluid causes an accident in the case of leakage. In indirect system, the heat recovered from the exhaust gas is transferred with an intermediate step of thermal fluid, which has not as harmful properties as heat pump cycle working fluid. The working fluid can be isolated strictly to the heat pump/chiller enclosure. Indirect system with thermal oils is usually preferred in ship installations because of stringent safety regulations. Water may also be used as an intermediate heat carrier fluid. (Butrymowicz et al. 2021)

4.3 Waste heat recovery from fuel cells

Waste heat recovery form fuel cells has been of research interest in the last years (Xing et al. 2021a, Kang et al. 2020, Cao et al. 2022, Evrin and Dincer 2019, Ouyang et al. 2020, Wu et al. 2019) although less studies can be found about WHR specifically on ships. There is also lot of recent research about FC WHR from road vehicles (Sun et al. 2021, Madheswaran et al. 2022, Wu et al. 2021, Şefkat & Özel 2022, Yu & Chau 2009), which is an environment with lot of similarities to ships, such as size limitations and mobility of the system, but due to a small power capacity these studies are not evaluated further.

Most of the studies are in relation to SOFC since they offer a great WHR potential due to high operating temperature. MCFC is also a high-temperature cell, but it has gotten less research attention regarding to WHR since it is newer and less common cell type than SOFC. Xing et al. (2021b) suggests that the hot exhaust from SOFC can preheat the fuel and air coming into the system and also the fuel reforming unit. Moreover, a steam Rankine cycle could be utilized for steam generation. SOFC coupled with organic Rankine cycle (ORC) has also been a subject of many studies. (Xing et al. 2021b)

Waste heat recovery from PEMFC, including HT-PEM, has also been studied (Kang et al. 2020). Since PEMFC has a lower operating temperature, WHR from it requires more complicated system to capture the heat in useful form. Most of the reviewed studies addressed FC WHR with ORC.

Kang et al. (2020) studied ORC with HT-PEMFC in operating temperature range 150-200°C. The study compared the load of FC stack, generated power, and system efficiency with respect to operating temperature and current density in the cell. It was found that the higher the cell operating temperature was, the higher the power generation and better the total system efficiency was. Moreover, the more waste heat the system produced proportionally to produced electrical power, the higher the efficiency was. However, this is not a very useful finding since typically the main product from FCs is electricity and the heat is just a byproduct meaning that the system is adjusted according to electricity need.

Cao et al. (2022) conducted a study on how changing parameters such as temperature, pressure, and current density affect SOFC system with WHR from both technical and economic perspective. The studied system was fueled with biofuel and the CO_2 emissions were also investigated. System encompassed a SOFC stack with afterburner and the hot flue gas preheating both the incoming fuel and air. Then two scenarios were evaluated: In the first one, the flue gas was further conducted to a gas turbine, which generated electricity, and from there to HRSG. In the second scenario, there was a heat exchanger for heating a bioprocess and then a HRSG which is illustrated below with figure 5.

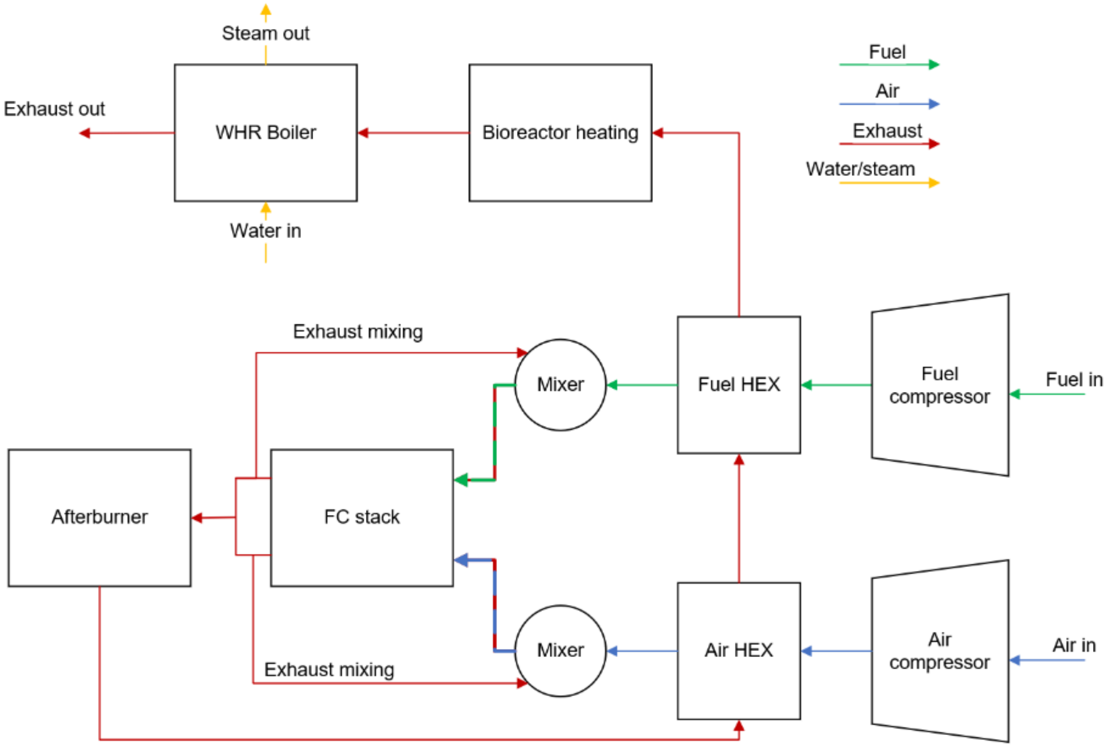

Figure 5. The FC WHR configuration in the study by Cao et al. 2022 (adapted). HEX = heat exchanger.

The study by Cao et al. (2022) found that the operating pressure of the cell affects the CO_2 emission intensity (amount of CO_2 emitted per produced kWh electricity) so that in the range of 3-8 bar, the smallest emission intensity is at 5 bar. Both smaller and higher pressures caused more emissions. The higher the fuel utilization factor, i.e. fuel efficiency, was, the smaller CO_2 emission intensity were. This is understandable since the more output can be achieved from the same amount of fuel, the less flue gas there will be allocated for unit of produced energy. The temperature of SOFC was 1,029 K at the maximum efficiency operating point. The article also points out that if the current density of the FC is increased, this means better output but also increased fuel consumption and higher cost of the plant. It was also found out that the higher the exergy efficiency of FC plant, the higher the investing costs are and thus the techno-economically best plant configuration is a compromise between low costs and high efficiency.

Xing et al. (2021b) describes the typical components for marine FC system. The system includes fuel storage and FC stack module with control unit. Batteries and a charger are included if needed. DC-DC converters and DC-AC inverter are also necessary since FCs produce direct current.

Evrin and Dincer (2019) assessed a concept SOFC system for ship. SOFC was operated on pure H_2 which was produced onboard with electrolyzer. The electricity was generated with solar panels and wind turbines onboard. The heat from SOFC was utilized in absorption chiller and HRSG, fulfilling the vessel's heating and cooling needs. The simplified system connections are illustrated below in figure 6. The temperature levels used in modeling were defined separately for the anode and cathode. Temperature at anode outlet was 307 °C and cathode outlet 840 °C, which seem very low considering SOFC cell type.

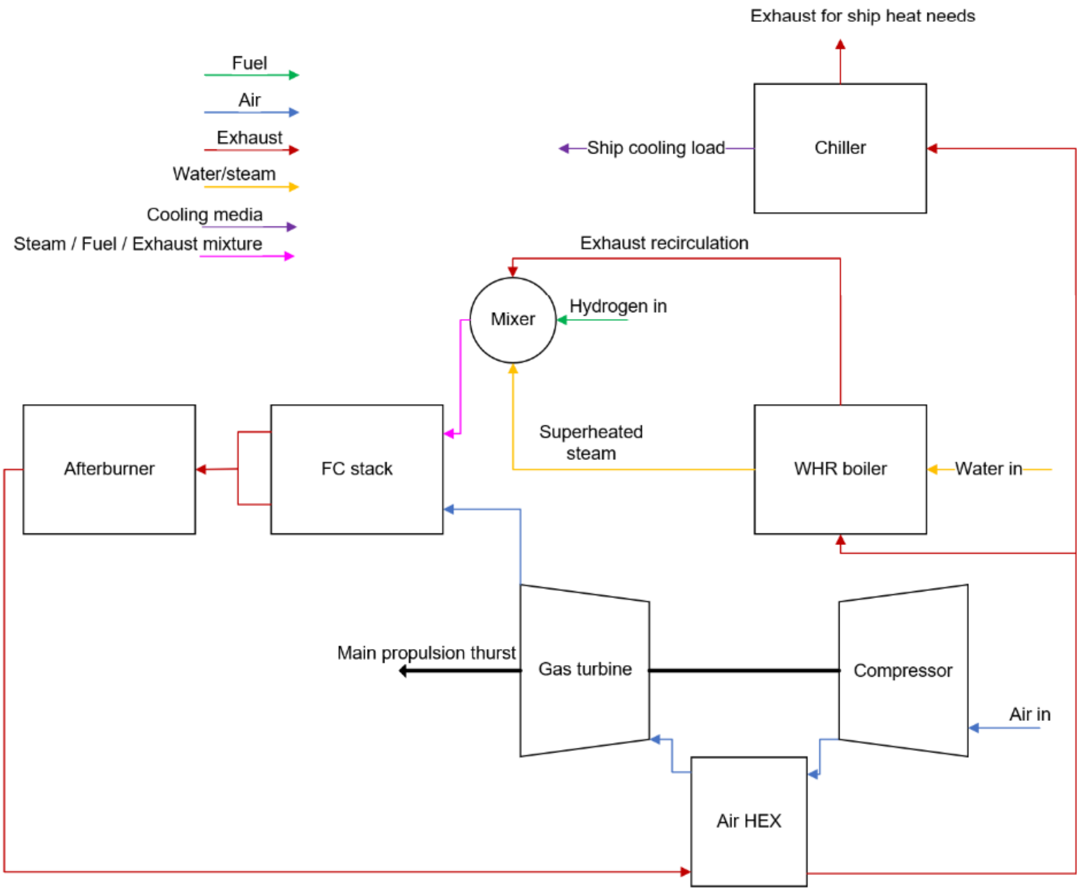

Figure 6. Simplified system configuration from Evrin & Dincer (2019), adapted.

Ouyang et al. (2020) names the most important WHR technologies for electricity generation. These are gas turbine, ORC, and Kalina cycle. The WHR technologies most commonly paired with SOFC are GT with afterburner, and ORC. If only one cycle is utilized after SOFC, it has been proven that ORC has a better performance than Kalina cycle. Ouyang et al (2020) simulated a complex SOFC WHR system for marine application consisting of FC module and two WHR cycles: Brayton cycle with supercritical CO_2 as working fluid and Kalina cycle with ammonia-water mixture as the working fluid. The article points out that it is important to optimize the working fluid selection of bottoming cycle to the SOFC exhaust temperature to get the best efficiency. The total efficiency of the SOFC-WHR system was calculated to be 71%, whereas for only SOFC without the WHR system it was 33%.

Wu et al. (2019) developed a power generation system for ship consisting of SOFC and HCCI (homogenous charge compression ignition) engine. The SOFC used natural gas as fuel which was pre-reformed before the cell stack with heat from the engine exhaust gases. The off-gas from SOFC anode was utilized as the fuel for HCCI engine. Pure H_2 was added to the SOFC flue gas going to the engine for combustion. The net electrical efficiency of the proposed system was 59%, which was found to be comparable to SOFC-GT system. The special advantage of this system was named to be fuel flexibility, since the engine can utilize a wide range of fuels.

Tse et al. (2011) evaluated a multi-generation system on a large luxury yacht. The system consisted of SOFC stack and a gas turbine for electricity production and cooling system for air conditioning on the ship as illustrated below in figure 7. The compressed methane was fed to the FC, and further to the GT. The turbine inlet temperature after afterburner was assumed to be 1,250 K at the design point. The GT exhaust was used for the chiller. Multiple chiller types were compared in the study, namely absorption chiller, desiccant wheel, and conventional HVAC. Due to concerns about technological maturity and load-following abilities, the SOFC stack was sized to be an auxiliary power system. The greatest system overall efficiency was achieved with absorption chiller, efficiencies being 45-53 % depending on the chiller manufacturer. Comparatively, the system with conventional HVAC had overall efficiency of only 22 %. The SOFC trigeneration has been focused by also other authors, such as Burer et al. (2003) who discussed techno-economical optimization of SOFC plant producing district heating and cooling as addition to electricity.

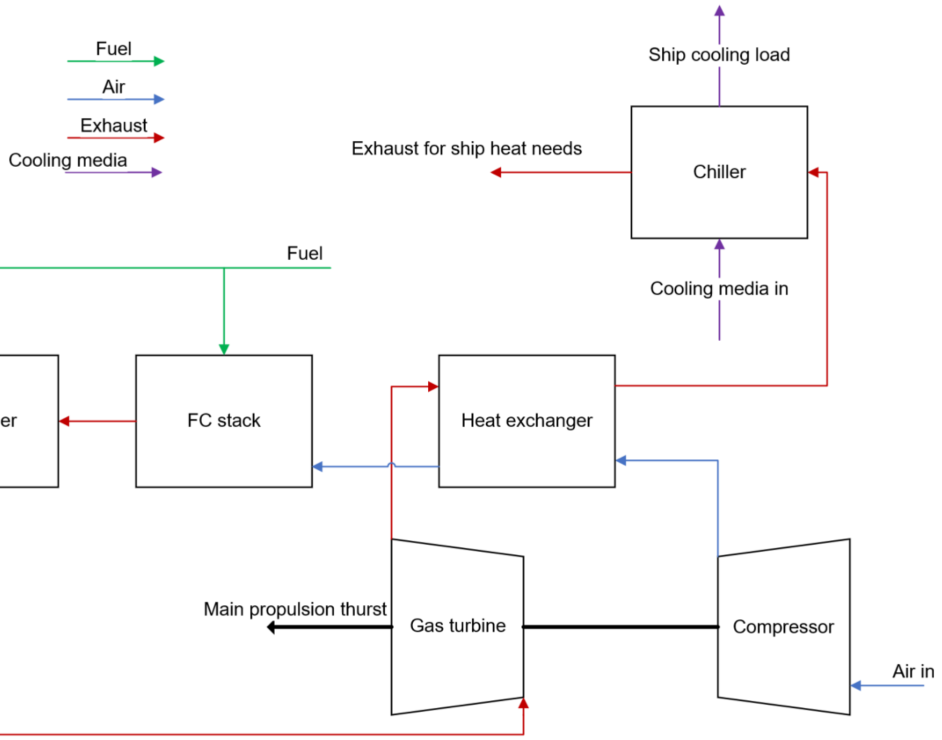

Figure 7. Multigeneration system diagram from Tse et al. (2011), adapted.

Ahn et al. (2018) studied a MCFC system on a LH_2 tanker. The study was a comparison of two WHR options: gas or steam turbine. The considered system was for propulsion of the tanker and the FC stack was the primary power source, with turbine being the secondary power source. The MCFC generated 23.5 MW electric power whereas turbine generated 4.6 MW. The gas turbine system was found to be superior compared to steam turbine from electrical efficiency standpoint. The MCFC was fueled with a mixture of natural gas and H_2. The system included a burner after the FC for combusting unburned fuel and extra hydrogen. The FC operated on atmospheric pressure, and the exhaust components after the burner are presented in the table below for reference. The total system efficiency was 54 % for GT system and 50 % for steam turbine system.

Table 7. MCFC exhaust properties after burner (Ahn et al. 2018)

	Gas turbine system	Steam turbine system
Component *(mol-%)*		
N_2	62.3	59.7
CO_2	4.6	5.4
O_2	4.5	2.2
H_2O	28.6	32.7
Temperature *(K)*	1,438	1,677
Mass flow *(kg/s)*	29.9	25.9

Mehr et al. (2021) point out in their review that in general, FC trigeneration systems are high efficiency and consume less primary energy than the alternatives. The techno-economic viability of a FC multigeneration system is decided by the choice of FC, not the heating or cooling technology. The review states that most combined cycle systems focusing on WHR from SOFC are producing electricity, heating, and cooling. For MCFC systems, the waste heat is utilized mainly also for electricity and heating production but also CO_2 capture. The authors state that the unique property of MCFC is that it is able to capture and separate CO_2 from the exhaust of conventional power production processes with high efficiency. Carbon capture with MCFC is advantageous over other carbon capture methods since it requires less energy than the alternatives.

5. MATERIALS AND METHODS

A case study is carried out in order to understand if the heat demand of a cruise ship can be covered by the waste heat from a FC system. Moreover, it is analyzed what needs to be considered when designing the waste heat recovery system for FC in a ship. In this chapter, the methods of the case study are described.

5.1 Research strategy and scope

A cruise vessel is chosen to be the subject of the study since Alfa Laval Aalborg Oy delivers waste heat recovery boilers for cruise and ferry types of vessels. The fuel cell system cannot be modeled after a real installation since FC power systems for ships in considered size do not currently exist to (Xing et al. 2021b). Therefore, the system configuration is chosen with the most reasonable possible presumptions and available literature. The research plan is summarized below graphically (figure 8).

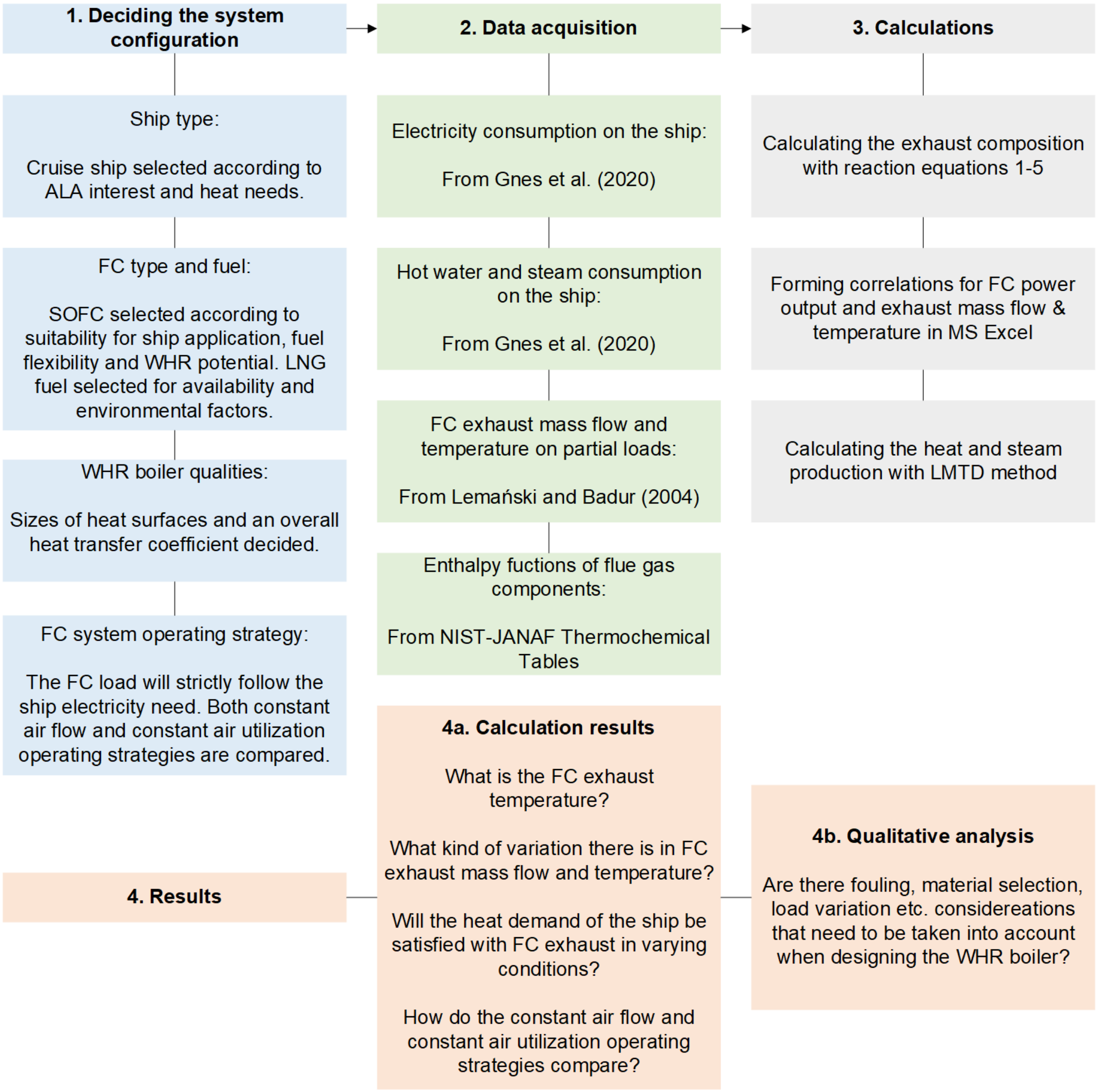

Figure 8. Summary of the research plan

For the case study, a SOFC cell type is chosen to be considered. This choice is made on the basis that as a high temperature FC, SOFC offers a great potential for WHR. SOFC is also deemed to be one of the most suitable FC types for ship applications and there has been a notable amount of demonstration projects with SOFC as a main or auxiliary power source for a vessel. (Xing et al. 2021b)

As can be recalled from the chapter 2.2, SOFC can utilize several fuels, such as pure H_2, natural gas, diesel, and methanol, due to its internal reforming ability. H_2 is the most environmentally attractive fuel choice, but for the time being, it has poor availability and next to nonexistent distribution network in ports. Diesel is readily available and well-known marine fuel, but for environmental concerns it is not considered further. Natural gas in liquefied form (LNG) is already used as a marine fuel and it has smaller emissions potential than diesel and other oil-based fuels. Therefore, the FC in the case study is presumed to be fueled by natural gas.

FCs can cover the whole energy consumption of a vessel, including propulsion power, or it can act as an auxiliary power producer. For the purposes of this case study, a fully FC-powered vessel is considered. This is both for easier analysis since the power demand does not need to be allocated between main engine and FC, and to take into account the tendency to fully electric propulsion power production. What is more, the increasingly strict emissions regulations force the shipowners to seek transformative power production solutions in the future so the fully FC-powered system might be interesting also regarding that.

The SOFC in the case study is modeled after the study conducted by Lemański and Badur (2004). In their study, a single tubular SOFC with internal reforming was considered. A parametric analysis of the FC was carried out by the authors, who studied the effects of different fuel mass flows, air and fuel utilization factors and recirculation factors to the cell performance. These research findings are utilized to model the operation of the FC system.

The output of a WHR boiler is modeled based on the mass flow and temperature of the FC exhaust gas entering the boiler. The produced amounts of steam and heated water are then compared to consumption demand data. Based on this comparison, it can be evaluated whether the heat demand of the ship can be fulfilled with the heat from FC exhaust and whether a WHR boiler is a good solution for this task.

The subject of this case evaluation an imaginary cruise vessel, that sails a week-long cruise route with several stops along the way. The vessel is assumed to be of electric propulsion type, and the electricity and heat consumption are modeled based on the study by Gnes et al. (2020), for both winter and summer cruises separately. In the mentioned study, the electricity is produced with diesel generators, but the electric and heat consumptions are assumed to be the same in the FC powered ship. The vessel uses electricity for propulsion system power and other technical consumers such as pumps, hotel functions and air conditioning during the summer.

In the aforementioned paper by Gnes et al. (2020), the steam consumed is assumed to be saturated at 10 bar pressure. Also, the hot water is assumed to be heated from 60 °C to 90 °C. These are assumed as the operating values of the WHR boiler, meaning that the feedwater is set to be 60 °C. The possible heat losses in the system are not considered in the case study.

The FC system needs to be pre-heated, and steam must be input to the system during the startup. This could be done with e.g. auxiliary fired boiler. This is excluded from consideration of this study. A cold start is not studied further, since during the cruise FC is always at least partially running to provide electricity for lighting and hotel amenities, for example. Considered system boundaries can be seen in figure 9. The SOFC module is supplied with pre-reformed fuel and air. The exhaust from FC stack is ducted to the WHR boiler.

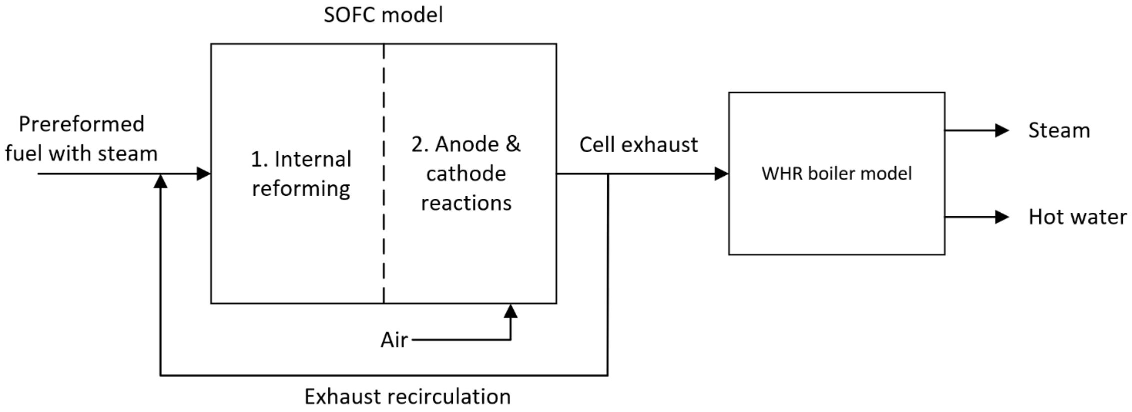

Figure 9. System boundaries considered in the case study.

As presented in the paper by Lemański and Badur (2004), there is also a pre-reformer involved in the system. The fuel composition was given entering the FC after the pre-reformer and thus the pre-reformer operation is not addressed further. Moreover, part of the exhaust gas was circulated back from cell outlet to the inlet to provide steam for the reforming reaction. This was described by a recirculation factor which means the mass ratio of recirculated exhaust to the inlet gas.

5.2 Modeling of fuel cell partial load operation

As can be recalled form chapter 2.3, there are several strategies for FC partial load operation. In the case study calculations, two operating strategies are compared: operating on constant air utilization factor U_a and constant air mass flow $\dot{m}_a$. The most notable difference between these operating strategies is that for constant U_a the ratio of reactants entering the cell stays constant and therefore the exhaust composition can also be approximated as unchanged. However, for constant $\dot{m}_a$ operation the exhaust composition keeps changing as the same amount of air is input to the cell with varying amount of fuel.

The number of cells in the FC stack is decided by assuming that the largest recorder value for unit cell power production in study by Lemański and Badur (2004) is the maximum for the cell. The peak power demand is divided by this maximum unit cell power, which gives the number of cells. Each individual cell has the same dynamic behavior, so the cell stack can be modelled as a multiplication of a single cell as Yang et al. (2017) states.

It is assumed in the case study that the FC operation strictly follows the electrical load. The corresponding exhaust composition and temperature are then calculated and compared to the heat demand on the ship at the same moment. As a result, it is obtained if the varying heat demands can be covered by a WHR boiler operating on FC exhaust.

The relevant fixed values and results from modeling carried out by Lemański and Badur (2004) for constant U_a operation are presented in the table 8. The fuel mass flow and correspondingly air flow are varied, which affects the cell temperature and electrical power output. The fuel and air utilizations as well as recirculation factor are kept constant, with respective values of U_f = 0.85, U_a = 0.25, and α_{rec} = 0.235.

Table 8. Lemański and Badur (2004) study parameters and results related to SOFC partial load operation on constant $\boldsymbol{U_a}$.

Fuel mass flow $\dot{m}_f$ [kg/s]	Air mass flow $\dot{m}_a$ [kg/s]	Cell temperature T [K]	Electrical power output P_{cell} [kW]
0.0000098	0.00015	1,194.9	0.082
0.0000163	0.00025	1,238.8	0.134
0.0000229	0.00035	1,269.7	0.185
0.0000294	0.00045	1,294.1	0.235
0.000036	0.00055	1,314.8	0.284

For constant $\dot{m}_a$ operating strategy, the relevant measurements from the study by Lemański and Badur (2004) are presented in the following table. Now the air utilization factor U_a is varied. The air mass flow per one cell is $\dot{m}_a$ = 0.00035 kg/s, and the recirculation factor and fuel utilization are staying the same than during constant U_a operation.

Table 9. Lemański and Badur (2004) study parameters and results related to SOFC partial load operation on constant $\dot{m}_a$.

Fuel mass flow $\dot{m}_f$ [kg/s]	Air utilization factor U_a [-]	Cell temperature T [K]	Electrical power output P_{cell} [kW]
0.0000137	0.15	1,192.4	0.113
0.0000183	0.20	1,233.7	0.149
0.0000229	0.25	1,269.7	0.185
0.0000275	0.30	1,302.1	0.220
0.0000320	0.35	1,331.5	0.255

In the same study by Lemański and Badur (2004), the fuel composition was also fixed. The SOFC was fueled by natural gas, which was mixed with some steam to make the steam reforming reaction possible. Moreover, before entering the cell the fuel is already pre-reformed so that it contains already some H_2. The assumed fuel gas composition is given in table 10.

Table 10. Fuel composition Lemański and Badur (2004) study and assumed air composition.

Component	mol-%
Fuel	
CH_4	17.1
CO_2	4.36
CO	2.94
H_2	26.26
H_2O	49.34
Air	
N_2	78
O_2	22

Since the exhaust composition is not published by the authors, it is calculated based on given fuel and air utilization rates in a spreadsheet program. For a simplified analysis, the reaction is calculated in two steps: it is assumed that the reforming reaction is happening first and then the anode and cathode reactions. In the reforming step, it assumed that according to the U_f = 85%, 15% of the fuel gas is left unreacted. The recirculated flue gas is also returned to the cell at this stage, which results an iterative problem.

The reacting part of the methane undergoes the total reforming reaction according to equation 4, and the reacting part of the carbon monoxide reacts according to the water-gas shift reaction (eqn. 5). From the calculations it is seen that there is enough water brought to cell so that it is not a limiting factor. In the next phase, air is brought to the cell and the anode and cathode reaction happens according to equation 3.

During constant U_a operation, U_a= 25%, meaning that 75% of the oxygen passes thorough the cell unreacted. The needed amount of air input to the cell is calculated again iteratively. As a result, the mole fraction composition of the exhaust is obtained. The exhaust temperature is assumed to be fixed according to Campanari (2000) on FC operation on constant U_a.

The validity of the calculation for constant U_a operation can be at least partially assessed by comparing the necessary amounts of air fed to the cell reported by Lemański and Badur (2004) in table 8 and based on own calculation. There is a linear relation between the fuel and air mass flows since constant air utilization operation is assumed. Moreover, it is clear that when zero units of fuel is input, no air is required. Therefore, the relation can be simply described with the $\dot{m}_a/\dot{m}_f$ ratio. For the experimental results, the slope of the closest fit line is 15.29 and for the own calculation, the ratio is 15.70. This yields a relative error of 2.70 % which can be regarded acceptable when considering the simplified calculation procedure.

For constant $\dot{m}_a$ partial load operation, the exhaust composition changes when the mass flow of fuel input changes. There is a linear dependency between the fuel input mass flow and the concentrations of different components of the exhaust. Therefore, linear correlations can be formed for calculation of the exhaust composition.

Based on data obtained by Lemański and Badur (2004) in tables 8 and 9, a linear correlation between the single cell electrical power output and fuel mass flow can also be formulated for both operating strategies. Correlations are also formed for the cell temperature with respect to the fuel mass flow based on the data, although not linear ones. These correlations and the measurement results by Lemański and Badur (2004) are graphed in the following chart. Figure 10a illustrates the constant U_a operation and figure 10b the constant $\dot{m}_a$ operation.

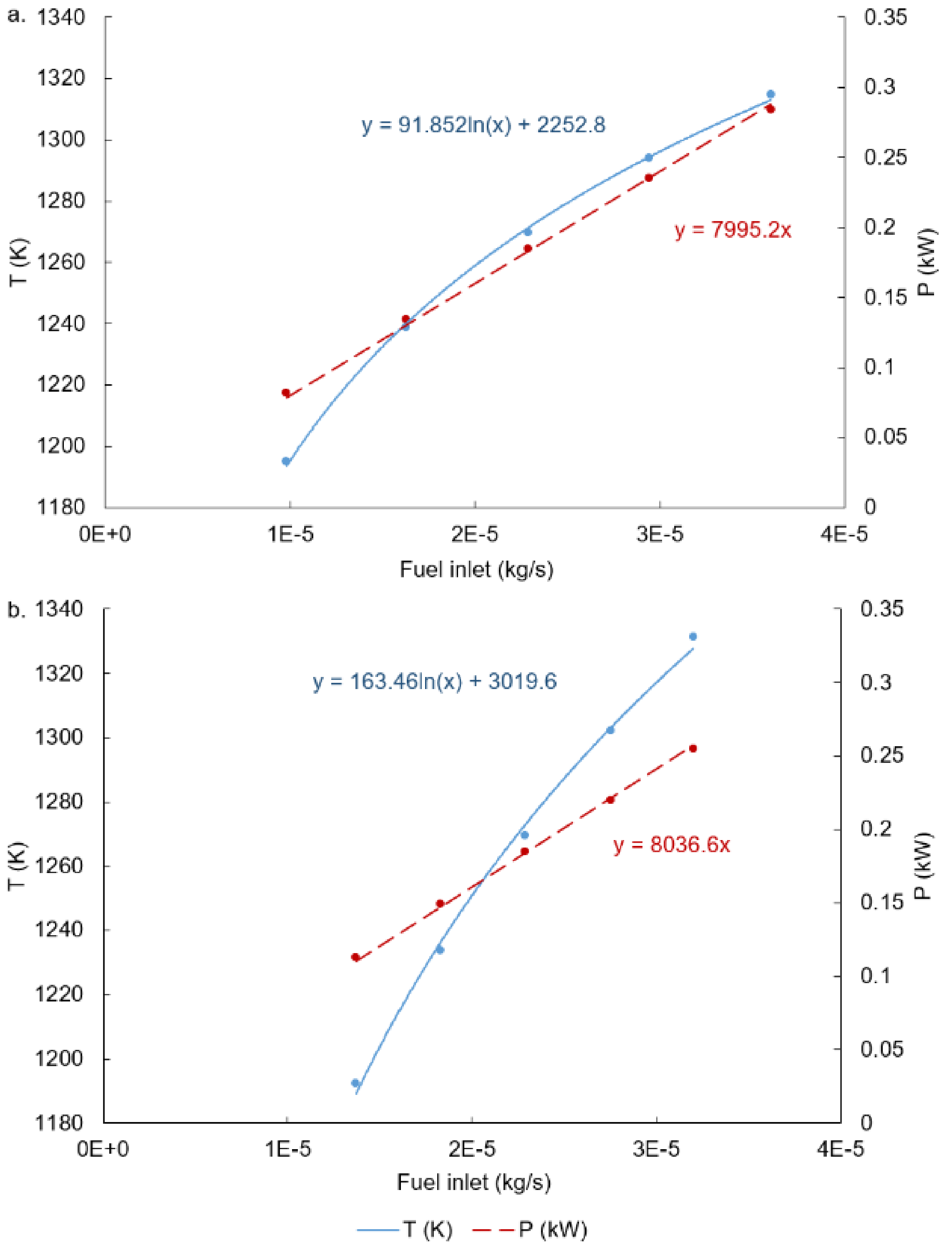

Figure 10. Curves fitted on Lemański and Badur (2004) measurements for a unit cell. a. Constant air utilization b. Constant air mass flow.

The correlations are fit for the data in Microsoft Excel and utilized in calculations. Moreover, correlations for the enthalpies as a function of the temperature were formed based on data form NIST-JANAF Thermochemical Tables (NIST Standard Reference Database 13, 1998).

5.3 Production and consumption profiles

The heat and power consumption curves are taken form the work of Gnes et al. (2020) who studied the electrical power and heat consumption on large cruise vessel on week-long cruise in both winter and summer conditions. During the cruise, the vessel visits several ports and there is variation in the heat and power loads according to the time of day and whether the ship is sailing or berthed. The electricity and heat consumption profiles for both winter and summer cruise can be read below form pictures 11a and 11b. The electrical consumption is the sum of propulsion and maneuvering propellers, other technical users, pumps, galley, lights, and air conditioning (only for the summer cruise). The electricity consumption varies between high level when sailing and lower level when at port. There is always some need for electricity, since e.g. lights and kitchen facilities are on all the time on the cruise.

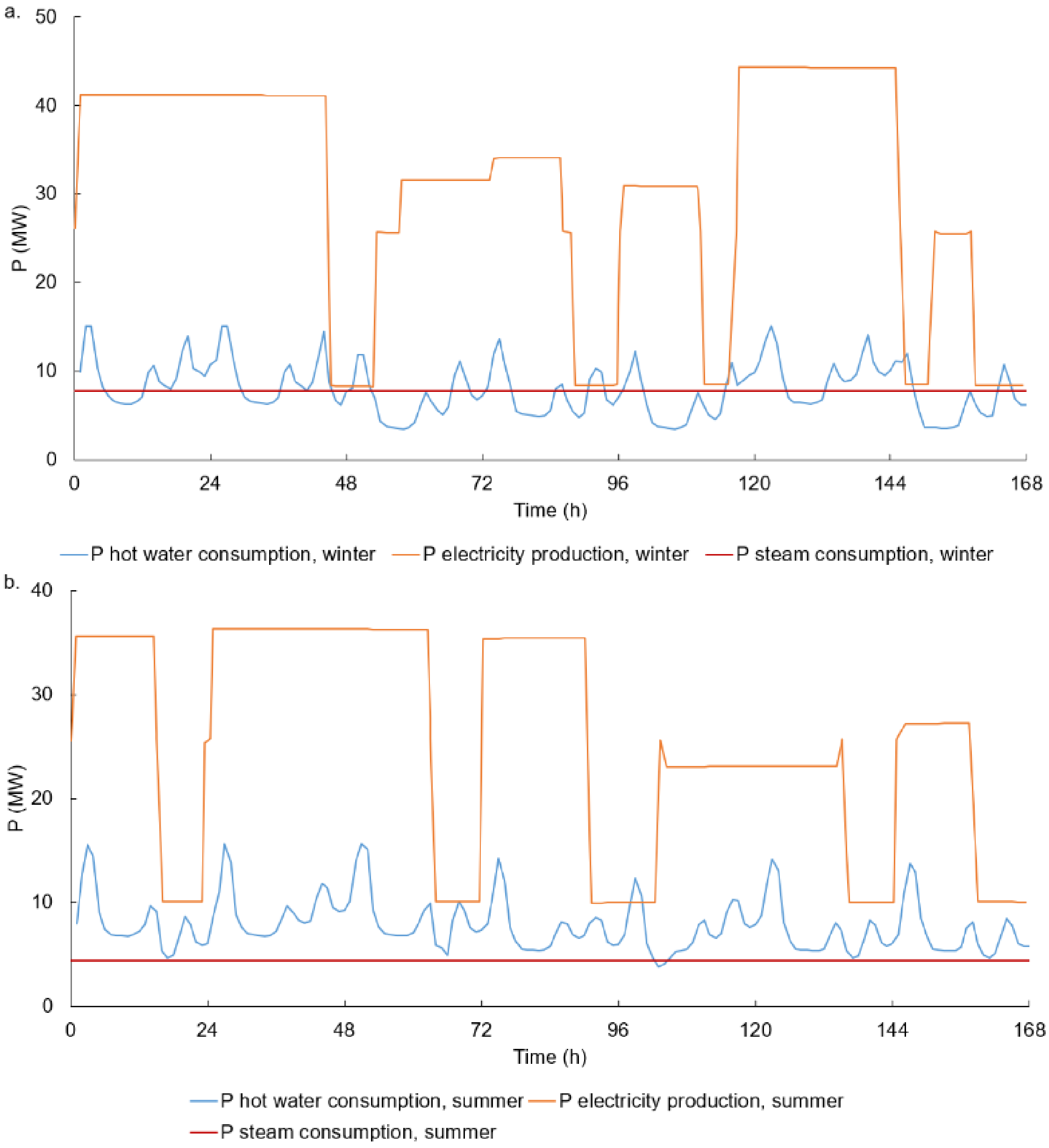

Figure 11. The electricity, steam, and hot water consumption on a cruise ship a. during the winter cruise, b. during the summer cruise. Adapted from Gnes et al. (2020).

The heat is consumed both as steam and hot water, and the exact consumers have been listed in the previous chapter in the table 6. As can be seen from the diagrams, the steam consumption is assumed to be constant throughout the cruise. Contrasting that, the hot water consumption varies noticeably with a somewhat consistent pattern. This consistent variation is most likely due to the passengers taking a shower either in morning or at night, water needs in the kitchen just before and after mealtimes etc. Moreover, during the winter cruise more electricity and heat is used than during the summer.

5.4 Waste heat recovery boiler model

The WHR boiler is modeled in a simplified manner by utilizing the logarithmic mean temperature difference (LMTD) method as described in the chapter 4.1. The boiler has of two separate water circuits for the steam and water heating. The boiler is assumed to be of water tube construction and that it operates in countercurrent manner, meaning that the hot exhaust coming in the boiler encounters first the evaporator, then economizer and lastly the water heating heat surface. This is illustrated in figure 12.

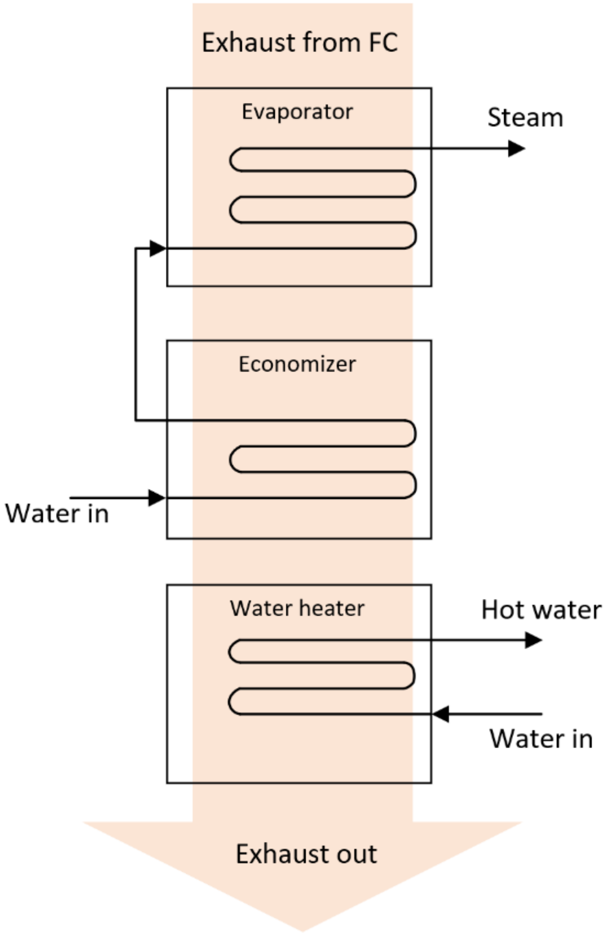

Figure 12. The considered WHR boiler heat surfaces.

In considered boiler configuration, the temperature differences are illustrated in the rough graph below. These temperature differences are needed in calculating the heat rate according to equation 9.

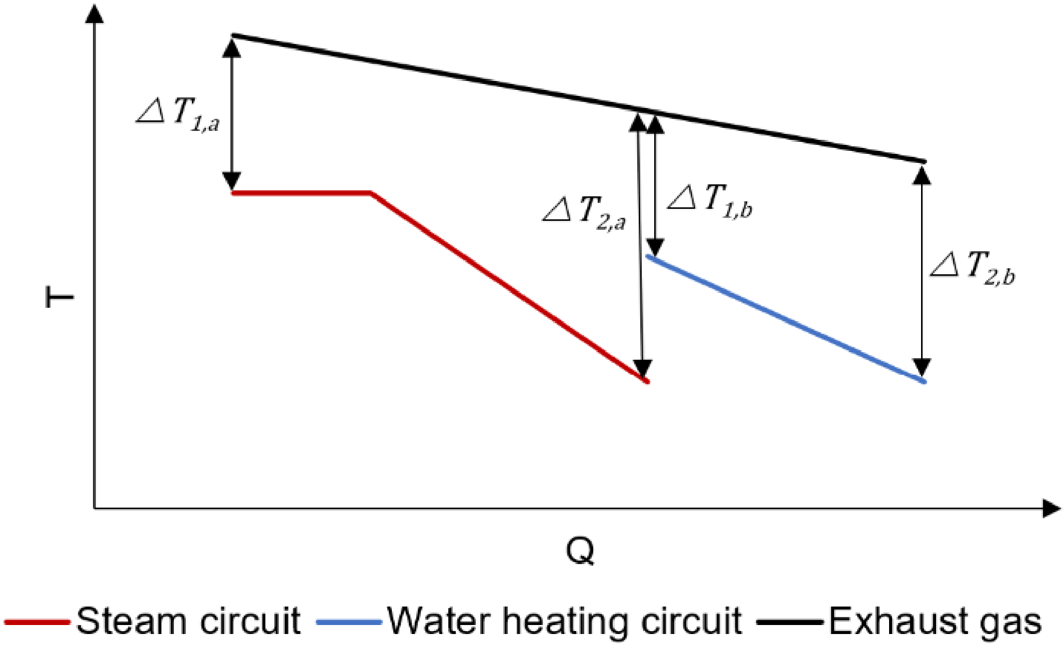

Figure 13. Temperature differences in the WHR boiler calculation.

It is worth noticing that the calculation must be carried out separately for the steam circuit and water heating circuit. For the steam circuit, ΔT_1 is the difference between the exhaust gas inlet temperature and the saturated steam temperature which is denoted by $\Delta T_{1,a}$ in the above graph. $\Delta T_{2,a}$ is the difference between exhaust gas temperature after the steam heating section and the feedwater temperature. For water heating circuit, the corresponding temperatures are also the exhaust gas temperature after the steam heating section and hot water outlet temperature for $\Delta T_{1,b}$ and exhaust gas outlet temperature and feedwater temperature for $\Delta T_{2,b}$.

After finding out ΔT_m according to the equation 10, the heat rate can be calculated from equation 9. The boiler heat surface area and U are constants depending on the construction of the boiler and they are defined separately for both steam and water heating circuits. For case study, the values in the following table are assumed.

Table 11. Assumed WHR boiler characteristics.

A_{steam}	600	m^2
$A_{water\ heating}$	218	m^2
$U_{steam} = U_{water\ heating}$	40	$W/m^2/K$

The enthalpy values for the exhaust components are found from the Janaf-NIST tables as previously explained and for water and steam enthalpies the Xsteam Excel functions are utilized. The described calculation method leads to iterative calculation since the exhaust intermediate and outlet temperatures that are not outright known are needed for finding out the LMTD. The iteration is carried out in Excel by using the Solver feature.

6. RESULTS AND DISCUSSION

The WHR system for a passenger ship is evaluated according to the method developed by Salonen (2020) described in the previous section. The source of waste heat is set to be the hot flue gases from FC stack. The heat consumers of a passenger or cruise ship were discussed above. These are heating of the cabins, kitchen, and laundry facilities, for example. Since there is a source and a need for waste heat, the theoretical potential for WHR exists, and the assessment can be continued to technical evaluation.

In this chapter, firstly the results from calculating the flue gas composition, mass flow and temperature variations are considered for both partial load operating strategies. Based on the flue gas properties, the hot water and steam production potential was evaluated, and the consumption and production profiles are compared below in the subchapter 6.2. Finally, it is qualitatively considered how suitable the waste heat recovery boiler is for FC marine applications and some remarks are given for what needs to be taken account in WHR boiler design.

6.1 Flue gas quality

The FC exhaust composition is calculated based on method described in the previous chapter. For the constant U_a operation the composition is presented in table 12. According to calculation, the biggest component of the exhaust is N_2 followed by residual O_2 and water. All hydrogen was consumed in the cell and carbon monoxide is existing only in trace amount.

Table 12. Calculated exhaust composition for constant air utilization U_a.

Component	mol-%
CH_4	0.2
CO_2	2.5
CO	0
H_2	0
H_2O	11.8
N_2	70.5
O_2	14.9

For the constant air flow operation, the exhaust gas composition varies when the cell load changes as explained in the previous chapter. In the following table, the exhaust composition is presented at two points for reference. It can be seen form the table that the amount of water in the exhaust increases with increasing air utilization. This is expected result since oxygen in air reacts to form water in the cell and the more air is utilized, the more water is formed. The inverse is true for the relative amount of oxygen.

Table 13. Calculated exhaust composition for constant $\dot{m}_a$ *at selected loads.*

Load (%)	50	100
Component (mol-%)		
CH_4	0.3	0.4
CO_2	3.1	4.2
CO	0	0.1
H_2	3.3	4.3
H_2O	11.9	15.7
N_2	67.2	63.7
O_2	14.2	11.7

For constant U_a operation, since the cell power production is directly depending on the fuel and air consumption, the mass flow of flue gas closely follows the electricity production curve. It was calculated that 2.01 kg/s exhaust was emitted per 1 MW produced electrical power. For constant $\dot{m}_a$ operation, there is less variation in the exhaust mass flow since the same amount of air is always input to the cell.

The exhaust mass flow with respect to time for both winter and summer cruise are presented in the figure 14. According to the calculation, the maximum mass flow of flue gas is 90 kg/s for winter and 74 kg/s for summer for constant U_a. The minimum mass flow rates within the consider electricity production data are 17 kg/s for the winter and 20 kg/s for the summer for constant U_a.

As can be seen from figure 14, there is considerably less variation the exhaust mass flow for constant $\dot{m}_a$ operation. For summer case, the maximum and minimum exhaust mass flow rates were 65 kg/s and 62 kg/s respectively. For the winter cruise, the maximum flowrate was 66 kg/s and the minimum 61 kg/s.

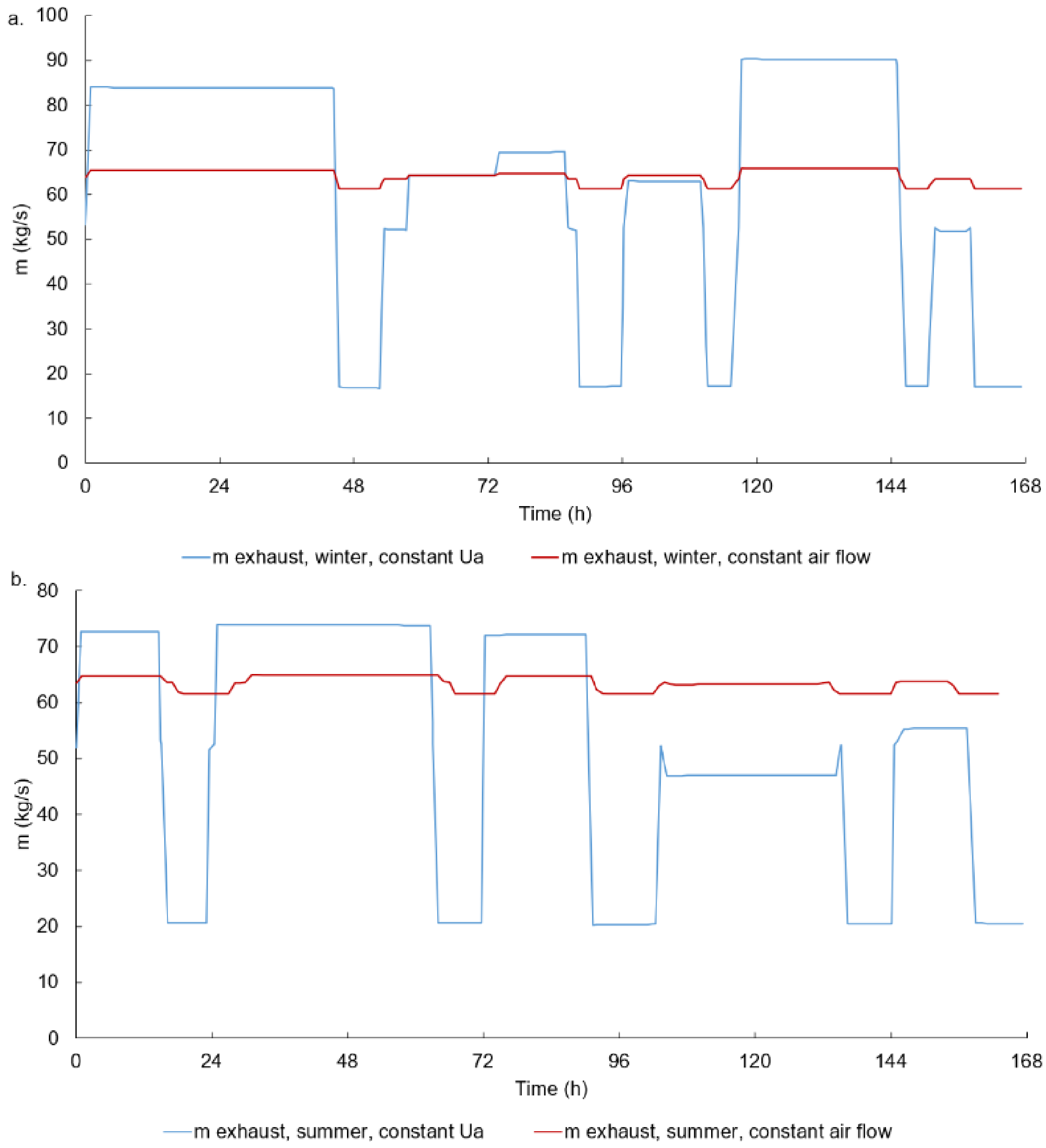

Figure 14. FC exhaust mass flows for both operating strategies a. during the winter cruise, b. during the summer cruise.

A correlation was developed for also the cell temperature according to the previous chapter. This was observed to not be a linear dependency, but in the considered range the behavior is approximately linear and thus lead to very similar curve shapes than for exhaust mass flow as can be seen from the picture 15. The constant U_a operation yields for less variation in the temperature compared to constant $\dot{m}_a$ operation as expected.

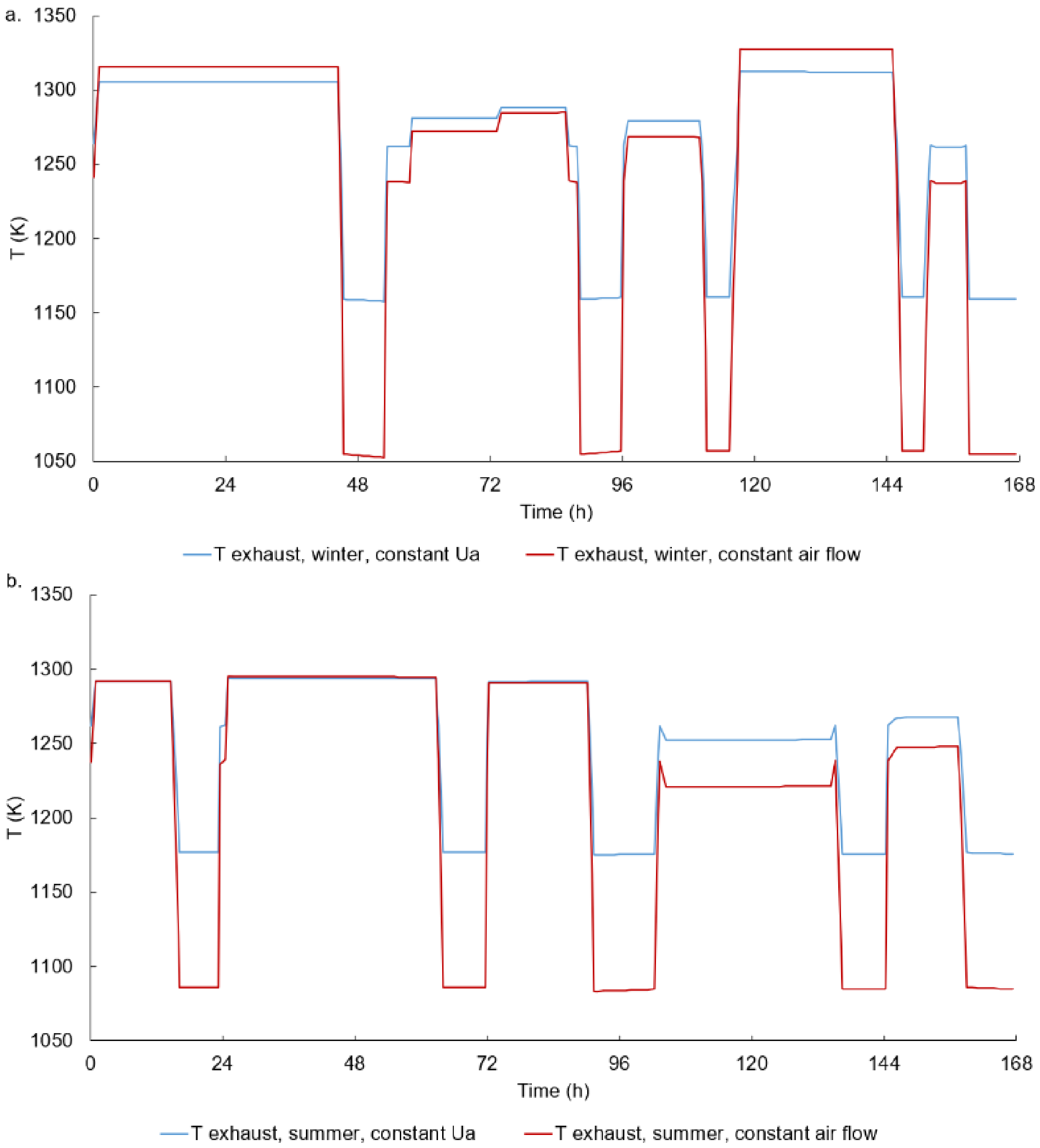

Figure 15. Exhaust temperature for both operating strategies a. during the winter cruise, b. during the summer cruise.

For constant U_a operation, the maximum exhaust temperature was calculated to be 1,294 K for summer and 1,312 K for the winter cruise. The minimum temperatures were 1,175 K for summer and 1,158 K for winter. For constant $\dot{m}_a$ operation, the maximum temperatures were 1,295 K and 1,328 K for the summer and winter cruise respectively, whereas the minimum temperatures were 1,083 K and 1,053 K for summer and winter cases.

6.2 Comparison of heat production and usage profiles

Based on the FC exhaust mass flow and temperature, the heat and steam production profiles are calculated according to the method described in chapter 5.4. The production profiles are evaluated separately both for the summer and winter cruise and both FC partial load operating strategies. It can be noted from all below graphs that the hot water and steam production closely follow the shape of the electrical demand curve especially for constant U_a.

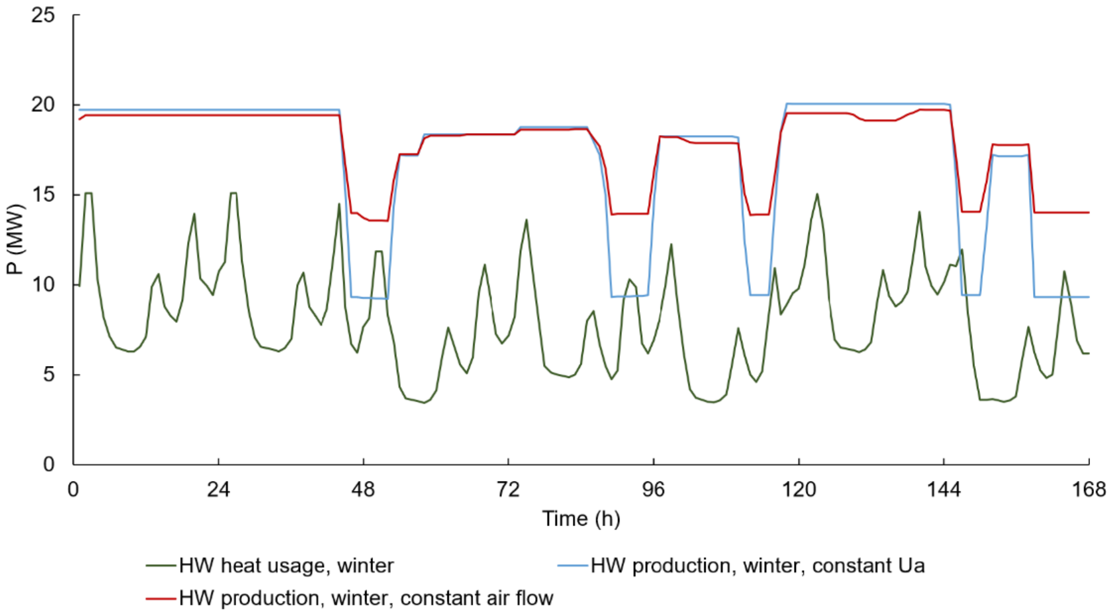

Figure 16. The hot water production and demand during the winter cruise.

As can be seen from the figure 16, the calculated hot water production is enough to cover the heated water demand at almost all times for constant U_a. Only relatively small amounts for short time periods are not covered. The coverage factor, meaning the percentage of the hot water consumption that was fulfilled, is calculated to be over 99 %. The remaining heating need could be easily countered with a heat storage, especially when it can be seen that there is a significant excess potential in the hot water production most of the time. For constant $\dot{m}_a$ case, the hot water demand is fully covered at all times and there is lots of excess production.

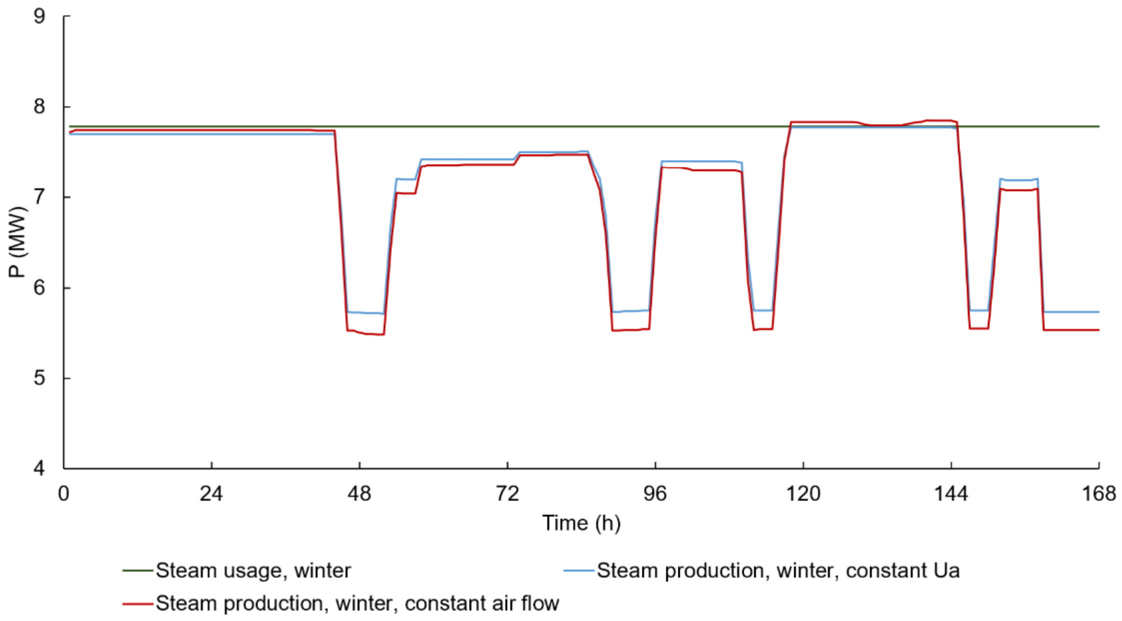

Figure 17. The steam production and demand during the winter cruise.

However, the vessel steam need is fulfilled only part time for both operating strategies during the winter cruise as figure 17 shows. Even though the steam need is not completely fulfilled, the coverage factor for the steam production on the winter cruise is 92 % for constant U_a and 91 % for constant $\dot{m}_a$ case. The boiler design could be optimized to produce more steam rather than hot water, or the steam could be produced by an auxiliary fired boiler. As explained above, there is a need for external steam production in the FC startups in any case.

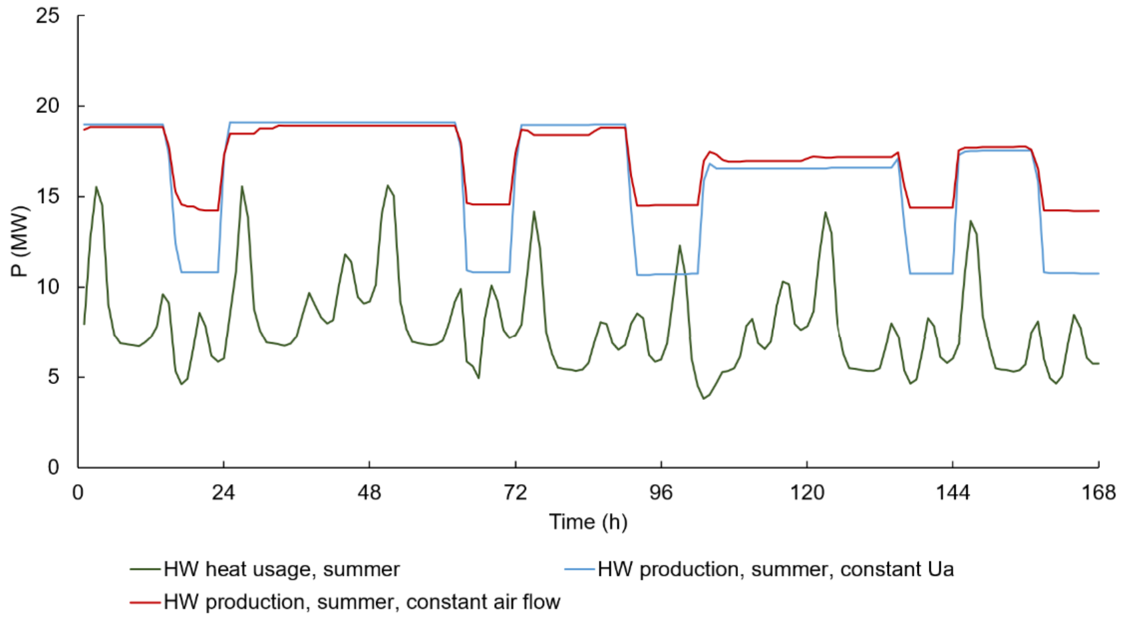

Figure 18. The hot water production and demand during the summer cruise.

During the summer, the hot water demand can be covered almost fully with lot of excess potential for constant U_a case as figure 18 illustrates. The coverage factor of the summer hot water production is 99 %. For constant $\dot{m}_a$ operation, the hot water need is again fully covered by the boiler output.

The steam demand is significantly lower during the summertime. The calculated steam production exceeds it at all times by a large margin for both operating strategies which can be seen form figure 19.

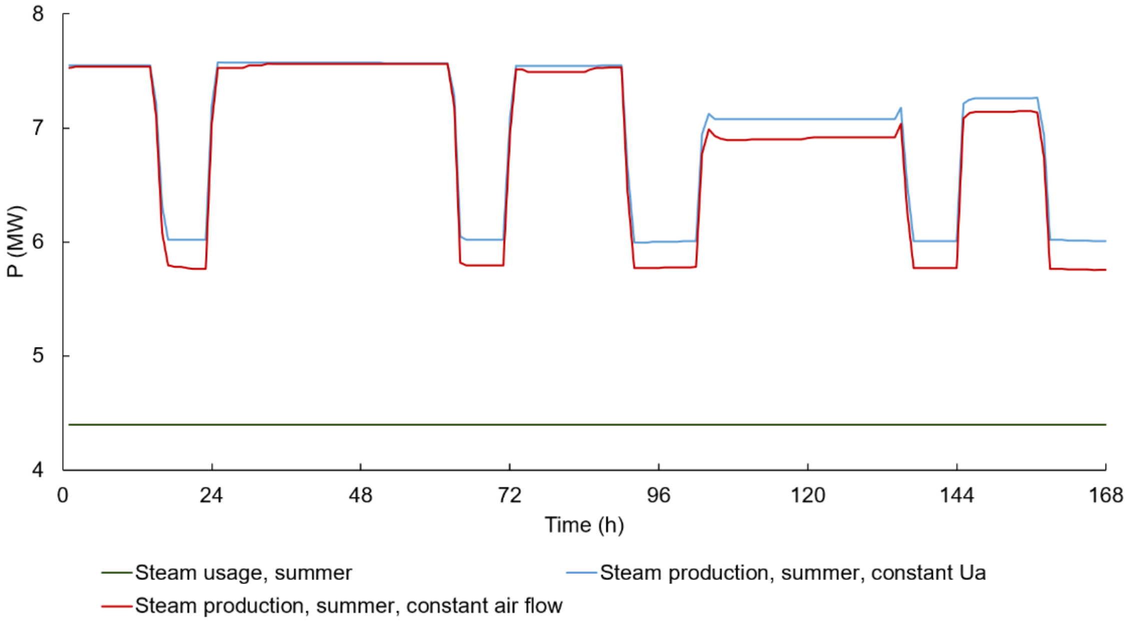

Figure 19. The steam production and steam demand with respect to time during the summer cruise.

Both of the two operational strategies show rather similar WHR potential, having a good coverage on the steam and heat needs for all considered situations. The most notable difference between strategies is that for constant $\dot{m}_a$, there is considerably less variation in the exhaust mass flow but more variation in the exhaust temperature. These effects somewhat counteract each other when it comes to WHR boiler output. The more steady exhaust mass flow can make the WHR boiler design easier, for example when considering the exhaust pressure drop on different loads. On the other hand, the ongoing variation of the exhaust composition makes the calculation of enthalpy more challenging. What is more, the constant $\dot{m}_a$ operation is charachteristic for FCs whereas constant U_a operation is more aligned with diesel engine load variation.

6.3 Waste heat boiler considerations

It can be seen from the results presented above that the chosen heat surface area for the WHR boiler might be too large to be techno-economically optimal solution since there is lot of excess production of steam and hot water for long periods of time. What is more, dividing the exhaust between two smaller WHR boilers could also be more realistic, especially since the exhaust mass flows are very high at times. Employing two smaller boilers could also help leveling the excess production to more accurately fit the consumption. Also, bypassing some of the exhaust, i.e. directing only part of the exhaust to the boiler, would be done in real operating situations with excess production or very high exhaust mass flow.

A temperature-heat (T-Q) diagram is drafted of the WHR boiler operation at one time point as an example. Figure 20 illustrates the situation at t = 80 h during summer cruise, operating under constant air utilization strategy. The cell load is 80 % of the maximum at considered timepoint. It can be seen from the T-Q diagram that the WHR boiler outlet temperature would be over 1,000 K at this situation. This means that there is still a large potential for WHR even after the boiler. This also explains why SOFCs are often coupled with gas turbines as was found in chapter 4.3.

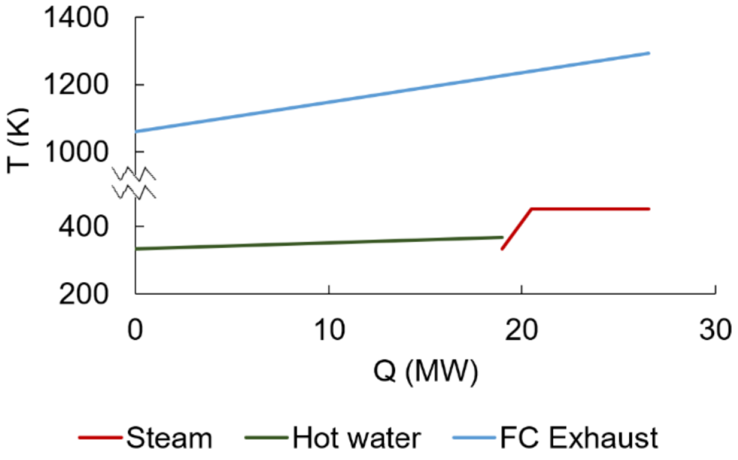

Figure 20. T-Q diagram of the WHR boiler, at t = 80 h in summer, constant air utilization.

To utilize more energy from the SOFC exhaust, the heat surface area of the WHR boiler could be expanded. However, as noted above, the steam and hot water prodcution is already almost fully covered with chosen boiler heat surface. Considering this, a steam turbine could have been added to the system after the WHR boiler. With also steam turbine producing electricity, the amount of SOFC stacks installed to the ship could have been lower.

Since the FC exhaust is very hot, it might be mixed with air berfore entering the WHR boiler to bring temperature down for the boiler material durability. This was not considered in the calculations. Moreover, in real-world systems the FC exhaust is preferably utilized in the fuel reformer and preheating the fuel and air incoming to the cell. This was also not taken into account in the case study. The space requirement for FC equipment compared to diesel engines and the additional weight was not considered in the vessel's power consumption.

Fouling is a significant problem in heat transfer equipment, including waste heat recovery boilers. Generally, the flue gas incoming to the WHR boiler might include ash particles and viscous and corrosive components. Ash and viscous components stick onto the boiler heat surfaces, making the heat transfer more inefficient and lowering the boiler output over time. Corrosive substances, such as sulfuric acid vapor, may cause erosion in the boiler tube banks and eventually weaken the pipe surface. (Li et al. 2017)

When comparing the fouling phenomena between FC exhaust and the more common flue gas sources, especially diesel engine exhaust, it can be said that the FC exhaust is cleaner and causes less fouling. One of the reasons for this is that the typical FC fuels contain very little ash. Moreover, since FC catalyst materials are intolerant of sulfur compounds, a sulfur removal system is installed if FC is to be operated on fuel containing sulfur. Therefore, there is no sulfur in the flue gas and the sulfur acid cannot form. (EG&G Technical Services, Inc. 2004) According to analyzed review articles (Lan & Tao 2014, Afif et al. 2016), no nitric acid is formed in the direct ammonia FCs that could hinder the waste heat recovery.

Considering specific FC types, PEM cells tolerate additionally carbon monoxide and halogens poorly so the concentration of these is tried to minimize even before entering the cell. For SOFC, the same is true for hydrogen chloride (HCl) which is also a corrosive substance. (EG&G Technical Services, Inc. 2004) When operating on hydrocarbon fuel, the exhaust can also contain unreacted hydrocarbons that could cause fouling.

The temperature levels of the FC exhaust are different for each cell type and can be considerably high, up to 1,300 K, for high temperature cells SOFC and MCFC. The exhaust temperature varies as the function of cell load. The magnitude of temperature variation depends on the partial load operation strategy. If the air utilization factor U_a is kept constant, there is less variation compared to constant air flow operation since there will be less air input to cell. In the case study evaluation, the temperature variation range was around 150 K despite rather big fluctuation in exhaust mass flow.

It can also be noted that the FC system might need an auxiliary boiler for both heating the cell stack and producing steam for the cell startup. The cell humidification is especially important for the PEMFC systems since high water content is needed in the electrolyte for ionic conductivity (EG&G Technical Services, Inc. 2004).

Based on the literature study in the chapter 2.2, the flue gas pressure coming from the cell can range from atmospheric up to 10 bar, not taking into account the possible pressure losses in the ducting. This is a quite wide range, but the individual FC system is designed for a certain pressure level meaning that the pressure variations within one system should not be large.

7. CONCLUSIONS

In this thesis, the waste heat recovery from fuel cell exhaust in ships was considered. Firstly, the potential for FC-WHR was mapped by combining various estimates of the future development of FCs among marine power sources. The fuel mix in the marine sector is currently starting to undergo a significant change due to increasingly stringent environmental regulations. Currently, the marine sector is almost exclusively fueled with oil-based fuels. Most sources agree that there will be a transition period with fuels containing some carbon, such as methanol, LNG, or ammonia, with the ultimate goal being fully carbon-free fuels such as green hydrogen. Whether the FCs will make a breakthrough in the marine sector depends on the availability of green hydrogen produced with renewable electricity, and the spreading of hydrogen refueling infrastructure. The evaluated sources place this era of potentially fully carbon-free shipping after 2050.

A literature study revealed that the FC types that are consider most suitable for marine use are PEM, SOFC, and MCFC cells. The SOFC and MCFC are so-called high temperature cells that produce hot exhaust at a temperature around 1,000 °C. This high temperature offers a lot of potential for waste heat recovery, but on the other hand, sets limitations for boiler materials. PEM cell is principally a low-temperature cell, but high-temperature PEM has been developed (temperature up to 220 °C). All cell types use H_2 as their fuel, but the high temperature cells can also internally reform other fuels containing hydrogen, such as natural gas or ammonia.

The FCs will compete in the marine power market against internal combustion engines using the same fuels. The ICEs are a far more established technology in ships, but the FCs have several unique advantages. These are a high efficiency even with partial loads, low emissions, modularity, durability, and low noise.

The FC-WHR system consists of the FC stack, fuel pretreatment (such as sulfur removal) and power conversion unit. Fuel pre-reformers are also often part of the system. Air and fuel, often pressurized, are input to the cell. An afterburner might be utilized for unburned fuel in the exhaust gas ducting after the cell. The pre-reformer and input fuel and air can be heated with FC exhaust. A WHR boiler can be used to capture further energy form the hot exhaust. An auxiliary fired boiler might be needed in the system for heating during startup and providing extra steam for steam reforming of fuel.

The most researched WHR options for FC systems are gas turbine or ORC heat recovery cycle, but there are no principal obstacles for WHR with finned tube boilers. The quality of exhaust is cleaner than diesel engine exhaust, for reference. For example, the FCs are easily damaged by sulfur compounds, so the sulfur is removed from the fuel before entering the cell stack. However, the exhaust temperatures might be considerably high for high-temperature cells which places limitations for the boiler material selection. This can be countered by mixing air with the hot exhaust.

The mass flow of FC exhaust varies depending on the FC load and more precisely according to the partial load operating strategy that the cell utilizes. From the work of Lemański and Badur (2004) it was estimated that a SOFC cell stack with constant air utilization produces 2.01 kg/s exhaust per 1 MW produced electrical power. With constant air flow operating strategy, the FC exhaust composition varies when the cell load changes. The FC exhaust consist of H_2O, O_2, N_2 and remnants of H_2 when the cell is fueled with pure hydrogen. With hydrocarbon fuels, CO_2 and CO are also emitted.

Finally, a case study was carried out on whether the steam and heated water needs of a large cruise ship can be fulfilled with the exhaust form a fuel cell stack. The considered vessel was a large cruise ship, which electricity and heat consumption were modeled after Gnes et al. (2020) during both winter and summer cruises. It was assumed that all of the electricity consumed in the ship was produced with SOFC. The SOFC exhaust composition, mass flow and temperature were modeled based on data by Lemański and Badur (2004) for both constant air utilization and constant air flow operating strategies. Steam and hot water were assumed to be produced by a WHR boiler with set overall heat transfer coefficient and heat surface.

As the result of modeling, it was found out that the FC exhaust mass flow follows closely the FC electricity production for constant air utilization case. For constant air mass flow, the exhaust flow is steadier but there is larger variation in the exhaust temperature. Based on calculations it was obtained that the hot water and steam consumption of the vessel could be covered by the considered exhaust gas boiler almost fully during the summer, with significant excess production most of the time with constant U_a. With constant $\dot{m}_a$, all of the consumption was covered during summer.

During the winter cruise, the steam production is lacking with respect to the steam consumption for both operating strategies. The hot water demand is almost fully satisfied with constant U_a and fully covered with constant $\dot{m}_a$ operation. The coverage factors of all considered cases were well over 90 %. These shortcomings could be countered with a reconfiguration of the exhaust gas boiler, a heat storage, or an auxiliary fired boiler.

However, it is necessary to bear in mind that the calculation was conducted in a simplified manner and therefore the results are not to be taken as exact. Moreover, the assumed

44 MW cell stack has significantly larger power capacity than any of the existing demonstration FC vessels. There is also a lack of tools for modeling the FC transient phenomena in load-change situations in a simplified way and that is reflected also on the results of this thesis. The purpose of the calculations was to gain understanding of the possible exhaust mass flow and temperature patterns rather than to extensively model the complicated electro-chemical phenomena in the FC.

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