Energy demand of a fuel cell-driven cruise ship

Analysis and improved prediction method of the operational power variation under different loading and environmental conditions

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TU Delft

DAMEN

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by

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TU Delft

Preface

Nowadays, everyone are talking about the energy transition and the way how to transform the maritime industry into a more sustainable future. Fuel cells are a promising alternative to replace fossil-fuel energy sources. However, many questions must be solved to install and operate those systems. In that process, I could take one step forward with the focus on the dynamic energy demand of an expedition cruise ship.

This thesis has been written as part of the Master of Science degree Marine Technology at the Delft University of Technology. The graduation project was performed in collaboration with DAMEN Shipyards over the last nine months under supervision of Dr.Ir.R.G. Hekkenberg from the Ship Design, Production & Operation section within the Maritime and Transport Technology department and Ing.R.L.J. van der Kolk from the design & proposal department at Damen Shipyards. In addition, Dr.Ir.A.A. Kana (Ship Design, Production & Operation) and Dr.Ir.Y.Pang (Transport Engineering and Logistics) joined as committee member from the Maritime and Transport Technology department (TU Delft) as well.

First of all, I would like to thank my supervisors for their support throughout the project. Robert Hekkenberg, I really appreciated your feedback, sharing ideas in our discussions and guidance, which I could use to improve my research project. With your comments, I could enhance my academic and scientific work.
Secondly, Richard van der Kolk, as my daily supervisor at DAMEN, I would like to express my gratitude for your support, believing in me and criticising my work. Without your advices, I would not get to where I am now. You offered further technical insights or other contacts as far as necessary and brought me back on track by keeping the bigger picture, which not only improved the thesis. In our discussions beyond the topic, you gave me valuable insights and inspiration for my upcoming professional career as well. - Dankjewel!

Besides my graduation committee, special thanks to Robin Brouwer, who gave me the opportunity to perform this research in cooperation with DAMEN Shipyards. Next to the whole D&P group, I would like to thank you all for your discussions and sharing knowledge, which greatly contributed to my work. Even the challenging time within the cruise sector did not halt you to support me with this project. In addition, I would like to show my appreciation to all other colleagues within other departments, Hans van Gemeren, Erik-Jan Boonen, Edward Sciberras, Tobias Schaap and many others, thank you for your feedback and time. - Thank you!

Especially within the time of the global COVID-19 pandemic, many restrictions and changes in our daily life, I would like to thank all my friends in Delft and anywhere else for their mental support, humour, drinks and dinners to keep the motivation at the highest level even if social contacts were reduced to a minimum. You made my studies more joyful and a great experience. - Grazie, Sağol, ευχαριστώ, Danke, Gracias, Dankje, Merci and thank you!

In the end, I would particularly like to thank my parents and sister for the support throughout my academic career. *Ich danke euch für die Unterstützung in all den Schritten der vergangenen Jahre, wohin ich auch gehen wollte.* - Danke von Herzen!

Finally, I am looking forward to my professional career and hope to see each other again not only in online meetings behind the screen. Now enjoy the thesis.

Delft, September 2020
Clemens Boertz

Abstract

The shipping industry contributes significantly to the global greenhouse gas emissions due to the use of cheap fossil fuels. The booming cruise ship industry is forced to reduce the emitted greenhouse gases and emission of carbon dioxide to be able to access remote areas with higher restrictions and to comply with upcoming regulations.
Fuel cells are a promising alternative to conventional diesel-powered systems to reduce the emissions. Next to the physical implementation, fuel cells have additional operational limiting factors, which have to be matched with the power demand. Compared to conventional combustion engines, longer start-up times and a lower dynamic response ability can be expected.

Typically, the energy demand is estimated for all electric power consumers with the load balance approach in the conceptual design phase. The actual power demand is calculated based on the absorbed power and additional predefined factors for specific conditions. This conflicts with the dynamic power demand of cruise ships in various operational conditions.

This thesis discusses the used bottom-up approach for such an improved prediction of the total power and energy demand of an expedition cruise vessel for the early design stages. The focus is on identifying the peak loads and load changes under consideration of the passenger behaviour, environmental and operational conditions on the basis of predefined typical days of operations.
The dynamic power demand is predicted for the different propulsion, auxiliary and hotel systems, as identified and grouped in the system breakdown. This is done by using separate prediction models for the defined groups of systems and electrical components. The required energy per day is calculated directly from a time-domain integration of the power prediction. The demand for a whole operational profile is obtained by adding different typical operational days.

The highest power is required by the main propulsion in sailing mode. However, expedition cruise ships often operate at lower speeds below the design conditions resulting in a considerably lower load. The maximum load of the hotel systems always appears in the morning, when all passengers are on board and several components ramp up from the lower night mode.
Comparing the total power demand shows that the load changes caused by the hotel systems gets smaller in relation to the changes within the propulsion system as soon as the speed varies. In port condition, the relatively constant auxiliary load, including the hotel systems, remains and describes the baseload throughout the day.

Generally, the dynamic prediction clearly shows the potential to better estimate the required power and energy, if varying operational conditions are considered. The method supports a well-founded decision on the power supply configuration, if it comes to hybrid systems including different power supply components and their operational characteristics.
A multi-criteria decision analysis on the power supply side can build up on the required energy and power demand of a certain part load. The required fuel cell size can be quantified based on the estimated maximal load and the fuel tanks by considering the predicted energy demand of the specific group of systems.

Contents

List of Abbreviations

ABS	American Bureau of Shipping
AC	Air Conditioning
AECO	Arctic Expedition Cruise Operators
AHU	Air Handling Unit
AIS	Automatic Identification System
ALB	Available Lower Berth
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.
ATA	Actual Time of Arrival
ATD	Actual Time of Departure
Bft	Beaufort
BOP	Balance of Plant Component
CAPEX	Capital Expenditures
CLIA	Cruise Lines International Association
CO	Carbon Monooxid
CO_2	Carbon Dioxide
COP	Coefficient of Performance
DE	Diesel Engine
DEM	Dynamic Energy Modelling
DG	Diesel Genset
DNV GL	Det Norske Veritas Germanischer Lloyd
ECA	Emission Control Areas
ECR	Engine Control Room
EEDI	Energy Efficiency Design Index
ETO	Energy Transition Outlook
FA	Fresh Air
FC	Fuel Cell
FCU	Fan Coil Unit
FSF	Floor Space Factor
FW	Fresh water
GHG	Greenhouse Gas
GHS	Globally Harmonized System of Classification and Labelling of Chemicals
GT	Gross Tonnage

H_2	Hydrogen
HFO	Heavy Fuel Oil
HT-PEMFC	High Temperature-Proton Exchange Membrane Fuel Cell
HVAC	Heating, Ventilation and Air Conditioning
IAATO	International Association of Antarctica Tour Operators
IAMCS	Integrated Alarm, Monitoring and Control System
ICE	Internal Combustion Engine
IGF	International Gas Fuel
IMO	International Maritime Organization
ISO	International Organization for Standardization
LB	Load Balance
LC	Load Change
LNG	Liquefied Natural Gas
LT-PEMFC	Low Temperature-Proton Exchange Membrane Fuel Cell
MCFC	Molten Carbonate Fuel Cell
MCR	Maximum Continuous Rating
MeOH	Methanol (abbr.), chemical formula CH_3OH
MEPC	Marine Environment Protection Committee
MGO	Marine Gas Oil
MLC	Maritime Labour Convention
MVZ	Main Vertical Zone
NH_3	Ammonia
NO_x	Nitrogen Oxides
OC	Occupancy Rate
OPEX	Operational Expenditures
PAX	Passenger
PEMFC	Proton Exchange Membrane Fuel Cell
PM	Particulate Matter
POB	Number of person on board, usually crew and passengers
PW	Potable Water
ROM	Rough Order of Magnitude
SCR	Selective Catalytic Reduction
SO_x	Sulfur Oxides
SOFC	Solid Oxide Fuel Cell
SOLAS	International Convention for the Safety of Life at Sea
SRtP	Safe Return To Port
SVM	support vector machine

SW	Sea Water
TDO	Typical Day of Operation
TRL	Technology Readiness Level
UPS	Uninterruptible Power Supply

List of Symbols

$(1 + k_1)$	From factor of hull; [-]
A	Area of room or space; [m^2]
B	Beam of ship; [m]
F_{Wind}	Wind force; [N]
K_{occ}	Actual Occupancy Rate in Room; [-]
LF	Load Factor
L_{Int}	Light intensity; [W/m^2]
L_{OA}	Length over all; [m]
L_{PP}	Length between perpendiculars; [m]
N_{Crew}	Number of crew members on board; [Pers.]
OC	Occupancy Rate; [-]
PAX_{ALB}	Number of passenger based on available lower berths; [Pers.]
POA	Number of person on board, usually crew and passengers; [Pers.]
P_a	Power abosrbed from net; power demand divided by efficiency; [kW]
$P_{BW,inst}$	Installed power bow thrusters; [W]
P_B	Brake power; [W]
P_{DEquip}	Power deck equipment and hull openings; [W]
P_D	Propulsion power; [W]
P_E	Effective towing power; [W]
P_{Galley}	Power galley; [W]
$P_{Laundry}$	Power laundry; [W]
P_{Light}	Power lighting; [W]
$P_{Survival}$	Power survival systems; [W]
P_{Water}	Power water supply and handling systems; [W]
$P_{support}$	Power propulsion support systems; [W]
R_{APP}	Appendage resistance; [N]
R_A	Model-ship correlation resistance; [N]
R_B	Additional pressure resistance of bulbous bow near water surface; [N]
R_F	Frictional resistance according to ITTC formula; [N]
R_{TR}	Additional pressure resistance due to transom immersion; [N]
R_T	Total resistance of ship; [N]
R_W	Wave resistance; [N]
T_D	Design draft of ship; [m]
Δ	Displacement of vessel; [t]
η_D	Propulsive efficiency; [-]

η_{TRM}	Transmission efficiency; [-]
∇	Displaced underwater volume of vessel; [m^3]
ρ_{Air}	Air density; *Defined as: 1.2kg/m^3*
ρ_{Room}	Passenger density in room; [Pers./m^2]
ρ_{SW}	Sea water density; *Defined as: 1.025t/m^3*
c_{Prop}	Proportionality factor for propeller law; [-]
$c_{p,a}$	Specific heat at constant pressure of dry air; *Defined as: 1.004kJ/(kg·K)*
$c_{p,v}$	Specific heat at constant pressure of water vapour; *Defined as: 1.83kJ/(kg·K)*
c	Index *c* used for operational condition
gt	Gross Tonnage; [gt]
g	Gravitational constant; *Defined as: 9.81m/s^2*
h_{max}	Predicted height of highest full deck of vessel; [m]
i	Index *i* used for time step; *in dyn. pred. model:* time steps of 30 min.
j	Index *j* used for areas as listed in table A.1
k_n	Number in Service, or number of actual running components
k_s	Simultaneity Factor
k_u	Utilization Factor
k	Index *k* used for different minor systems as defined in section 7.3.4
n_{cabins}	Numer of passenger cabins; [-]
n_{occCab}	Number of occupied passenger cabins; [-]
r_W	Evaporation of water; *Defined as: 2500kJ/kg*
v_s	Design speed of vessel; [m/s]

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Introduction

The global shipping industry contributes significantly to the global greenhouse gas emissions due to the use of cheap high sulphur fuel oils. The International Maritime Organization (IMO) is developing further regulations towards a greenhouse gas emission reduction by 50% until 2050. Different levels of ambition are defined to further strengthen the Energy Efficiency Design Index (EEDI) next to a declination of the carbon intensity of international shipping and overcoming the peak of the greenhouse gas (GHG) emissions.[45]
The shipping industry is confronted with the exploration of new fuel options and reduction of the overall consumption. The new IMO regulations and an increasing oil price bring the focus of developments even more towards improving the fuel efficiency and alternative power plant designs. The vessels can run more efficiently with optimized configurations. Speed reduction and additional exhaust gas treatment, like scrubbers, can reduce the emissions in operation as well. More effort, developments and implementation of further policies have to be made in order to promote the use of alternative fuels and achieving the goals of the IMO [28].

The cruise ship industry is forced to reduce the carbon footprint to be able to access remote areas with higher restrictions and as part of their marketing strategy towards more sustainability. Currently, liquefied natural gas (LNG) is used for some new vessels designed for cruise destinations, like Western Europe, where the infrastructure for bunkering is provided. Alternatively, corporations between shipping and bigger oil and gas companies trying to establish the required LNG bunkering network [16]. However, the majority of ships under construction, including smaller expedition vessels, still use the combination of conventional fuels together with scrubbers or selective catalytic reduction (SCR) systems in order to eliminate harmful exhaust gases. The additional use of batteries can let the engines constantly run at their optimal design condition by providing additional electric power in peak loads [41]. Nevertheless, the use of fossil fuels like heavy fuel oil (HFO) and marine gas oil (MGO) together with conventional engine arrangements is still a cheaper energy source. The competition and price fights within the market do not allow a costly investigation of more sustainable solutions, if it is not legally required. As a result, the only argument for higher investments of cruise lines into sustainable technologies remains an improved public image or compliance with potentially tougher regulations.

Meanwhile, research projects in cooperation of universities, shipyards and other stakeholders address the use of fuel cells with the purpose of eliminating all greenhouse gases, while reducing the high development costs. The storage of pure liquid hydrogen, at a temperature of -253°C [86] is an important challenge to overcome. Other fuels have to be reformed or pressurized. In general, the volumetric and gravimetric energy densities are lower than those of conventional fuels, which results in larger storage requirements on board when keeping the same operating range and speed. Accordingly, shipping companies are confronted with higher building costs together with the loss of available spaces for the crew or even the passengers. Smaller profitable hotel area extends the payback period of the project even more.

Next to the physical implementation, fuel cells have additional operational limiting factors, which have to be matched with the power demand. Compared to conventional combustion engines, longer start-up times can be expected as well as a lower dynamic response ability. This conflicts with the dynamic power demand of cruise ships in various operational condition [11]. Thus, a detailed analysis of the ship's energy use is required, to keep the size and cost of the fuel cell system as low as possible and to prevent undesirable mismatches between the dynamics of energy supply and demand.
Typically, the energy demand is estimated for all electric power consumers with the load balance approach in the conceptual design phase. The actual power demand is calculated based on the absorbed power and additional predefined factors for specific conditions. This conflicts with the dynamic power demand of cruise ships in various operational conditions.

The thesis presents a detailed breakdown of the different electrical consumers and subsystems, grouped in propulsion, auxiliary and hotel systems. On the basis of predefined typical days of operations (TDO), the operational conditions, passenger behaviour and environmental conditions are described. The resulting power prediction for every system focuses on the individual load behaviour. The combined energy demand of the typical operational days finally leads to the total energy demand of the entire operational profile. Driving factors of the actual load and additional peak loads can be assessed. The results of the power and energy analysis are finally related to the fuel cell characteristics by identifying more favourable systems to be powered by a fuel cell system. This brings up the title of the thesis project as follows.

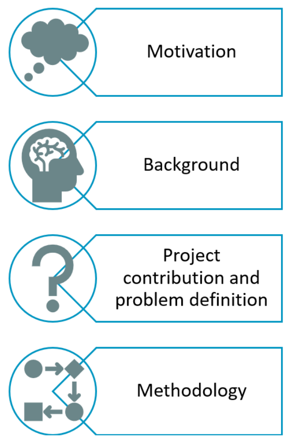
> *Energy demand of a fuel cell-driven cruise ship*
> *- Analysis and improved prediction method of the operational power variation under different loading and environmental conditions*

The project is executed in cooperation with the Cruise department of the DAMEN shipyards in Rotterdam and the Delft University of Technology in order to obtain the Master of Science degree in the field of Marine Technology. The duration is over nine months with beginning in January 2020.

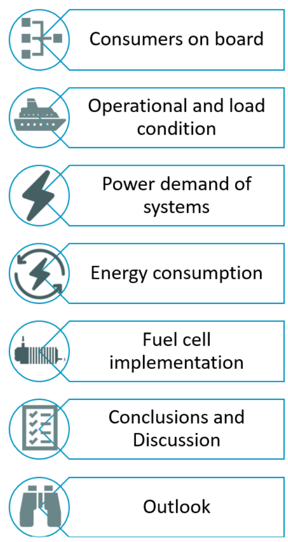
Thesis structure

In the first chapter more elaborated background information are provided about the climate debate as motivation of the application of fuel cells in the cruise industry. New technologies are arising the question about the societal acceptance and ethical implications as well.

Chapter 2 gives further background information. The fuel cell technology with the different fuel types and fuel cell options are described as conceptual framework. The differences of the operational characteristics are important to consider in relation to a conventional power plant design. Furthermore, the financial aspect is briefly mentioned as well, as a basis for further economic decisions of the cruise lines later on. In addition, an overview of the dynamic energy demand of a cruise ship is included considering. The characteristics of the energy demand of the cruise ships are elaborated and its influencing parameters. Previous prediction models and findings are included as relevant theory and concepts for dynamic modelling of energy flows.
The following chapter 3 starts with a gap analysis as a starting point of the project. Afterwards, the problem definition and the main research questions are described. The description of the methodology follows in chapter 4. The different steps of the approach are stated as structure of the project next to the scope and expected results.



Chapter 5 starts with the system breakdown. The different electrical consumers on board are grouped within subsystems as part of the propulsion, auxiliary or hotel systems. The operational conditions are described in chapter 6 also referred to as influencing factors.
This is the basis for the power demand prediction per system in chapter 7. Every system is analysed by its influencing factors to point out the maximum power demand, the daily variations and additional peak loads. The time-dependent load behaviour during the different operational days is the basis for the daily energy demand in the different operational conditions in chapter 8.
The following chapter 9 elaborates on the fuel cell implementation. The possibilities and limits of an efficient and reliable system can be demonstrated based on the analysed power and energy demand of certain systems. The study is concluded in chapter 10 by referring back to the stated research questions including the discussion. Finally, recommendations for further research are discussed briefly in the last chapter 11.



Chapter 1

Motivation

The world is confronted by the global climate change which requires sustainable solutions by satisfying the world energy demand. The following chapter 1.1 describes the motivation of the current research project based on upcoming policies and agreements within the shipping sector and cruise industry. New technologies, like fuel cell systems, are always coming with societal debates about the acceptance of certain risks as well. Those ethical implications are elaborated in the second section 1.2.

1.1 Climate Debate

The impact of extreme weather conditions is increasing worldwide because of the climate change. Consequently, the Paris Agreement in 2015 agreed on limiting the global average temperature to 2°C above pre-industrial levels. Further effort should be spent on reducing it to 1.5°C. Thus, the impact of extreme weather conditions on the population, economy and natural life should be reduced. [84]
However, other studies, like the Energy Transition Outlook (ETO) model from the classification society Det Norske Veritas Germanischer Lloyd (DNV GL) [27], are already predicting an increase of more than 2°C until the end of the century. Even if the models are predicting different results and developments over the years, the use of sustainable resources is an essential part to comply with the agreement. Therefore, a significant reduction of greenhouse gases like carbon dioxide (CO_2) and methane (CH_4) is necessary.

As a response to the Paris Agreement on climate change, the IMO defined the strategy on the reduction of emitted greenhouse gases and emission of carbon dioxide from ships in April 2018. Following this, the CO_2 emission per transport work should be reduced across international shipping by at least 40% on average by 2030 with further efforts towards 70% in 2050 in comparison to 2008. The greenhouse gas emissions should peak soon, together with a reduction by at least 50% in 2050 compared to 2018, as stated in the resolution of the Marine Environment Protection Committee (MEPC) of the IMO [46].

In addition, the Cruise Lines International Association (CLIA) announced in December 2018 their goal of reducing the rate of carbon emissions by 40% in 2030 [19] motivated by destinations, which are setting regulations for a more environmentally friendly shipping industry. For example Norway, as a first country, recently declared the first area in the fjords to be free of any greenhouse emission in 2026 [29]. This popular destination within the cruise market will be only accessible with the use of batteries or alternative fuels, like hydrogen, without any greenhouse gas emissions.

Similar developments and policies can be observed in other markets as well, which can be compared to the energy transition within shipping. The automobile industry is the frontrunner within the transport sector by eliminating greenhouse gases by using batteries. However, in the near future it will not be a feasible option for larger vessels due to the low volumetric energy density and limited options of recharging. Alternatively, different hybrid concepts or the use of fuels with less emitted greenhouse gases are currently being used and further developed in new projects, like LNG.
This marks only the first step within the energy transition and is mostly driven by the new regulations for the Emission Control Areas (ECA). The emission of sulfur oxides (SO_x) and particulate matter (PM) can be eliminated, by using LNG. nitrogen oxides (NO_x) can be reduced by around 80-90% and carbon dioxide (CO_2) by 20%. This

comes together with the risk of a higher methane slip, which has 25 times higher impact on the climate change than CO_2. [21]

Fuel cells are a promising alternative to conventional fossil fuel-powered systems to reduce the emissions. Pure hydrogen could even eliminate all greenhouse gases. However, the transmission of chemical energy directly into electricity brings up some operational challenges especially for cruise ships, which will be discussed in the following chapter. First, the social debate of implementing a new technology is elaborated in the following section.

1.2 Social acceptance and ethical acceptability

The technical application of LNG is ready for the market by using the traditional internal combustion engine (ICE). In addition, existing rules and regulations are providing the required regulatory framework for fuel handling and bunkering. In contrast, the fuel cells under investigation are part of the process to increase the sustainability and tackle the impact on environment while bringing new and significant risks. Traditional probabilistic risk assessment is developed to understand and reduce the technological risks. However, the social aspects are mostly neglected which are the basis for creating societal acceptance of certain risks and the new technology on the part of the public [79].
The following section 1.2.1 focuses on moral aspects of the technology as basis for obtaining an ethical acceptability followed by the key factors of societal acceptance in section 1.2.2. As stated by Wurster and Schmidtchen [94], the biggest risk is the human itself, all possible risks can not be eliminated. In addition, section 1.2.3 concludes the evaluation by pointing out important conditions and options to reach societal acceptance of the fuel cell technology used by the cruise industry.

Generally, representative surveys and studies are not available explicitly for the shipping industry. However, the evaluation creates a certain awareness of these ethical aspects, while approaching a new technology by transferring methodologies and findings out of similar investigations from the further developed automotive industry.

1.2.1 Moral aspects of technology

Generally, coherence has to be obtained by relating societal acceptance with ethical acceptability for any risky technology [79]. Moral aspects should reflect on different opinions and risks. Some major aspects are briefly discussed in the following paragraphs.

Assessing the hazard potential, pure hydrogen is gaseous at ambient condition and only cooled or pressurized in the liquid phase. Consequently, the storage demands additional attention. The public sees the highest risk in its explosiveness of the compressed gas as well as the skin contact with liquid hydrogen [24]. The same holds true for compressed ammonia especially due to the toxicity. However, Schindler et al. [71] do not see any major risks of leakages due to the double walled tanks and similarities and experiences with liquefied natural gas (LNG). In addition, the gas is lighter than air and would immediately rise into the atmosphere.

In addition to the integration of a fuel cell system, a crucial point is also the lower flexibility in reacting on immediate load changes on board. Due to preheating, not all fuel cell systems can react immediately to certain load changes, to be discussed more detailed later on within the fuel cell theory (see section 2.1.1). It brings up a certain risk of over- or undershooting the system. This would result in an unstable electrical power supply on a completely autonomously operating vessel which also has certain sensitive survival systems. They are not only responsible to ensure manoeuvrability, but also ensuring stability and additional hazard prevention systems. Consequently, a reliable electrical power supply is important especially for a remotely operating ship on the sea with several hundred people on board.

Another argument in public debates is still the production and lifetime of a fuel cell as well as the fuel itself. The obtained lifetime does not compete with diesel engines, which results in additional produced cells for a vessel and more waste to recycle afterwards. Furthermore, it has to be clarified, how the alternative fuel is produced, either primarily by fossil fuels or by renewable energy sources in the case of pure hydrogen. If the overall carbon dioxide balance is not improved, then the new technology is questionable in its purpose to reduce emissions. [31]

Lastly, the necessity of the whole cruise industry is morally debatable by looking on the environmental impact caused by the passengers while having the consequences on all humans especially in ports of the destinations. Even though, the industry has been booming within the last years with more than 5% increase of passengers per year [20].
The emissions are approximately three to four times higher per passenger-kilometre in relation to international aviation[40]. This results in one of the most polluting form of holidays. Under those circumstances, also the cruise lines are interested to polish their image by focusing on more sustainable technologies like fuel cells.

1.2.2 Factors of societal acceptance

After pointing out the moral aspects, the theoretical framework has to be understood in order to obtain societal acceptance of the new technology of fuel cells by replacing former familiar and well proven technologies like diesel engines. Renn [66] is formulating three levels of acceptance as follows:

- Tolerance
- Positive attitude
- Active commitment or involvement

No further actions of any parties or persons can be expected in the first step, even if they would refuse it. The new technology is generally tolerated[68]. Additionally, representatives of the second and third level are beneficial to get a wider support and involvement of other parties and stakeholders. With a positive attitude, the people would understand the project as a useful technology for the society. Lastly, an active commitment can spread the knowledge and would be the optimal case for the implementation.[66]

In order to obtain a certain level of acceptance, four different factors have to be considered [66].
At first, the *necessity* results in a broader approval, if an actual problem is going to be solved. In this case, the climate change could be combated by reducing carbon emissions in the cruise industry.
Secondly, the *purpose* of the technology should be clear by having a certain benefit for the society. Actually, the image of a polluting cruise industry could be improved, as discussed previously, by keeping this type of leisure industry as a competitive and more environmentally friendly option for passengers while strengthening policies.
Another aspect is the *fairness* within the energy transition between all stakeholders. People tend to agree with any changes and developments when all opinions, expectations and concerns regarding the project are considered and evaluated comprehensible.
Lastly, a positive *benefit/risk ratio* can increase the acceptance. Thus, everyone who are confronted with a certain risk should also have the chance to take the advantage of the project.

1.2.3 Gaining societal acceptance

As a conclusion, the height of the societal acceptance can be obtained by assessing the previously mentioned parameters. However, this requires social awareness and knowledge of the topic due to further public education, that the hydrogen technology is more considered as a safe alternative. Additionally, Roche [68] recommends building up the familiarity with the concepts and ideas before the attitudes of the people are explored due to the gained knowledge which might influence their opinion. Information campaigns and further development of international hydrogen technology-related training programmes can create a higher acceptability within the society. The technological risks can be explained including the safety measures, which have to be adapted by personnel and people who are handling the fuel.

The *Technology Roadmap* of Körner et al.[51] sees politicians as a leading stakeholder to overtake the extension of educational programs. The argumentation of having a certain necessity should be focussed on a safe and environmentally friendly transportation. Additional arguments are not within the societal focus, as discussed by Dinse [24], like independence of fossil fuels and certain countries.

To spread the knowledge, it is also beneficial to bring the society in contact with the technology. A study on hydrogen driven buses, called AcceptH2, concluded a wide acceptance of the technology after using hydrogen

buses in different cities. Around 80% of the people stated that it is a good option to test.[5]
One of the first maritime examples is presented by the cruise operator AIDA, who is going to test a fuel cell on board of one of their vessels. It should prove the technology in real life as well as bringing the technology in the focus of passengers as a green alternative for the future.

1.3 Conclusion

All in all, LNG symbolizes the first step to deal with the global climate change and the necessity of reducing emissions, but is not the final solution for the future towards a *green* cruise industry. Further effort has to be spent on developing new technologies like fuel cells in order to comply with upcoming regulations. In addition, new system arrangements on board have to ensure reliable and safe operations in all extreme conditions as well, to eliminate any further danger of life of several hundred people on board.
The acceptance of fuel cells and possibly pure hydrogen is generally high and can be expected [24, 71], even if only obtaining social tolerance would be enough as a level of acceptance [66]. In addition, the provision of knowledge to the public is helpful as well as bringing them into contact with the technology.
The current project is a significant step towards the use of fuel cells but has to consider any decisions from an ethical point of view as well, by setting parameters and ratios carefully while properly assessing any following risks or safety issues.

Chapter 2

Background

The following chapter provides some further background information about the fuel cell technology in section 2.1. The specific operational characteristics of the fuel cell have to be matched with the dynamic energy demand of a cruise ship. Already completed research projects on dynamic energy demand modelling are summarized in the following section 2.2.

2.1 Fuel Cells

Currently the most discussed option to design carbon neutral vessels is the implementation of fuel cells. The greenhouse gases and local emissions could be reduced even further or fully eliminated by using pure hydrogen. However, the implementation brings up several challenges and limits to store and handle the fuels as well as within the operation. As basis for the project, the following chapter gives relevant context information about the fuel cell technology.

Section 2.1.1 focuses on the most promising fuel cell types and describes the operational characteristics as energy producer on board. Significant differences in relation to conventional fuels has to be considered by an implementation in a cruise ship regarding fuel handling and storing as well. Thus, following section 2.1.2 examines the suitable alternative fuels based on previous studies and investigations, which can be used in a fuel cell. A brief overview of the costs is given in section 2.1.3 as all economic decisions are finally made based on costs. However, the installation and operational costs are not taken into consideration in the current research project due to the price fluctuations in the present market and are only included as general background information.

2.1.1 Operation of fuel cell

The fuel cell, as energy producer, brings along some operational limits and characteristics to consider for ensuring smooth operation. Different types of fuel cells are on the market which are suitable for different purposes and currently with a different technology readiness level (TRL). At this stage, only the proton exchange membrane fuel cell (PEMFC), solid oxide fuel cell (SOFC) and molten carbonate fuel cell (MCFC) are used for maritime applications and running in research projects [82]. The key parameters of the systems are shown in table 2.1, where the distinction is made between low temperature-proton exchange membrane fuel cell (LT-PEMFC) and high temperature-proton exchange membrane fuel cell (HT-PEMFC). The advantages and disadvantages can be described for the different options compared to the conventional diesel-electric drive within a cruise ship. The corresponding energy producer in table 2.1 is called genset, which includes the diesel engine and generator to obtain electric power.

The PEMFC operates at lower temperatures in comparison to the SOFC and MCFC, while providing a good efficiency of the fuel cell itself. The start-up as well as load transient time are also lower by using pure hydrogen, which results in a wider application within the automotive industry. Further reforming of a hydrocarbon fuel would need more time in a separate reforming step.
Additionally, the high power density ratios in terms of volume and weight are beneficial in comparison to a conventional diesel engine and other fuel cell types. However, the implementation of a PEMFC becomes more difficult for large projects and loads like within the maritime industry due to the high purity requirements and

separate reforming, even if the technology readiness level (TRL) is higher. Various manufacturers are offering currently PEMFC-modules, which are usually in a range of up to 120kW for a LT-PEMFC and 30kW for a HT-PEMFC [82].

Table 2.1: Key parameters of selected fuel cells regards operations [82, 85, 89] compared to conventional genset [13, 58, 65, 85, 91, 92]

	LT-PEMFC	**HT-PEMFC**	**SOFC**	**MCFC**	***Genset***
Temperature	65-85°C	140-200°C	650-700°C	500-1000°C	*>60°C* [1]
Electrical efficiency	50-60%	50-60%	60% (incl. heat recovery 85%)	60% (incl. heat recovery 85%)	*35-45%*
Start-up time	<10 s	10-60 min	<1-2 h	<1-2 h	*<10 s*
Load transients	<5 s	2-5 min	<30 min	<30 min	*<15 s*
Waste heat recovery	-	-/+	++	++	*++*
Volumetric power density	300-1550 $\frac{W}{L}$	300-1550 $\frac{W}{L}$	4-32 $\frac{W}{L}$	1.75-20 $\frac{W}{L}$	*32.5-55* $\frac{W}{L}$
Gravimetric power density	250-1000 $\frac{W}{kg}$	250-1000 $\frac{W}{kg}$	8-80 $\frac{W}{kg}$	7.75-25 $\frac{W}{kg}$	*45-71.5* $\frac{W}{kg}$
Cost	≈1900 €/kW	≈2500 €/kW	≈8000 €/kW	≈4000 €/kW	≈300 €/kW
Technology Readiness Level TRL	9	6	6	5	*common*
Internal reformation possible	-	-	+	+	*n/a*

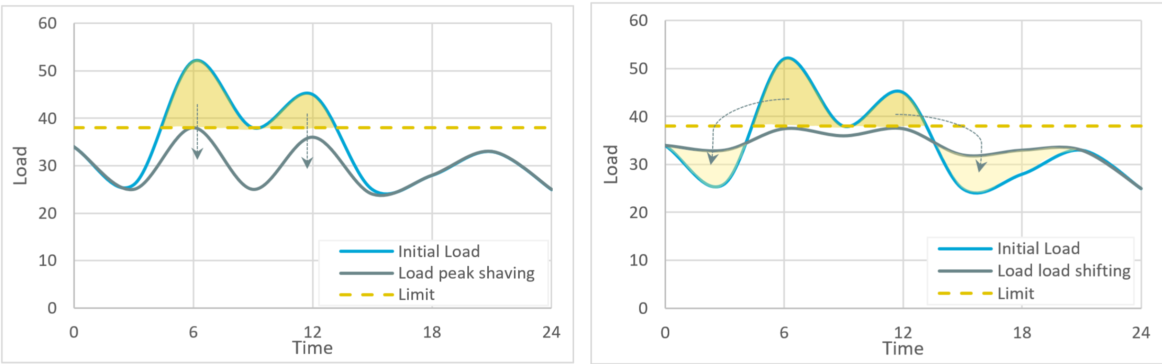
The main advantage of the higher temperature fuel cells, like SOFC and MCFC, is the high efficiency, which can be increased by using the waste heat of the fuel cells up to 85% [85]. Secondly, the reforming of syngas (hydrogen and carbon monoxide) occurs within the fuel cell, which lowers the fuel purity requirements.
However, the start-up time has to be considered of several hours due to heating of a large thermal mass by an assumed heating rate of ca. 2°C min^{-1}[37]. Meanwhile, the material brings limits to the temperature gradients, like the brittle ceramics within a SOFC[85]. The same holds true for the load transients, which are longer as well. The lower TRL results also in higher costs for these options. Consequently, the most favourable use of these fuel cells is for higher scale applications but within a constant load demand over time.

The different alternatives can be compared with a conventional genset, as energy producer. At first, a significant difference can be observed between the efficiencies. Diesel generators can achieve electrical efficiencies up to 45%, which is lower than fuel cells. This is obtained at their most efficient operational point. Especially in part loads, it can be even lower due to mechanical losses. Fuel cells can operate still at higher efficiencies under part load condition by switching of a part of the fuel cell modules [85], as discussed later on.
Nevertheless, the diesel engines have low start-up times and load transient responses, which are mainly limited by the constraints set by the engine manufacturer to avoid damage by rapid change of temperature or air pressure [13]. The higher waste heat is commonly used for other auxiliary systems.

Apart of the specific parameters, fuel cells have additional properties based on their chemical operation which can be beneficial also in hybrid concepts. They are built up modularly. Consequently, by running on part loads, the fuel cell stack can be reduced by a modular switch-off without reducing the efficiency significantly. Mechanical losses are only within the secondary machinery within the fuel handling and support [85]. Alternatively, the fuel cells can be a part of a hybrid system on board by keeping the conventional internal combustion engine. The fuel cell can be operated on a certain constant *baseload* without frequent load changes [11].

[1] based on SOLAS [43] for minimum flashpoint for marine oil fuels, like HFO or MGO, normally around ≈ 250°C [21]; temperature for LNG can be lower based on IGF-code [44]

Meanwhile, the diesel engine and optional batteries can be reserved for peak loads or periods where high power is required. The commonly called *peak shaving* would result in a reduction of installed power due to batteries as additional energy storage [34] as shown in the principle sketch in 2.1a. In addition, more efficient systems and power suppliers can reduce the power peaks as well.
Alternatively, the total energy demand would stay basically the same while *load shifting* is applied, as depicted in figure 2.1b. The installed power is lower, and the power producers are running more constantly within their operational windows with better efficiencies and lowering the consumption.



(a) *Peak shaving* (b) *Load Shifting*

Figure 2.1: Principle of *load shifting* and *peak shaving*

Lastly, vibrations and noise can be reduced with fuel cell systems in comparison with diesel engines and its rotating mechanical parts, due to an electric energy production directly out of a chemical process [75, 85]. This results in an additional benefit for the passengers and crew on board as well as harbour communities and sea environment. Thus, it could be installed all over on board as well, which is particularly advantageous for a cruise ship with its many small electric users all over the decks [67]. However, the fuel supply has to be considered as well and can be difficult for example for LNG by complying with current regulations[44].

2.1.2 Options of suitable alternative fuels

In the following section, different fuel types are represented as energy source of a fuel cell system to assess the energy demand quantitatively before replacing the conventional power plant and fuel system. Different investigations have been made in previous studies to find the optimal alternative fuel for a fuel cell. Basically, the fuels can be categorized into hydrogen, hydrocarbons and ammonia, where hydrogen (H_2), ammonia (NH_3), methanol (MeOH) and LNG are the most promising solutions [89]. Further storage options are under investigation in combination with metal hydrides or chemical compounds [85]. Other available options are not considered due to the high sensitivity for impurities or low efficiencies [82]. The main parameters of the fuel types mentioned are discussed briefly and are shown in the table 2.2 in comparison to conventional MGO.

Technically, pure hydrogen can be used directly in any fuel cell. NH_3, MeOH and LNG have to be reformed before the hydrogen can react chemically. However, hydrogen has a much lower density than the other fuel options as well as conventional crude oil distillations or natural gas due to non-existing carbon chains. Pure hydrogen can only be stored in liquid phase under pressure of usually more than 350bar or preferably at a temperature of less than -253°C at ambient pressure. The compressed storage of the gas is not considered due to the additional safety risks and a higher energy density under cryogenic conditions. Anyhow, the cooled hydrogen is mostly stored under small pressure as well, to avoid evaporation over time and is referred to as cryocompressed hydrogen.[85]

Ammonia has to be cooled down to a temperature of -33°C or preferably compressed under 10bar to avoid additional cooling, while liquid methanol is available in normal ambient conditions. In comparison, LNG has to be cooled as well, to increase the energy density along with a higher gravimetric density. MGO is often slightly heated in the tanks to improve the viscosity.

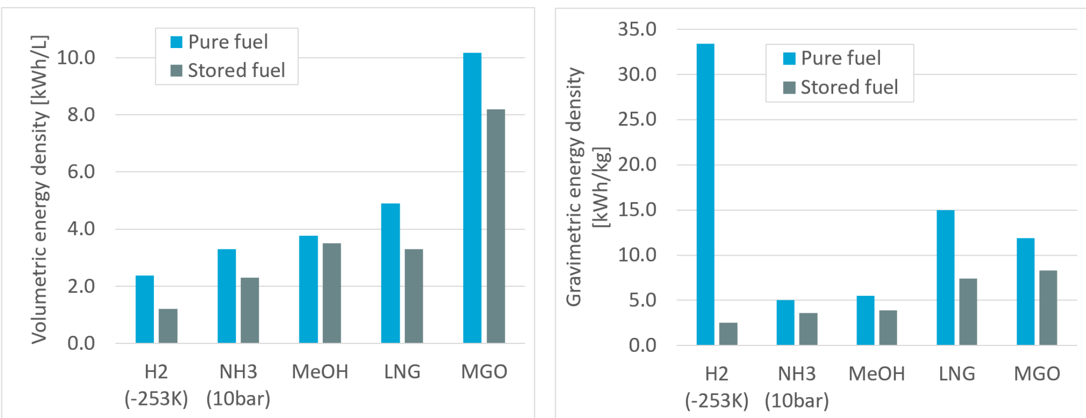
As a consequence of the pressure, NH_3 and H_2 must be stored in cylindrical pressure tanks to obtain the liquid phase and to prevent boil-off losses. There is much more space required for hydrogen and ammonia because of secondary machinery for cooling while storing, heating to avoid frosting and the compressors as well as additional insulation for hydrogen [89]. This is also the case for LNG. MGO does normally only need heaters to keep a certain temperature, as discussed.

Table 2.2: Key parameters of selected fuels regards storage and handling [22, 82, 85, 89] compared to MGO [3, 25, 49, 92]

		H_2	NH_3	MeOH	LNG	*MGO*
Use in Fuel Cell		Heated	Cracked	Cracked	Cracked	*n/a*
Fuel Density	[kg/m^3]	70.9	792	682.3	450	*890*
Temperature	[$^\circ C$]	-253	25	25	-161	*35*
Pressure	[bar]	1-3	10	1	1	*1*
Cost fuel	[€/kWh]	0.075	0.164	0.072	0.018	*0.054*
Cost fuel storage	[€/kWh]	5.0	0.31	0.04	1.440	*0.02*
Special Tank Shape		Cylindrical (20% Radius), Insulation	Cylindrical (5% Radius)	-	-	-
Secondary Machinery		Compressors, Coolers, Heaters	Compressors, Coolers, Heaters	-	(Compressors,) Coolers, Heaters	*(Heaters)*

More difficult is the assessment of the economical perspective, because of ongoing developments and increasing availability of different fuels over the year, which will influence the price significantly in the next years. However, available data from suppliers and other studies can be used and shown in the table as well, for first rough predictions.

The fuel options can be also rated based on the energy density, which includes the different structural or operational equipment to store the fuel. NH_3 and MeOH have a higher density than H_2, see table 2.2. The volumetric energy content of the pure fuel is also higher, as illustrated in figure 2.2, but generally lower than (low sulphur) MGO with 8.2kWh/L [85] and LNG. Differences can be seen between the density of the pure fuel and the stored fuel, which includes the operational equipment to cool or heat as well as for fuel processing. Consequently, the volumetric density of the stored fuel is lower.



(a) *Volumetric energy density for selected fuels* (b) *Gravimetric energy density for selected fuels*

Figure 2.2: Energy density ratios[85, 89] for selected pure fuels and including the storage systems

The same holds true for the differences within the graph 2.2b for the gravimetric energy densities. Especially pure hydrogen is a light and energy dense fuel. However, the structural elements and operational equipment for the storage lowers the gravimetric energy density significantly. In this stored condition, the density is even lower than all other considered fuel types. Finally, the conventional MGO has a higher energy density in terms of volume and weight than all other alternative solutions under consideration of required storage equipment.

2.1.3 Costs

Even if the costs are not further considered in the current conceptual study, the following background information provides a brief overview concerning the costs and availability of the used technology within the market. This is a key variable later for further economic decisions when the concept is ready for the market.
Generally, the costs for a fuel cell (see table 2.1) including implementation and their operational costs are higher than for normal combustion engines and additional exhaust gas treatment to comply with upcoming regulations. However, the costs are varying due to the ongoing developments and increase in production. These days, capital expenditures (CAPEX) of around 3000-4500$/kW of installed electrical power can be expected for a fuel cell by further reducing it to 1000$/kW by 2022 [30], which is still significantly higher than costs for a conventional medium-speed diesel engine with a price of 200-350$/kW [92].

More uncertainties are existing by predicting the operational expenditures (OPEX) for the usage of fuel cells onboard. The price is influenced by an increasing availability over the upcoming years. Currently, a rough prediction of the price is made by around 75€/MWh for pure hydrogen, while having a price of around 54€/MWh for MGO (see also table 2.2). This indication does not consider the different costs for the storage systems, which vary as well. Important to consider is the limited lifetime of the available fuel cells, which increases the costs as well. The decision paper of DNV GL is pointing out, that further developments need to be achieved, before the operational costs will be competitive. Following this, the time and costs of exchanging an end-of-life fuel cell should be comparable with a general engine overhaul[30].

2.1.4 Conclusion

All in all, fuel cells are a considerable option in order to comply with regulations in the near future. However, the focus is currently not on the disadvantage of a not fully existing infrastructure at this point. The research project is more future-oriented and focused on the general feasibility of an implementation. As shown in various research studies, it seems impractical to power a whole cruise ship with fuel cells and *green* hydrogen. Hybrid systems in combination with batteries and diesel generators are alternatives to power the vessel reliable in the different operations. At the same time, fuel cells are beneficial by transferring towards an *all-electric-ship* by reducing mechanical and rotating power producer with its losses.

The problem and driving factor of any investment decision is currently the high investment and operational cost of a fuel cell system, as discussed in 2.1.3. Manufacturer of the fuel cell systems are still improving the efficiencies, total energy densities and storage options, which will have a positive impact on the final costs. On the other side, shipyards are working on the most efficient implementation of the fuel cells based on the operational profile and expected conditions of the vessel. Based on the working principles in 2.1.1, the fuel cells would be a good alternative for constant loads over time of a specific system or energy consumer group. The limiting factors are the difficulties of fast load changes and longer start-up times.
Additional peak loads can be still powered by conventional internal combustion engines or additional batteries [11]. The existence of additional waste heat within fuel cells on higher temperatures, like SOFC, has to be considered, which can be used for supplying other systems with heat. At the same time, the overall efficiency would be even higher and hydrocarbon fuels can be used due to the internal reforming and yields it to a considerable option for maritime applications [85].
All in all, the understanding of the load changes is just as important as the total power demand at a certain condition, under consideration of the starting and transient load response time of a fuel cell. Thus, the fluctuation within the energy demand of a cruise ship has to be predicted under dynamic conditions.

2.2 Dynamic energy demand on board of cruise vessels

The dynamic energy demand should be known to properly design the size and configuration of a fuel cell and further optional hybrid components. This chapter elaborates on the relevant theory and concepts to define the energy demand of a cruise ship including explored findings and methods in previous studies.
The common approach to investigate all the equipment and functions is discussed in section 2.2.1 by forming main groups of propulsion, auxiliary and hotel systems on board. In a second step, section 2.2.2 describes alternative methods to predict the energy demand. Afterwards, the influence of the number of passengers and volume of the ship on the proportional energy demand of propulsion and auxiliary systems is shown in section 2.2.3. Finally, additional significant influencing factors on the energy demand are mentioned in the last section 2.2.4 which require a *dynamic* energy modelling.

2.2.1 Conventional investigation to determine power demand of propulsion, auxiliary and hotel systems

At first, the following main groups are the basis to classify all systems on board and to quantify the total power demand.

- Propulsion systems
- Auxiliary systems
- Hotel systems

The propulsion systems include all components directly related to thrust generation of the ship, while the auxiliary systems are providing the platform functions to ensure survivability and mobility of the ship [92]. By focusing on cruise ships, the hotel systems can be discussed separately, next to the auxiliary systems, due to the large contribution within the fuel consumption [74]. The hotel functions are including any auxiliary systems or electric components, which are more related to the passenger comfort and entertainment[11], including the HVAC system as main contributor.

Typically, the energy demand is estimated for all electric power consumers with the load balance approach in the conceptual design phase at a shipyard [92]. All systems are designed for the maximum operational power demand.
The actual power demand is calculated based on the absorbed power P_a of an electric power consumer i from the net and additional predefined factors for several different operational conditions j, as shown in equation 2.1. The 'number in service' k_n describes the number of running components in the defined operational condition. In case of redundantly installed components, like lighting, the factor can be also between 0 and 1. In addition, the load factor LF is defined as relative load of the maximum electric power of the component to be absorbed in the actual situation. The third factor, the simultaneity factor k_s, varies between 0 and 1 as well, and describes the relative mean operational time of the component. Thus, a factor lower than one considers not continuously operating consumers. The last two factors are often combined as service factor [92] or even together with the 'number in service' as utilization factor k_u [23]. The product results in the actual absorbed power per component, which can be summed up to obtain the total power for the given operational condition.

$$P_{total,j} = \sum_i P_{a_i} \cdot k_{u_{i,j}} = \sum_i P_{a_i} \cdot LF_{i,j} \cdot k_{n_{i,j}} \cdot k_{s_{i,j}} \tag{2.1}$$

Following this, the actual power demand P_{total} in different operational conditions j can be predicted. Reference vessels can be used to get an idea of the proportional demand of the propulsion, auxiliary and hotel systems in the different operational modes. Figure 2.3 shows the available data of the cooperating shipyard for an expedition cruise vessel, where the hotel and auxiliary systems are displayed together next to the propulsion systems.

It can be clearly seen, that the propulsion power demand is mostly around two third of the overall demand in sailing condition (e.g. 70% for sailing 17kn in summer and 71% in winter, but 58% with a speed of 14kn in summer and 60% in winter). The average demand of the hotel functions and auxiliary systems is 38% while sailing. In harbour condition and shore supply mode, the propulsion power demand is obviously nearly zero and the hotel functions are defining the power demand.
This proportional distribution can be obtained with the common prediction method in a load balance for a cruise

ship. It shows the distribution of the electric power demand for specific modes in order to determine the rating and number of generators[87]. However, only specific modes are considered in the way the owner would like to operate the vessel, where the maximum power demand is expected. The individual dynamic load behaviour can not be analysed to match it with various power supply components including a fuel cell with different operational characteristics.

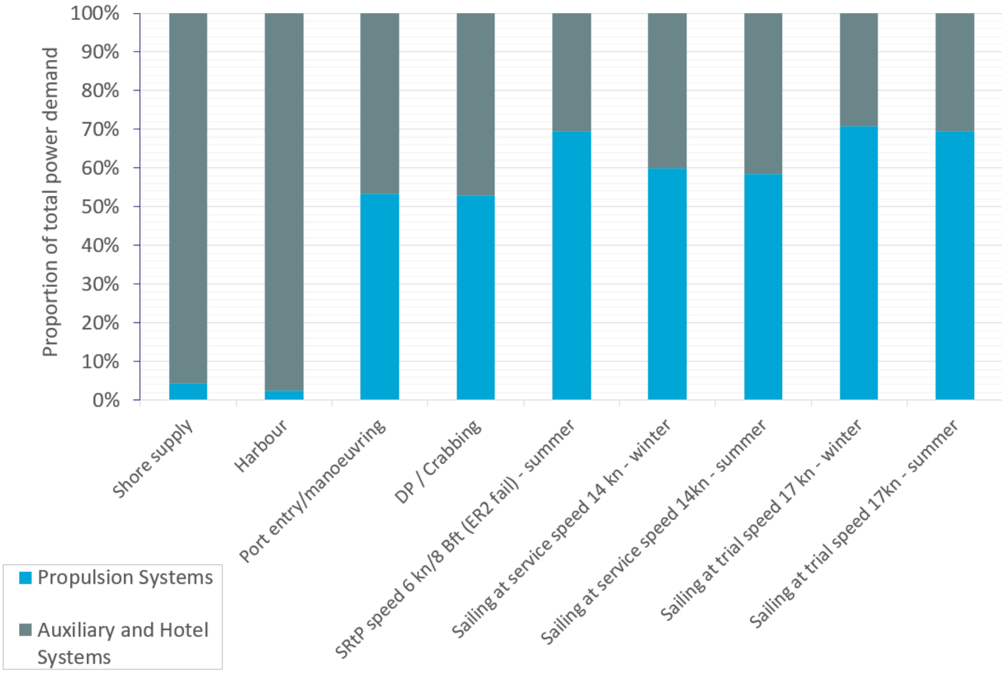


Figure 2.3: Amount of total used power (in kW) and power of propulsion together with percentage

2.2.2 Top-Down and Bottom-Up approach to asses energy demand

Other research projects are predicting the energy demand not for the electric components statically in specific operational modes, but rather for the different functions and activities. However, the distribution between propulsion, auxiliary and hotel demand can be observed as well.
Real-life data is mostly used to assess emissions or evaluating energy reduction strategies. Basically, there are two different approaches. The IMO concludes, that both options are resulting in a good estimation of the emissions or energy demand. They are coming to similar results by containing both different uncertainties about allocation of fuel consumption [76]. Some research projects are briefly discussed and compared to the results out of the load balance approach and can partly be used to validate certain predictions later on.

The bottom-up approach is using the operational data as a starting point. The energy demand and emissions can be calculated for every activity. As an example, Howitt et al. [40] predicted the emissions of international cruise vessels along the coast of New Zealand by using operational data like rated power and average load of the main and auxiliary engines, the speed and planned itinerary. The actual power could be predicted under dynamic operational conditions. However, the estimation based on real-life data and can only be used to validate alternative predictions in the first design stage of a new vessel. Further distinction of different systems is not made as well. Within this study, the energy demand related to the auxiliary engines are at a per-vessel-based mean of 30%, which he is considering as *hotel functions*[40]. This would be comparable with the findings out of the data of the shipyard in the early design stage, in section 2.2.1, for a demand of the hotel functions.

Secondly, the top-down approach is based on data sources like the AIS-signal which is recording the vessel position over time including additional operational information, like speed and draught. In a second stage, technical data for the specific vessel can be connected to the recorded time history. Based on the total installed power, the energy demand can be predicted.
Simonsen et al. [74] is calculating the energy demand and resulting emissions for cruise ships along the Nor-

wegian coast based on operational data. The distinction is made between the size of the vessel, where slightly different approaches are applied due to the impact of the hotel functions.
For smaller ships, the power demand of the hotel systems is kept constant in different conditions like at sea and in the harbour, while the propulsion demand is correlating with the ratio of actual speed over service speed. However, it is also concluded, that the hotel demand and propulsion power demand should be considered separately, especially for ships with a GT of more than 25,000, because of more extensive hotel functions on board [74]. Thus, operational data can be used to predict the energy demand dynamically over time, but does not show the individual load of systems apart of the main propulsion.

As a basis for further emission reduction policies, the UK Ship Emissions Inventory 2010 brings up similar ratios by using a top-down approach, with real lifetime data. The given average of the ratio of the power of the auxiliary engines over the total engine power is at 25% percent for passenger vessels. However, no distinction is made between the size of the passenger ship neither the load conditions. [90]

2.2.3 Influence of cruise ship size and number of passengers on hotel functions

The application of the conventional approach in 2.2.1 does result in a power prediction for different predefined operational conditions. The research projects and methods in 2.2.2 result in a whole energy demand prediction under consideration of dynamic operational conditions and real-life data. Obviously, the speed and size of the vessel are a driving factor of the energy demand of the propulsion load. However, also the auxiliary and hotel systems are influenced by different parameters and can not be just easily scaled, as discussed below.

Ottaway Marine Consultants presented a few further graphs about the *installed* power demand as a basis for the power plant design within a cruise ship [88]. Similar trends are visible, which were also obtained or assumed in other research projects.

Figure A.1 in the appendix shows the increasing installed power of cruise ships over gross tonnage (GT). The installed power for the propulsion is roughly two thirds of the total power. Consequently, one third is considered to be for auxiliary systems, including further hotel functions, as obtained by other reports in the previous sections. However, the graph shows also slightly decreasing ratio of the installed propulsion power for higher GT-vessels, by comparing the *Anthem of the Seas* with the smaller *Seaborne Pride*. The Cunard Line ships (*Queen Elizabeth II* and *Queen Mary II*) have a high maximum speed as transatlantic liners and are not fulfilling the trends.

Larger ships with more than 100,000gt are built not earlier than 1996. The rate of increase of installed power for these ships is smaller in figure A.1 (see appendix). This relates to more efficient cruise ships and smarter systems on board, which are regulating the consumption and usage of all auxiliary systems more dynamically.

The graphic A.2 in the appendix shows the decreasing installed power per passenger of new cruise ships on the market over the years. The proportional propulsion power out of the total power demand seems to decrease as well. Consequently, the proportional power for auxiliary systems and hotel functions increased over the years. The distinction can be also made in correlation of the space per passenger ratio, which mostly decreased over the years considering the labelled vessels in the graph. This means, that more people are accommodated within the same space on board. Bigger ships (here Costa Fortuna, Anthem of the seas and Harmony of the seas) have usually a space per passenger ratio between 30 to 35 gt per passenger [17], while the ships with a higher installed power per passenger have also a higher space per passenger ratio, like the ships of Seabourn around 60 gt per passenger[17]. However, this data shows the *installed* power on board and is not considering any dynamic energy flows during the varying operational conditions.

Known data in figure 2.4 shows a relation between power used for the hotel functions over gross tonnage *(GT)* in port. The power goes up by increasing GT. A rising trendline can be drawn to represent the hotel load over GT, similarly for the corresponding ratio.
The ships are used more extensively by increasing the volume of the ship along with more passengers per volume as well as more entertainment and hotel facilities. This increase of energy for hotel systems is also obtained in the study by Simonsen et al. [74] and considered by using a different approximation for bigger ships. However, the rate of increase of the power per GT is getting smaller with higher GT-vessels.

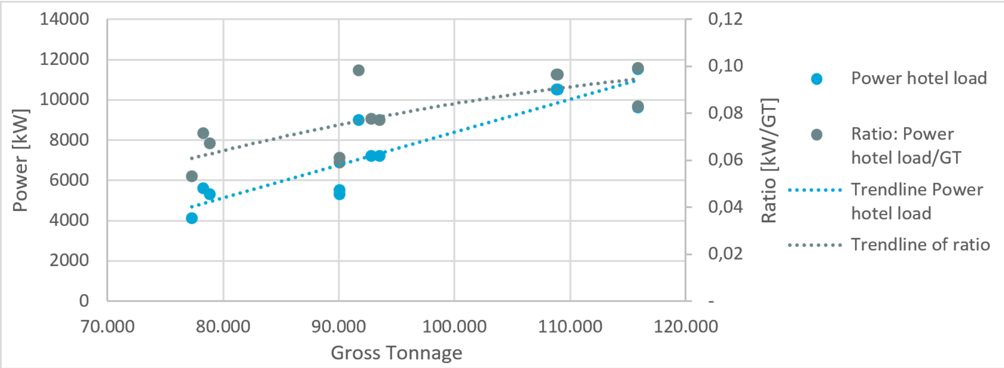


Figure 2.4: Hotel load [MW] versus gross tonnage (GT)

Some relations can be extracted from the investigations mostly based on real-life data. With an increasing volume or gross tonnage, the following statements can be made for the majority of ships:

→ mostly the ships are younger

→ more passengers are on board, but decreasing space per passenger ratio

→ less total installed power per GT (figure A.1) and per passenger (figure A.2), due to decreasing space per passenger ratio and higher efficiencies [35]

→ less installed propulsion power per GT (figure A.1) and per passenger (figure A.2), due to higher efficiencies

→ more installed power for hotel functions and per GT (figure 2.4), but also more power per passenger due to more leisure facilities [74]

→ as a consequence, increasing proportional power of hotel functions

All in all, the studies show some important considerations to keep in mind for the energy predictions later on. The difference between the smaller expedition cruise ships and high-GT vessels can be seen, with the result that reference data has to be selected wisely for the intended type of vessel. In addition, the influence of passengers on the proportional hotel load can be seen and should be further analysed.

2.2.4 Influencing factors for dynamic modelling of energy flows

Previous studies are distinguishing between the different operational modes and the consequences for the propulsion load while keeping the energy demand of the hotel systems constant, as discussed earlier. Even if Simonsen et al. [74] is stating, that the ”bottom-up” approach is more complex, a more systematic approach is necessary to study the dynamic energy behaviour of every system. As a consequence, the operational behaviour has to be considered more detailed already in the predictions in the design phase [35]. This section briefly summarized essential considerations and factors to be considered for an appropriate dynamic energy analysis.

At first, the interaction between the systems has to be investigated as well. Baldi et al. [10] is considering the energy demand of the ship as a whole system, where the energy as well as exergy balance can be analysed. The propulsion power, electric power and heat flow within the system of the ship is assessed. Basically, inserted energy $\dot{H}_{in}$ in formula 2.2 describes the input energy due to the fuel in the boilers and engine as well as the air used in the combustion processes. The outcoming energy $\dot{H}_{out}$ describes the electrical power, further heat required on-site and discharged waste heat due to the exhaust gas. The exergy balance in formula 2.3 considers similar processes with the additional destroyed exergy within irreversible phenomena like in chemical reactions.

$$\sum_{in} \dot{H}_{in} = \sum_{out} \dot{H}_{out} \tag{2.2}$$

$$\sum_{in} \dot{E}_{in} = \sum_{out} \dot{E}_{out} + \dot{E}_{d} \tag{2.3}$$

As a second fact, [10] is modelling the ship operations within typical operational days, where the variation can be included in the power profile instead of using defined operational conditions statically in the conventional load balance approach. The variation of speed is directly related to the propulsion power, which is not only operating at optimal efficiencies in part load conditions.
Additionally, the impact of the environment is often mentioned in the studies but barely used in the predictions for the hotel systems, which includes the HVAC system [18, 74]. However, section 2.2.1 and 2.2.2 shows the high demand of hotel systems especially in cruise ships. Thus, different weather data needs to be used to consider the impact of the environmental conditions as already used in the Dynamic Energy Modelling (DEM) in the building industry [60].

Lastly, the **occupancy** is important, especially when certain systems can be switched off in unoccupied areas [80] even if the distribution of the passengers on board is difficult to predict [72]. In addition, the total number of passengers on board can be defined based on known occupancy rates. Occupancy at 100% is defined based on the available lower berth (ALB) of a cruise ship. In this case, one passenger is considered per non-removable bed, which results usually in two persons in one cabin. The ultimate passenger limit is even higher and is limited by the International Convention for the Safety of Life at Sea (SOLAS). Consequently, the following formula 2.4 can be formulated for the occupancy rate OC with the number of passengers PAX_{ALB} and number of cabins n_{cabins}, as stated by Lee and Brezina [54]:

$$OC = \frac{PAX_{ALB}}{2 \cdot n_{cabins}} \tag{2.4}$$

The average occupancy of high-GT cruise ships exceeds usually the ALB-case. Some shipping companies are providing the average occupancy over the year in their annual reports. The occupancy rates in table 2.3 are reported by the four biggest cruise shipping groups. However, no distinction is made between the different subsidies, which are operating in other markets and following different business plans. Consequently, the occupancy rate is not necessarily the same for smaller and more luxurious expedition cruise vessels. Only the TUI Group is reporting a lower rate for their brand Hapag-Lloyd Cruises in 2018 of 78.3% [83], which are operating in a more luxurious market with focus on expedition cruises.

Table 2.3: Occupancy rates of four biggest cruise shipping groups in 2018 [15, 62, 63, 69]

Cruise Line Group	Occupancy Rate in 2018
Carnival Corporation & plc	106.9%
Royal Caribbean Cruises Ltd.	108.9%
Norwegian Cruise Line Holdings	107.6%
MSC Cruises	111.8%

As a conclusion, the mean average rate for the passenger occupancy on board of a cruise vessel is depending on the size and type of cruise ship and has small variations between the different seasons[53] and destinations[55]. However, by focussing on smaller exploration cruise vessels, the occupancy can be assumed to be at 100% ALB.

2.2.5 Conclusion

All in all, the coefficients in equation 2.1 in section 2.2.1 are containing margins to consider design changes and a dynamic energy demand, which are increasing the estimated actual power of each consumer. Oversized power demand are the consequence which results in costly installations of larger main engines.
Due to simplicity the hotel functions are mostly assumed to run constantly in different conditions and the focus is on the power demand of the propulsion, their efficiency, the emissions and further improvements within the machinery, as discussed in 2.2.2. The optimizations can decrease the consumption and emissions per passengers for new projects. Especially new high GT-vessels in the last years have a proportionally higher demand of hotel functions due to the propulsion improvements and their extensive entertainment facilities, following section 2.2.3.
Finally, out of 2.2.4 and as basis for the dynamic energy modelling, important factors has to be considered like the varying operational profile, the environmental conditions and distribution of passengers over the day on board.

Chapter 3

Project contribution and problem definition

Previous research projects and methods in chapter 2.2 can only be used as a first step towards a successful implementation of fuel cells on board of cruise ships under consideration of its dynamic energy demand. The following section 3.1 arises certain gaps in previous studies as starting point of the improvements within the project, which illustrates its contribution and importance towards the energy transition in the cruise industry. Based on that, the final problem definition can be stated in section 3.2, followed by the corresponding research questions in 3.3.

3.1 Gap analysis and importance of study

As a result of upcoming regulations, the implementation of fuel cells is a possible step towards a significant emission reduction. The use of alternative fuels for a fuel cell comes with a low volumetric energy density. Previous research projects are focused on the improvements of the efficiency of conventional power plants. However, first pilot projects and feasibility studies are showing the challenges on the supply side of the technical integration of a fuel cell into a ship including the storage and supply systems.
The right size and type of fuel cells have to be chosen for the expected loads, while the tanks should be kept as small as possible, in order to increase the energy density ratio and efficiency. This would result in a financially more attractive solution by lowering the costs per installed kilowatt.

At the same time, the energy demand side has to be understood properly to match the fuel cell characteristics with the system behaviour. Looking on the starting and transient load response time, the understanding of the load changes is just as important as the total power demand at a certain condition, as normally investigated statically in load balances. In other words, the dynamic energy demand of all systems has to be modelled under consideration of important influencing operational and environmental conditions, as mentioned in section 2.2.4. Generally, the utilization factor (see eq.2.1) within the calculations have to be replaced by assessing the time-dependent load of passengers, operational profile and the actual environmental condition. Additional margins within the factors can be avoided, which are ending in overestimations of the systems.

A bottom-up approach can bring up the behaviour of all systems separately[35], without keeping hotel functions constant over time. Especially these functions can not be neglected for cruise ships due to the high proportion and varying behaviour, as normally done by emission assessment studies [40, 74]. In addition, a systematic bottom-up approach is in contrast to the mostly used methods based on real-life data like fuel consumption, which are predicting the energy demand on a more generic level.

3.2 Problem Definition

Fuel Cells can not directly replace auxiliary or main engines on board of cruise ships due to the varying power demand over time which is in conflict with the operational characteristics of a fuel cell, as pointed out in the gap analysis (see sec.3.1) and background information (see sec. 2.1.1). An improved prediction model in the first design phase helps designing the fuel cell-based power system and its properties in the most efficient way. As a consequence, the following problem definition can be stated for the current project:

> *Powering certain loads or operational conditions by a fuel cell system can only be assessed with a systematic bottom-up approach to consider the dynamic energy demand of certain systems in different conditions over time.*

Specific research questions in this context will be introduced in the following section which are formulated out of the gap analysis of previous research projects.

3.3 Research Questions

The following main research question can be posed to follow up on the problem statement. Further sub-questions are providing a basis for the following project execution.

> *How can a systematic bottom-up approach be built up in the first design stage to assess the potential loads or operations to be powered by a fuel cell system under consideration of its specific operational characteristics?*

3.3.1 Consumers on board

> *What are the main energy consumers on board and how can they be grouped?*

The project focuses on the different consumers on board. Typical groups of consumers are to be defined, which are usually on board with a significant impact on the overall energy demand. Clear distinction should be made between the propulsion systems and auxiliary systems. Due to the high demand and variations of hotel functions related to the comfort of the passengers, these systems should be considered separately from the operational auxiliary systems, as discussed in chapter 2.2.1.

3.3.2 Influence of simultaneity

> *How can the simultaneity and variable use of systems be modelled?*

As discussed in 2.2.4, the simultaneity has to be considered as a varying parameter over time. The dynamic behaviour influences the factors, when the use is different per actual operational condition.

3.3.3 Driving factors of energy demand

> *What are the driving factors of the energy demand of a cruise vessel and their peak loads?*

Reports are assuming a demand of around one third of the overall power demand coming from the hotel functions and auxiliary systems, as discussed in chapter 2.2.4. However, uncertainties are mentioned in other research projects while modelling the energy demand. The influence of dimensional parameters, like the number of passengers or space per passenger, has to be proven as well as comfort parameters, which are defining the load of systems like room or hot water temperatures. In addition, the impact of the varying operational and load conditions over the day can be analysed as well.

3.3.4 Localisation of peak loads

> *Where are the peak loads during normal operation and does it hold true for different operational days?*

The peak loads of the energy demand has to be identified. Especially the hotel load is varying under the consideration of the additional loading and environmental conditions. Consequently, not only the peak value is of interest, also the localisation over time has to be identified.

3.3.5 Systems powered by fuel cells

What are the options and limits of powering a cruise ship by fuel cells under the dynamic energy behaviour?

The specific operational characteristics of a fuel cell, as mentioned in section 2.1.1, has to be matched later on with the dynamic energy demand of a cruise ship. Additionally, high volumetric energy densities of the alternative fuels, see chapter 2.1.2, yielding to larger tanks or a lower endurance of the ship.
Consequently, after analysing the power and energy demand behaviour, certain systems or operations are to be identified which are favourable for a fuel cell under its limits of performance.

Chapter 4

Methodology

The methodology is based on a systematic bottom-up, as described in 2.2.2. First of all, the power demand is predicted for every system. As shown in figure 4.1, the project starts with a system breakdown, where a given load balance is split up by all systems in order to understand the main systems and consumers on board. Groups of smaller systems are grouped together. The main dimensions of the ship are the required input data and further spaces on board are defined parametrically based on reference data as far as necessary.
As conclusion out of Taen [80], Baldi et al.[10], Cichowicz et al. [18] and Sfakianakis together with Vassalos [73], the power and resulting energy demand is mainly depending on a varying operational profile with a different speed, the different passenger behaviour and occupancies on board as well as the environmental conditions. They are also referred to as the three main influencing factors of the load behavior. Although users of the method can define their own settings for these aspects, thus making it suitable for their specific application.

The power demand of the different systems or groups of smaller systems are modelled. First, the prediction model is built up, followed by the implementation of the three different influencing factors.
Following this, the first varying condition is introduced, the environmental condition. The different power demand is proven for summer and winter condition. Secondly, the varying condition over the day has to be implemented using a typical temperature profile in summer and winter.
In the next step, the passenger load has to be defined. Without a variation of the speed, the impact on the power demand is assessed, when the passenger behaviour and occupancies are varying.
Lastly, the varying speed is introduced. The different operational profiles have to be implemented with the speed variation over the day. Usual itineraries of cruise ships are providing the basis for these exemplary operational conditions. Together with the varying passenger load, the typical days of operation are estimated in summer and winter condition.

Finally, all systems are brought together and the power demand is displayed in different conditions and varying loads. Driving factors can be pointed out by analysing the impact of the influencing factors on the power demand of the different systems.
The required energy per day is calculated directly from a time-domain integration of the power prediction. The demand for a whole operational profile is obtained by adding different typical operational days. Based on the general operational characteristics of a fuel cell in section 2.1.1, predictions are made for an efficient implementation of a fuel cell for specific part loads.

Any values for operating efficiencies, loading factors and coefficients in the conceptual model should be validated either qualitatively or subjectively. There are different ways of validation[70] and a combination of techniques which might be necessary to apply for the current case, as there are limited data sources available. However, reference data is also used to validate specific subsystems or assumptions made during modelling. On shore hotels can also be comparable for a few specific cases, for example, the time of operation of the lighting system. [77].

The scope of the current project and its limits are defined in the following section, followed by first expected results in section 4.2.

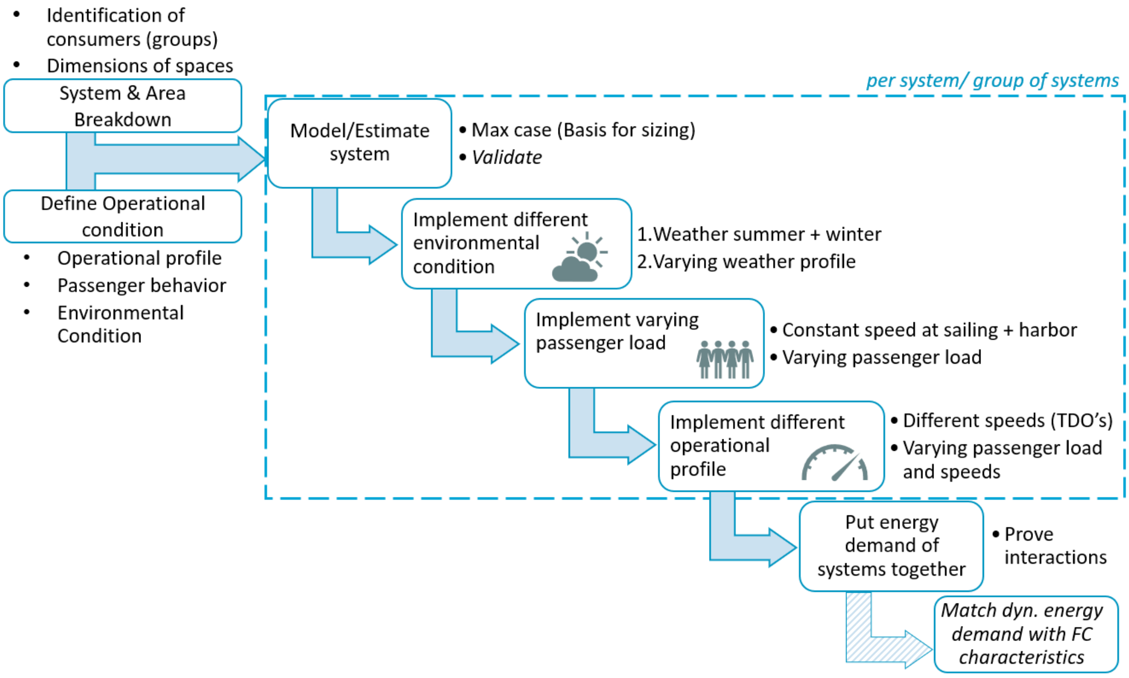


Figure 4.1: Systematic bottom-up approach of research project

4.1 Scope

The efficient and suitable implementation of a fuel cell system has to be proven individually for every ship type. The focus of the current study is on expedition cruise vessels. Few definitions are made in the first section 4.1.1 to define the boundary conditions. Based on that vessel type, the definitions of the rooms and areas dimensions (see Appendix A.3) can be built up to parametrize the vessel as far as necessary for the following power and energy prediction. In addition, the study investigates the dynamic energy demand, without going into the detailed implementation on the supply side, as mentioned in section 4.1.2.

4.1.1 Expedition cruise vessel

Focussing on cruising, the newbuilding market is confronted by a bipolar development. On the one hand, the trend is going towards huge cruise vessels with mostly more than 3000 passengers and more than 100.000GT. Mass tourism can decrease the fuel consumption per person and consequently the price for the passengers. The space per person is decreasing, as discussed in chapter 2.2.3. At the same time, the market of more luxury and smaller cruise vessels with mostly less than 1000 passenger is growing rapidly. Around 50% of 19 new cruise ships in the year 2020 are operating in this market [20]. In total there are 30 expedition cruise vessels on order, in January 2020 [81].
Similar to the portfolio of the cooperating shipyard DAMEN, the research project will focus on these smaller new-build expedition cruise vessels.

Next to the requirements for comfort, leisure and exploration facilities, as described in the following paragraphs, some parameters and definitions are set within the technical arrangement and general dimensions.
In order to use appropriate data, the chosen reference ships should be within the definition of an expedition cruise vessel, which are usually in the range of up to 50,000gt. However, in order to formulate a suitable database, cruise ships are considered up to a size of 90,000gt. This mostly correlates with the maximum dimensions for the Panama canal. Bigger ships have slightly different ratios between lengths and volumes and are therefore taken out of the study.

Destinations The demand comes from more curious, adventurous and nature focused people. Passengers would like to go into smaller harbours, which are accessible by these small and medium sized ships with a limited depth. The destinations are usually located in more remote areas. Many cruise ships are often operating in the Antarctica in the winter seasons (or Antarctic summer) while the summer brings them also into warm areas, like the Caribbean, Mediterranean or Amazon region.

This results in extensive operating weather window with different air and sea water temperatures with an impact on the heating and cooling systems. Furthermore, excursions are offered directly with the on-board equipment and boats, when the ship is at anchor or observations of the nature are made at slow speeds. The operational profile has to consider this in the typical day of operations.

Typical system configuration The power and energy estimation is for the first stages in the design process, so called rough order of magnitude (ROM) phase. Before the budgetary offer is asked by the client, the shipyard has to judge general technical decisions under consideration of the conceptual design requirements. Thus, rough estimations are necessary to assess the feasibility and costs of the used technology. At the same time, not many of the general dimensions are finally known, while reference ships are providing the basis for first predictions.

As a consequence, the goal is to keep the number of input parameters as small as possible for the first estimation of the required power, because the decision of the power generation and optional fuel cell implementation is made in the early design stage as well. The owner specifications can provide a rough order of magnitude of the main dimensions and volumes. Based on that, the following dimensions are necessary for the estimations later on:

- Number of passenger PAX_{ALB} at available lower berth (ALB) condition (or number of cabins) and crew N_{Crew}
- Length over all L_{OA}
- Length between perpendiculars L_{PP} (if unknown, alternatively assumed as 90%L_{OA}[89])
- Beam B
- Design draft T_D
- Design speed v_s
- Predicted height of highest full deck h_{max}

Based on the known main dimensions, the energy demand is predicted for the different systems. The used indicators and prediction models will adapt typical system configurations and facilities. Different saving strategies or energy saving devices could be applied on board to further reduce the energy demand but are out of the scope of this study.
For example the propulsion system will make use of typically two installed azimuth thrusters, placed in pods, which are also used as rudders. In addition, two bow thrusters are in the front of the cruise vessel for a better manoeuvrability of the ship. Furthermore, the ships are normally powered by a diesel-electric configuration. The generated power from the conventional diesel engines is transferred into electrical power. This is an advantage, because most of the consumers have an electrical power demand. Also the power transmission towards the azimuth thrusters is done electrically instead of using a traditional direct mechanical drive. Another advantage, especially for cruise ships, is the fact that one or more engines can be taken out. The remaining engines can be run at their most efficient operating point. This results in a flexible system for the variable loads on the vessel. This conventional arrangement forms the basis for the power prediction before a replacement by fuel cells.

Comfort As already mentioned in section 2.2.3, smaller expedition cruise vessels are usually built with a higher space per passenger ratio, which is often called as luxury level of the vessel [17, 88]. The different markets are described by the luxury level (LL), which is the ratio between gross tonnage and number of passenger as defined in equation 4.1.

$$LL = \frac{GT}{PAX} \tag{4.1}$$

Following this, the higher the ratio, the more space is available per passenger. Obviously, this is also related to higher quality of furnishing, equipment and comfort standards as well. The different levels of luxury are defined by Levander [56] as displayed in table 4.1. The expedition cruise vessels are usually operating in the luxury market or at least the premium level. As a consequence, the cabins are usually larger. Public spaces are offering larger lounges and leisure facilities. However, due to the size of the vessel, extensive entertainment facilities are not considered to be part of these projects. Theatres, roller coaster and other innovative features are more common on high-GT vessels.

Table 4.1: Definition of luxury levels of cruise ships

Market	Boundaries	
Budget	<30	gt/PAX
Premium	30-50	gt/PAX
Luxury	>50	gt/PAX

Ship total volume The volume is also described by the gross tonnage (GT), which is related to the total volume of the ship and the basis for assessing port fees. However, regression data can be used to obtain a preliminary value for further predictions, if the volume as well as the GT is not known in this design stage. The database of the cooperating shipyard is used as shown in figure A.3 in the appendix. With a sufficient correlation coefficient (R^2=0.93), the following relation is obtained between the gross tonnage and the known number of passenger for luxury cruise ship (see definition of luxury level in table 4.1):

$$GT = 52.25\,PAX_{ALB} + 5194.3 \tag{4.2}$$

After obtaining the GT, the total displacement of the vessel has to be defined for the calculation model of the propulsion power. As a basis, the gross tonnage can be used either obtained via the regression data, as mentioned earlier, or by the defined GT in the owner specification. Following this, a first displacement Δ can be defined for the calculations out of a linear relationship out of the database from the shipyard. All available ships are plotted in the graph in figure A.4 in the appendix. As a result, a linear relation with a strong relation (R^2=0.98) is obtained between the displacement and the known GT with the following equation 4.3. Additionally, the volume of the vessel ∇ could be calculated by dividing the displacement by the sea water density.

$$\Delta = 0.5048\,GT + 1992.6 \tag{4.3}$$

4.1.2 No design of the fuel cell and storage systems

The focus of the study is on the energy demand of a fuel cell-driven expedition cruise ship. The energy demand prediction model provides further insights into the demand of certain systems, while a successful fuel cell design as power supply solution can built up on it in a later stage. Thus, the detailed fuel cell design as well as the implementation into the ship hull is not in the scope of the project.
Fixed efficiencies are going to be used for the fuel cell and potential fuel types as shown in table 2.1 and 2.2. Only rough predictions of the impact on weight, volume and costs are made, using more favourable loads and operations for a fuel cell under consideration of the general operational characteristics, as described in 2.1.1. Further technical and economic feasibility studies of the whole (hybrid) system are not within the scope.

4.2 Expected Results

With the current study, the individual system behaviour is evaluated more clearly with defined indicators for varying conditions. The model should be validated in order to use it in further conceptual studies and to predict the technical feasibility of a fuel cell for certain loads.

The peak loads and quick ramp ups can be defined not only by comparing different operational modes. Different situations are taken into consideration. Consequently, peak loads are expected in more extreme conditions, for example in a cold environment and situations, where various facilities are used on board at the same time.
Even if on shore hotels could provide validation data for certain system behaviour, the energy demand of the hotel functions on board of a cruise vessel are expected to be higher due to regulations, higher comfort standards and occupancy. Next to the speed, the main driving factors are expected to be the number of passengers on board per volume and the required comfort parameters as defined by the owner and classification standards, like defined indoor temperatures and air exchange rates [8]. In addition, the passenger behaviour and occupancy might only influence the energy demand significantly, if systems are operating demand-actuated based

on the actual occupancy rate and use.

Coming back to the fuel cells, the need of alternative energy producers in the future is generally known. The option of using fuel cells on board of a vessel in a hybrid configuration is already assessed, even if efficiencies, energy densities and costs are still going to be improved. Going on step further, the current project will propose part loads and systems which can be powered efficiently by a fuel cell under daily varying load and operational conditions and is consequently of high importance towards a *green* cruise industry.

Chapter 5

Consumers on board

The ship type and its characteristics are now described. Before the energy consumption can be calculated, the whole system *cruise ship* has to be subdivided into the main consumers in this chapter. After, further predictions are made for every individual system or group of components, based on the specific usage under the varying operational conditions (see chapter 6). Before grouping the systems on board, the common approach of analysing the required power has to be understood. Based on the commonly used *load balance* of a reference vessel, the actual system breakdown is compiled in the following section 5.1.

5.1 System Breakdown

Usually, all electrical consumers are listed in the overall load balance (LB). First, all components are designed for the maximum condition to obtain the required installed power. In the balance sheet, different operational conditions are defined, whereas every electrical component gets a fixed loading and utilization factor assigned, as stated and described earlier in equation 2.1. This steady state calculation considers different margins and ends in an overestimation of the power load. This procedure will be improved, but is used in the first step for a system breakdown as follows.

The energy prediction is made for every system or component with a significant contribution to the overall demand. As a consequence, smaller systems are grouped together, based on their function or operations, to simplify the model. Strictly speaking, the higher the power demand, the higher the need of a closer look into the certain group of systems. The latter is further split up into different subsystems to have a better understanding of the individual behaviour.

For identifying the biggest consumers, the focus is on the following three operational conditions. Additional considered operations in the load balance (LB) approach, like manoeuvring in port or Safe Return To Port (SRtP)-condition (see overview in figure 2.3), are occurring more rarely in the operational profile. In addition, the final installed power is also determined by the following conditions, while other modes have a lower power demand and are considered in a later stage (out of scope) to optimize the power plant settings for other condition as well.

- Sailing at service speed in summer
- Sailing at service speed in winter
- Harbour mode

Every component in the load balance is included in a specific system (based on system distinction in Klein Woud and Stapersma [93]), which is part of one of the three main systems as mentioned earlier on (see section 2.2.1). Their contribution is shown in the pie charts in figure 5.1 for the considered operations based on the LB approach of the reference vessel. The propulsion demand is the highest in sailing conditions, while having a lower total power demand in harbour condition with a high hotel load contribution.

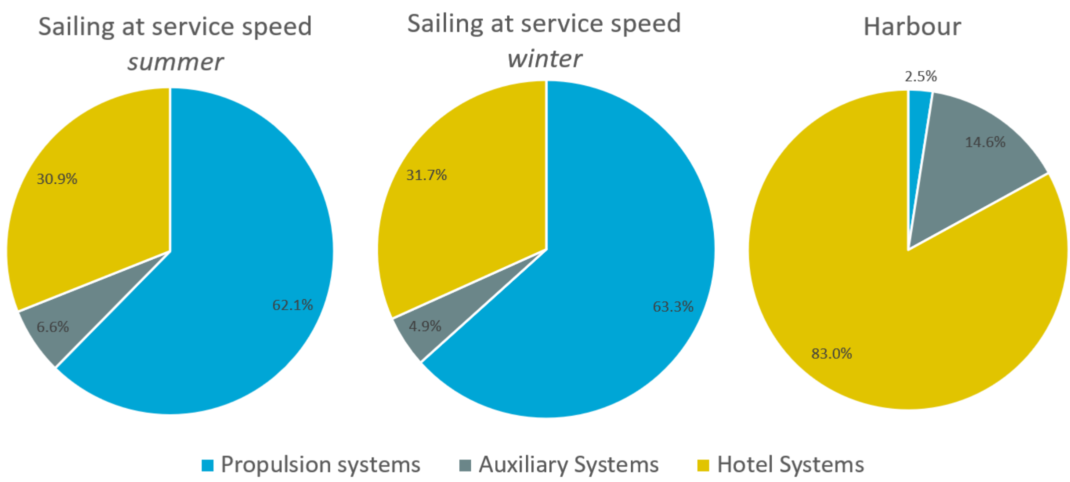


Figure 5.1: Distribution of power for general systems within load balance for three operational conditions

In order to improve the accuracy and pointing out the individual power demand behaviour, further subdivision is necessary based on their system behaviour under varying operational conditions. Figure 5.2 provides an overview of the systems and their subdivision including the proportion of the required power of the overall power in the specific operational condition (here: harbour and sailing in summer and winter). Important to consider is the significantly lower overall power demand of the vessel in harbour mode, due to no propulsion power. This leads to proportionally higher demand of the hotel systems, even if its absolute value might not differ significantly from the sailing condition.

The systems are grouped based on their purpose and the usage on board. The main consumers can be clearly seen in figure 5.2. The subdivision is made on the basis of the belief that if a specific system or component contributes a higher proportion to the overall power demand, temporarily or constantly over time, then it should be modelled with a higher degree of detail. For instance, the highest power demand is contributed by the azimuth thrusters while sailing (here nearly 60%). On the other hand, the bow thrusters need a significant amount of electric power while manoeuvring. Thus, a more detailed investigation can point out the temporarily high loads.

Furthermore, some components or systems can be modelled together if they are highly dependent on each other. For example, the heating, ventilation and air conditioning (HVAC) system is modelled together with the chilled water plant even if both systems consume a significant amount of energy. The cooling demand by the HVAC system is directly supplied by the chilled water plant (compare contrary power contribution of HVAC system and chillers in summer and winter in figure 5.2). Thus, the systems are directly related and are modelled together under varying conditions.

The third consideration of grouping the components is to take the operating conditions into account. If systems are operating in different conditions, then they should be modelled separately, even if the overall power contribution is low. For example, the emergency systems are only running on stand-by mode in normal operation, while having the higher load in emergency situations.

All in all, a reasonable way of an energy prediction within the bottom-up approach has to be defined separately for all identified subsystems. Given data for the power demand per system is varying in different conditions only because of different assumed utilization factors in the LB approach. The different characteristics of the systems are briefly described in the following subsections 5.1.1, 5.1.2 and 5.1.3, followed by their individual prediction models in chapter 7.

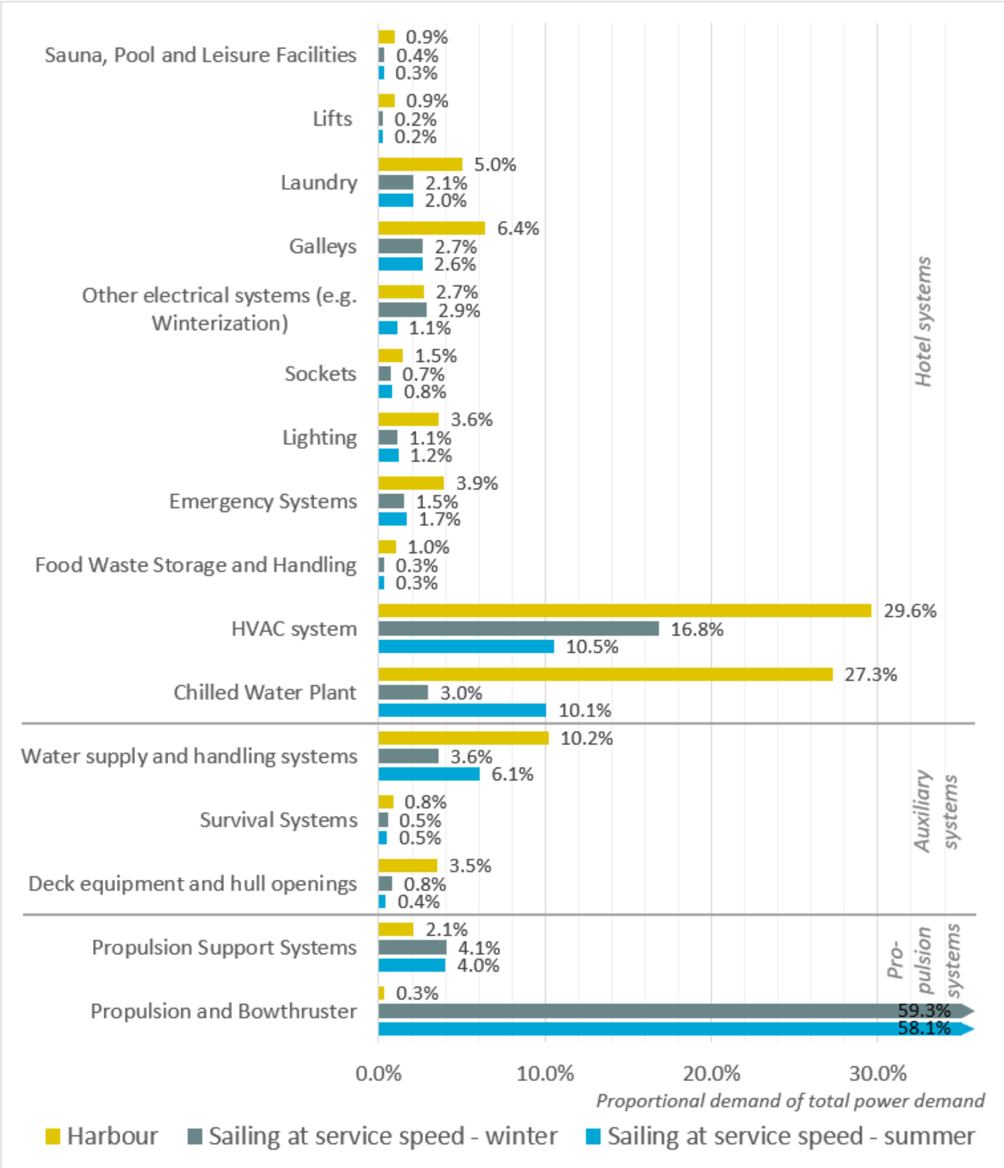


Figure 5.2: Systems out of system breakdown and its proportion of overall power in chosen operational conditions

5.1.1 Propulsion/Machinery

The energy demand of the propulsion system is split up in the propulsion load of the azimuth and bow thrusters next to the supporting systems, with around 60% of the overall demand while sailing.
As expected, the azimuth thrusters are the biggest consumers. The bow thrusters are not running in the considered conditions (sailing and port condition), but contribute to a significant peak while manoeuvring. The supporting systems include all components, which are necessary for a good functioning of the propulsion system, based on the distinction by Klein Woud and Stapersma [93], mainly:

- Fuel cleaning, supply and transport
- Lubrication oil system
- Combustion air and exhaust gas systems
- Pre-Heating and cooling pumps

5.1.2 Auxiliary systems

In addition to the propulsion support system, the auxiliary systems contain further systems to ensure all operations on board beyond the propulsion. As stated earlier in section 2.2.1, the hotel systems are usually a minor part within the auxiliaries. For a cruise ship, they are discussed separately due to the large contribution within the fuel consumption [74] in the following section 5.1.3.
The group of deck equipment and hydraulic systems include any equipment to ensure safe operations while mooring as well as for handling and lifting the excursion equipment and boats. In addition, hydraulic systems like doors and platforms are in the same group, due to the similar operating time windows.
Survival systems are split up by the hazard prevention and hazard fighting system. This includes the bilge and ballast water system together with the firefighting and escape systems. Together it results in a power demand of around 1% in the chosen operation but is designated for the emergency operations. Thus, it is considered as one group of systems even if it does not have a significant contribution in stand-by mode. Further operations to comply with safety regulations (e.g. SRtP) are not considered in this study, even if the power supply has to fulfil these intermediate demands in an emergency case as well. However, the total power demand is expected to be lower than any other case.
All systems for supply and handling of fresh and sea water as well as the wastewater are grouped into the third auxiliary system group. The power demand of the water systems can slightly vary due to the passenger behaviour.

5.1.3 Hotel systems

The actual hotel systems are more related to the passenger comfort and entertainment[11] with its significant contribution on a cruise vessel. All subsystems are displayed in figure 5.2.

Cruise ships are vessels, where the HVAC system has a significant proportion of the overall power demand due to high comfort requirements, passenger and crew behaviour as well as the outer environmental conditions. Different areas have different standards, based on ISO regulations and customer requirements. The different influences can be seen already in the bar chart generated out of a load balance in figure 5.2. The power demand is varying between 10-18% in summer and winter condition.
Generally, the system is designed by central air handling unit (AHU)s for public areas and local fan coil unit (FCU)s for passenger cabins. The electrical components can be summarized as follows:

- Fan, to circulate the air
- Cooling element, cooled by chilled water
- Heater, to add heat
- Humidifier, to add moisture

Central chilled water plants (also referred as *Chillers*) are usually installed for cooling the air or any perishable goods by extracting the heat from systems like the HVAC system. The power is estimated depending on the cooling demand. The expected difference between winter and summer conditions can be clearly seen in the figure 5.2. Local installed components can be avoided by distributing cooled water from the centrally cooled system. As a consequence, the chilled water plant is modelled together with the HVAC system later in section 7.3.1.

The galleys and laundry consist of all plugged components, which are used by the crew to prepare the food and beverages as well as to ensure the whole process of washing and drying. Rough predictions are made in section 7.3.2 based on the passenger behaviour and crew working schedule.
Coming to the smaller systems, the lighting on board does not have a large contribution to the overall demand, but is influenced by the dynamic operational conditions and is modelled separately in section 7.3.3.
The remaining systems are taken together and referred to as minor systems, calculated in section 7.3.4. The food waste storage and handling system includes all components related to the recycling, food shredder or carbonization units. The emergency system consists of emergency lighting, lifeboat chargers and the integrated alarm, monitoring and control system (IAMCS) as well as further crucial components like the main bridge and internal communication via uninterruptible power supply (UPS).
Particular mobile devices brought by passengers or simply plugged components are powered and considered by the sockets as displayed separately in figure 5.2, next to the lifts. The so called *other* electrical systems include

remaining components, mainly local heaters and automatic defrosting. However, this will be also considered as margin added to the total demand. Finally, the limited number of leisure facilities (typically for an expedition cruise ship, see section 4.1.1) are taken together in the group of sauna, pool and leisure facilities, which includes any electrical components related to these services like heating panels, steam generator or even the barbecue equipment.

Chapter 6

Operational and load condition

Before going one step further and analysing all systems with their components, the main input data for the expedition vessel can be defined. This operational data is the basis for further predictions of power and energy demand, as mentioned in the methodology and figure 4.1. The operating speed over the day is defined in section 6.1 within the operational profile. Basically, it is expressed in five typical day of operation (TDO). Considering that, the passenger and crew behaviour on board is defined for these days as well, in section 6.3. The third influencing parameter is the weather condition as described in the third section 6.2.

6.1 Operational Profile

The operational profile is necessary to calculate the energy demand of the propulsion. The speed is a driving factor of the power demand prediction and resistance of the vessel. Especially cruise ships have usually a very dynamic operational profile while spending a long time in partial load condition as well [50].

Cruise ships are not following daily the same schedule. Sailing the whole day might be followed by a harbour day in order to offer land excursions. Alternatively the ships might also travel at low speeds in remote areas or while observing the nature next to laying at anchor in a bay. Especially the latter might be more usual for expedition cruise vessels in relation to bigger cruise liners with weekly itinerary like usually done in the west Mediterranean. Consequently, the ship is operating less frequent at design speed, as usually considered in the power load balances.

Following this, a typical operational profile is essential for quantifying the actual power demand. The activity-based approach is using operational data, like speed, linked with technical data of the vessel [50] as basis for the power prediction. Even if the general approach of this study follows still the bottom-up strategy, in order to define the operational profile, the activity-based approach is applied to obtain typical speed profiles of cruise vessels. The actual position and corresponding speed can be obtained out of the Automatic Identification System (AIS) over a time period of one month. All destinations are logged as well, together with the changes of speed while sailing. The voyage timeline can be gained out of the ship tracking and maritime intelligence provider *MarineTraffic* [59].

The different destinations and possibly varying routing of the vessels has to be considered (see section 4.1.1). Eight explorer cruise vessels are chosen from different shipping companies and within the range of a gross tonnage of up to 50.000GT (in accordance with ship type definition in section 4.1.1). All listed shipping companies are also member of the Association of Arctic Expedition Cruise Operators (AECO) [4] as well as the International Association of Antarctica Tour Operators (IAATO) [42], which are one of the biggest associations of expedition cruise lines which are operating within the polar regions under compliance of specific guidelines for environmental friendly and safe operations. This provides a wide range of different cruising itineraries and destinations as sufficient database for the following assumptions. The following vessels are used:

Table 6.1: Cruise ships considered for obtaining operational profile

Cruise ship	Shipping company	GT
Europa 2	Hapag-Lloyd Cruises	42,830 gt
Hanseatic nature	Hapag-Lloyd Cruises	15,651 gt
Le Laperouse	Compagnie du Ponant	9,976 gt
Roald Amundsen	Hurtigruten	20,889 gt
Scenic Eclipse	Scenic Cruises	17,085 gt
Seabourn Quest	Seabourn Cruise Line	32,477 gt
Silver Wind	Silversea Cruises	17,400 gt
World Explorer	Quark Expeditions	9,923 gt

The speed profiles of the months January 2020 and September 2019 are being used. The AIS signal coverage is partly incomplete and some gaps occur in the timeline. Additionally, the used data contains only the simplified voyage timeline due to data limits. Only changes in course or significant changes in speed are logged. The average time step is around a few hours while sailing, which is accurate for the current prediction. Further correction of the speed is not made by proving distances or routes. The speed at the data points for ”Arrival and ”Departure” are assumed to be zero.
An operational profile can be developed which correlates to the itinerary on the homepages of the shipping companies. The dynamic behaviour can be clearly seen in the figures B.1 and B.2 in the appendix B.1.1.

6.1.1 Speed profile

Out of the speed profile, the speed over ground can be obtained over time. The maximum speed of all expedition cruise vessels can be found in online resources and is reached at 100% of maximum output (or maximum continuous rating (MCR)). The design speed is assumed to be around 70%-85% of the MCR. No distinction could be made between manoeuvring in the ports and lying at anchor, as these speeds are both mostly between zero and one knot. Following this, the varying speeds are grouped into the following conditions.

Table 6.2: Ranges of speed and corresponding proportions of maximum speed

Speed Range	Percent of max Speed
High Speed	85-100%
Design Speed	70-85%
Medium Speed	40-70%
Low Speed	1kn-40%
Manoeuvring/Anchorage	$<$1kn
Port	0kn

The time spent at a certain speed condition can be summed up for every vessel for September 2019 and January 2020 to achieve the proportional distribution in graph B.3 in the appendix B.1.1. Further incidents, which has to be considered by processing the data, are discussed in the appendix B.1.1 as well. It can be clearly seen, that the design speed is not always used while sailing. In average, high speed is reached only temporarily. Operating in medium speeds and higher is only the case in roughly half of the whole time. The ships are more often at anchor in the summer period, while using the port more often in winter. However, the time spent for manoeuvring or at anchor and in harbour condition is in total around 40% of the whole time in summer and winter.

The average time spent at a certain speed can be obtained for summer and winter (values for September except data of *Europa 2* due to docking):

Table 6.3: Proportion of operations in certain speed ranges in summer and winter

Speed Range	Proportion in summer	Proportion in winter
High/Max Speed	4%	2%
Design Speed	25%	23%
Medium Speed	27%	25%
Low Speed	8%	9%
Manoeuvring	21%	15%
Port	21%	26%

The result can be expected, that the ships are not always operating at design speeds. In contrast to other cargo vessels, the cruise ships are following a very diverse operational profile which are defined by different fixed arrival times in the ports and destinations. This can be later used by defining typical day of operations and defining a typical operational profile.

6.1.2 Typical days of operation

In order to model now the power demand for the operational profile, the obtained speed profile is transferred into five typical day of operation (TDO), as proposed by Fazlollahi et al.[33]. Even if the cruise ships are not following a fixed schedule, most of the days are similar to one of these defined cases. For example, during crossing the open sea, the schedule might include sea days at design speed (TDO2), next to days operating in remote areas and observing the nature in lower speeds. For shore excursions, the ships are spending a whole or half a day in a harbour (TDO1 or TDO3).

The TDOs are set as follows. It considers sailing at lower and design speed, manoeuvring as well as harbour and at anchor conditions. The energy demand over a week or the whole year can be estimated in a later step by adding up different days similar to the planned schedule. This is a simplified procedure, but is sufficient for the current parametric study of the energy demand of the subsystems and identification of driving factors.

- TDO1: Moored in port all day
- TDO2: Sailing all day
- TDO3: Moored in port for half a day
- TDO4: Moored in port for 3/4 of the day
- TDO5: Slow speed sailing and anchoring for half a day

The basic idea of clustering the operations within typical days based on the ideas of Baldi et al. [10] with the systematic approach proposed by Fazlollahi et al. [33]. However, the mathematical algorithm of their research is not used to process the data by developing mean values and performance indicators. The idea is to keep the TDOs with their peak loads. An optimization and usage of mean power demands, like other research projects, might end up with a representation of a yearly energy demand but would not help with the current study of identifying the peak loads within a typical daily schedule.
Exemplary day one in figure B.4a (see fig.B.4 in appendix B.1.2) represents a day where the ship is staying in the harbour all day long. TDO 2 in fig.B.4b shows a sailing day. The vessel is sailing between two ports or even crossing the sea at design speed. The variation of speed in the following three days follows out of the outcome of the speed profile in the previous part and table 6.3. Figure B.4c shows a day where the ship is in the port during the day from 8:00 till 20:00. Within one hour before berthing, a certain bow thruster activity can be assumed while manoeuvring. The same holds true after departure. Longer stays in the port are considered in the exemplary day 4 in figure B.4d. Lastly, option 5 in figure B.4e shows the operation mostly in remote areas, where expedition cruise vessels are operating with lower speeds before anchoring for a few hours (here in afternoon, between 12:00-18:00) and offering some excursions.

6.2 Weather condition

It can be expected, that the ambient air temperature and humidity would have a significant influence at least on the HVAC system. Thus, the indoor conditions can be defined by applying International Organization for

Standardization (ISO) regulations and owner specifications in the following section 6.2.1. In addition, temperature profiles are providing typical ambient conditions for a summer and winter day next to defined maximum conditions out of regulations[48], as described in section 6.2.2.

6.2.1 Indoor conditions

The indoor climate is an important comfort factor for the passengers and crew and is defined in the international standard [48]. However, under consideration of the usually applied comfort zones by the American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. (ASHRAE), the ISO standard can be improved. Thus, the following values can be used, the same for summer and winter.

Table 6.4: Design conditions for air-conditioning and ventilation of accommodation spaces for indoor spaces[7, 48]

Season	Temperature	Humidity
Winter	+22°C	50 % Rel. Hum.
Summer	+22°C	50 % Rel. Hum.

6.2.2 Outside conditions

The systems are usually designed for the maximum expected conditions which are defined by the ISO design conditions for air-conditioning and ventilation of accommodation spaces [48]. Accordingly, the following values in table 6.5 can be used for the current project. In winter condition, no design condition for humidification are defined in the international standard. The humidification should take place only during longer periods of cold and dry weather whereas the risk of the formation of ice has to be considered[48].

Table 6.5: Design conditions for air-conditioning and ventilation of accommodation spaces for ambient air [48]

Season	Temperature	Humidity
Winter	-20°C	-
Summer	+35°C	70 % Rel. Hum.

Varying outside temperatures and humidities have to be compensated in order to provide the right indoor climate in the all areas on board. In order to consider the daily variation of the temperature and humidity, typical weather profiles can be used for a typical climate condition.
Consequently, the following locations are used, which do not exceed the maximum conditions, as defined earlier on, but provide a varying profile for warm and cold condition. Additionally, one profile is used for medium conditions. The weather profiles are shown in the appendix B.2 in figure B.6.

- For cold condition: Resolute Bay in Canada (winter condition used)
- For warm condition: Singapore (summer condition used)
- For medium condition: Amsterdam in the Netherlands (summer condition used)

6.3 Passenger and crew behaviour

The third varying parameter in the methodology in 4.1 is the passenger and crew behaviour. The occupancy of a certain area is also related to the power demand in terms of used facilities and components at a certain time. Thus, the following passenger and crew behaviour can be defined in order to consider this in the predictions later on. The definition is in accordance with the already used TDOs.

6.3.1 Passenger behaviour on board

The ISO7547 regulation [48] provides occupancies in different areas, which has to be considered as a maximum case for designing the heating and ventilation system. For example, the maximum number of passengers in a cabin is equal to the maximum number of beds. Consequently, this can exceed the ALB condition and can include even more than two passengers per cabin. In public rooms, the maximum number of humans is defined based on the area of the room and brings up a density in the room ρ_{Room}.

$$\rho_{Room,i,j} = \frac{PAX_{ALB,i,j}}{A_j} \tag{6.1}$$

However, for a dynamic model under typical operational conditions, the maximum number of people per definition is obviously not in all areas at the same time. Thus, a passenger behaviour has to be defined, even if no comparable data or real life observations are available.
First of all and similar to the thesis of Taen [80], the occupancy factor can be formulated as ratio between actual number of people per zone divided by the maximum number of people on board. Every type of area can be related to an actual occupancy rate K_{occ} per area j in the specific time step i (one day, subdivided in blocks of 30 minutes). Consequently, the sum of all factors within one time step should be 1 in order to distribute all humans on board in different rooms.

$$K_{occ,i} = \frac{PAX_{i,j}}{PAX_{ALB}} \tag{6.2}$$

The spaces for sizing the areas and volumes in the appendix A.3 are grouped into the following main areas due to simplicity.

- Passenger cabins
- Restaurants
- Leisure spaces
- Outdoor
- Passenger public spaces
- Not on board/port

The distribution per time step of passenger and crew is based on logical assumptions for typical passenger movements and crew working hours and is plotted in the graphs in the appendix B.3. For example in the night, most of the passengers are sleeping in the cabins. Secondly, the main mealtimes are in the morning and in the evening after 18:00. While moored in port, most of the passengers are not on board due to excursions or other individual trips. The area *Outdoor* describes the outdoor areas on the ship, like sun decks or pool areas.

6.3.2 Crew behaviour on board

Similar to the previous procedure for the passengers, the crew is distributed over the different defined areas. The behaviour is plotted in the graphs in the appendix B.3 as well. Due to different shifts, a certain proportion is always assumed to stay in the crew cabins.The crew public spaces include for example the crew mess. Mostly during the day, the crew is working in the passenger restaurants and leisure facilities. The machinery rooms are always occupied by a few people. However, no major differences exist between the different TDOs, as the crew is also often working and staying on board while berthing. The different crew areas and working environments are considered as follows.

- Crew cabins
- Crew public spaces
- Laundry
- Galleys
- Passenger Restaurants
- Passenger leisure spaces
- Flux, Machinery and Outdoor

Chapter 7

Power demand of systems

Before implementing the fuel cells, the energy and power demand has to be understood under the operational conditions, as discussed in the previous chapter. Based on the system breakdown in section 5.1, the main subsystems and groups of components of the *propulsion systems* (section 7.1), *auxiliary systems* (section 7.2) and *hotel systems* (section 7.3) can be estimated in the following chapter. The separate prediction models are described and validated, followed by the results including the system behaviour. Generally, the focus is on identifying the maximum power demand to assess the power plant (or fuel cell) size. Additional power fluctuations can be analysed as well (see third and fourth research question, sec. 3.3.3 and 3.3.4), which are critical for fuel cell systems. If an additional peak load cannot be considered within the used time step size of 30 minutes, then it is listed as immediate peak load manually.
The differences to the common load balance approach can be pointed out (see second research question, sec. 3.3.2) by comparing it in the first design phase with the new estimation under dynamic conditions. The influencing factors refer to the passenger behaviour, environmental influence and operational condition in terms of speed, as defined earlier in section 6.

7.1 Propulsion systems

The propulsion system is one of the main consumers on board of a cruise ship, as pointed out in other reports and in the system breakdown of the reference ship in section 5.1.1, with around two-thirds of the overall demand. Consequently, for a better understanding of the system behaviour under varying operational conditions, it has to be subdivided. The main contributors are already the *propulsors*, the azimuth thrusters (see section 7.1.1). Additionally, the *bow thruster* (see section 7.1.2) and *propulsion support systems* (see section 7.1.3) are considered as separate consumers as shown in the breakdown in figure 7.1.

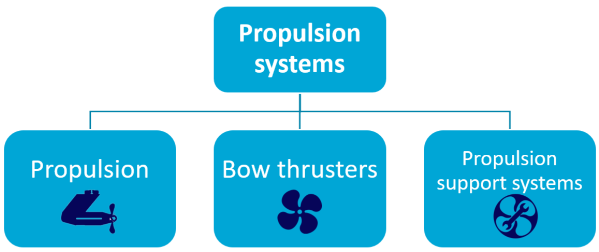


Figure 7.1: System breakdown of propulsion system

Influencing factors Obviously, the speed of the vessel is the main driving factor of the propulsion power demand. It is directly related to the resistance and consequently to the required power. The additional varying conditions are neglected, which are mentioned in section 6, because the passenger behaviour onboard does not have an influence on the power demand. Even a different number of passengers can be neglected on board, because no significant change of the displacement would occur due to the low payload. Thus, the draft and resistance will basically stay constant. In addition, the ship is always fully occupied at 100% (see section 2.2.4) in most of the cases anyway.

Secondly, the different weather profiles are not considered in the prediction of the propulsion power demand. Different wind directions and speeds as well as waves and currents [18] can influence the required propulsion power which are also related to higher waves and sea states. Out of statistics it is assumed, that better weather conditions might occur in the summer season. However, the impact of these different weather conditions is negligible for the current study, because no rapid and significant weather changes are expected to occur within one day, which is the used time scale (see TDOs in section 7.1). The main goal of the study is the identification of load behaviour, peaks and power ramp ups under typical operational conditions. As a consequence, no major differences are expected between summer and winter, like in the common load balance approach.

7.1.1 Propulsion

Generally, rough predictions are made in order to achieve a model for a parametric cruise vessel hull without a detailed computational simulation with any other dedicated software. Assumptions for the main dimensions and areas are made based on the main input data and definitions in section 4.1.1 and common arrangements for expedition cruise vessels.

Prediction model

First of all, the volume is estimated with the predefined or estimated GT (see equation 4.3), sea water density and equation 4.3. Now, the empirical method of Holtrop and Mennen [39] is used to calculate the propulsion power of the vessel. The total resistance R_T of the ship at design speed is calculated out of the sum of the frictional resistance R_F and the form factor $(1+k_1)$, appendage resistance R_{APP}, wave resistance R_W, additional pressure resistance of bulbous bow R_B, additional pressure resistance of immersed transom stern R_{TR} and the model-ship correlation resistance R_A.

$$R_T = R_F\,(1+k_1) + R_{APP} + R_W + R_B + R_{TR} + R_A \tag{7.1}$$

The whole calculation is involved in the Appendix C.1 including all coefficients and form parameters. The total resistance multiplied by the ship speed results in the effective towing power P_E:

$$P_E = R_T\, v_s \tag{7.2}$$

By using the propulsive efficiency η_D, the propulsion power P_D is obtained. The propulsive efficiency consist of the hull efficiency, the relative rotative efficiency and the open water propeller efficiency. The latter is depending on many factors of the propeller loading and design and varies at different speeds. However, in order to reduce the computational time, the overall propulsive efficiency is assumed to be constant for the current study and equal to 70%. This correlates with the study of Volger[89] and internal discussions at the shipyard for the first design phase. Consequently, it can be stated:

$$P_D = \frac{P_E}{\eta_H\,\eta_O\,\eta_R} = \frac{P_E}{\eta_D} = \frac{P_E}{0.7} \tag{7.3}$$

Similarly for the brake power P_B, additional efficiencies has to be considered, combined into the transmission efficiency η_{TRM}. As described previously in section 4.1.1, the supplied power from the Diesel gensets is transmitted electrically to the two azimuth thrusters. Thus, the overall efficiency of the transmission considers the losses within the cables, electric motor, drive, transformer and generator. The efficiencies are assumed based on discussions with experienced engineers at the cooperating shipyard and displayed in table C.1 in the appendix. They are kept constant for all speeds in the model.

$$\begin{aligned} P_B &= \frac{P_D}{\eta_{Gen}\,\eta_{Tr}\,\eta_{Dr}\,\eta_M\,\eta_{Cab}} \\ &= \frac{P_D}{\eta_{TRM}} = \frac{P_D}{0.894} \end{aligned} \tag{7.4}$$

Now, the propulsion power has to be examined also for speeds unequal to the design speed. The propeller law is used by formulating the coefficient c_{Prop} in design condition and scaling the propulsion power as described by equation 7.6.[57, 92]

$$R_T = c_{Prop}\, {v_s}^2 \tag{7.5}$$

$$P_{B,i} = R_T\, v_s = c_{Prop}\, v_i^3 \tag{7.6}$$

Validation The required propulsive power for the design speed condition for the used reference case is calculated by the following value. This value is in the right order of magnitude by comparing it to the given value for the reference vessel.

$$P_{B,HM} = 3813 \text{ kW} \tag{7.7}$$

As described earlier, the remaining speeds are calculated with the propeller law and displayed in the graph in figure 7.2.

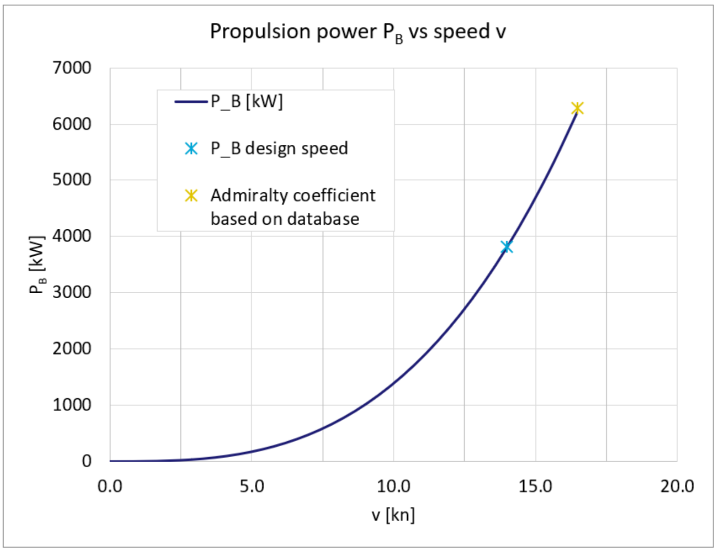


Figure 7.2: Propulsion power P_B over speed in knots based on Holtrop&Mennen and propeller law for off-condition as well as admiralty formula considering regression data

Generally, the calculation of the propulsive power is done by applying a commonly used empirical method by Holtrop and Mennen for the first design phase to obtain a first power prediction for a vessel. However, already built cruise ships can be compared by obtaining the admiralty constant out of the database and the given propulsion power in maximum speed condition. A relationship is formulated between the known propulsion power and the calculated admiralty factor $\left(\Delta^{2/3}\, v_S^3\right)$ of the reference vessels, as plotted in figure 7.3 and stated in equation 7.8.

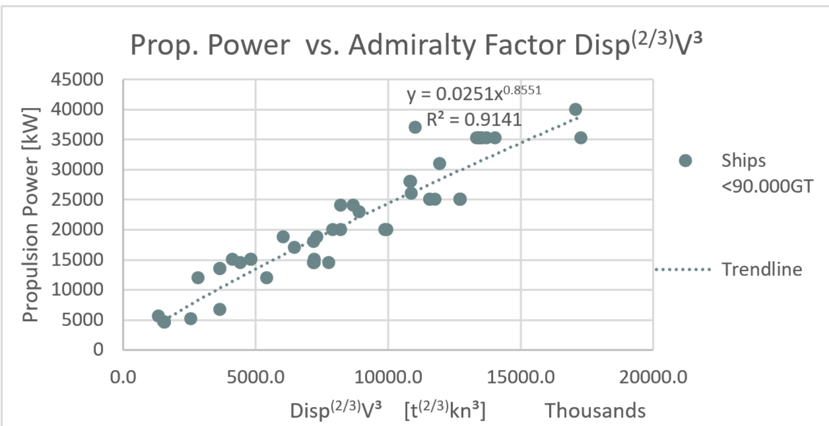


Figure 7.3: Propulsion power vs admiralty factor $\left(\Delta^{2/3}\, v_S^3\right)$ of built cruise ships with less than 90,000gt

$$P_{B,adm} = 0.0251 \left(\Delta^{2/3} \, v_s{}^3\right)^{0.8551} \tag{7.8}$$

The known displacement and maximum speed in the ship specification brings up the second predicted propulsive power. The value for the test case is calculated in equation 7.9 and is compared with the estimated value for the maximum speed condition. The result is also plotted in the graph 7.2 as well.

$$P_{B,adm} = 6278.6\text{kW} \tag{7.9}$$

$$\rightarrow \delta_{P_B} = \frac{P_{B,adm} - P_{B,HMmax}}{P_{B,adm}} = 1.1\% \tag{7.10}$$

The difference of 70kW is equal to only 1% above the obtained propulsive power out of the applied Holtrop and Mennen approach. As a result, the used assumptions of dimensions and areas are validated and result in a reasonable value for the required power, which is compared with similar ships in the database.

System behaviour and calculation results

As described in the definition of the typical days of operation, the power of the propulsion systems is mainly based on the variation of the speed. The passenger behaviour does not have an influence on the power demand of the propulsion of a cruise ship due to the negligible load change in contrast to a containership and its load of containers and different drafts. The weather condition can have an influence as soon as the cruise ship is operating in extreme conditions. These weather occurrences are the basis for the installation of components and are considered in the sea margin. However, the focus of this study is on the power behaviour within the predefined *typical* days. Thus, no sudden changes due to weather changes are expected during one typical day and the propulsion systems are in the end only defined with the expected speed.

The propulsion demand is plotted over time by using the calculated value P_B in 7.7 and the used load in the certain time step, as defined in section 6.1.2. The figure D.1a in the appendix D.1 shows the power demand for the five defined typical days. The maximum value occurs at maximum speed (due to definition in TDO5) as summarized in table 7.1. However, due to the change of speed over day, the power demand of the main propulsion is also varying significantly. Thus, the average demand over one sailing day (TDO2) is obviously close to the maximum value, while the system is more rarely operating at its maximum load under consideration of the typical operational profile of cruise ships (see section 6.1) where the TDO3, 4 and 5 will occur more often.

In addition, high load changes are expected (table 7.1, 2613kW over 30min for reference case) while changing the speed. In addition, immediate peaks are expected while manoeuvring in port. Consequently, the high power and energy demand is in sailing condition, while having significant load changes in port days.

Table 7.1: Characteristics of calculated power demand of main propulsion for chosen reference vessel

Parameter	Value		In situation
Max. power demand	4526	kW	Max. speed (here: as defined in TDO5)
Max. average power demand per day	3813	kW	TDO2; sailing day
Max. load change over 30 min.	2613	kW/30min	TDO4; increasing speed
Max. peak load (expected)	1600	kW/1-3min.	Manoeuvring
Max. daily energy demand	329,430	MJ/day	TDO2, all day sailing

As a conclusion, for the efficient design of the power plant (including fuel cells), the comparable high demand has to be considered while having high load changes at off-design conditions at a lower power level in port days.

7.1.2 Bow thruster

The thrusters would only have an effect on the side motion of the vessel at low speeds and are used for manoeuvring in the harbour in a short period of time. However, the required power of the system is significantly high and is important to consider in the common load balances in the port condition. The current study applies the *"Crabbing criteria"*, which defines the maximum installed power for the bow thrusters. The specific loading is defined based on normal use in the harbour later on within the TDOs, independently of the passenger behaviour. Furthermore, any extreme or varying weather conditions are not considered as well, as elaborated earlier in section 7.1.

Prediction model

Usually the targeted cruise ship size (as described in 4.1.1) has two bow thrusters in order to provide a sufficient side force while manoeuvring. This number is set for the current model. Basically, the installed power of the bow thrusters $P_{BW,inst}$ is calculated with the specific power and the required thrust force out of the equilibrium of moments around the pivot point of the vessel. The specific power q_{BW} is defined as used constant at the shipyard in the basic design stage and equal to 11.7kg/kW.

$$P_{BW,inst} = \frac{F_{Thurst}}{q_{BW}\, g} = \frac{F_{Thurst}}{11.7\frac{\text{kg}}{\text{kW}} g} \tag{7.11}$$

The thrust force is obtained under consideration of the wind force[14]. The detailed estimation is shown in the appendix C.1.1. It is summarized with the following equation considering the different points of action (see fig.C.1 in appendix) and the wind force F_{Wind}.

$$\begin{aligned} F_{Thrust} &= \frac{F_{Wind}\,\frac{L_{PP}}{2}}{0.92\, L_{pp}} \\ &= \frac{F_{Wind}}{1.84} \end{aligned} \tag{7.12}$$

Validation The estimation of the thrust power results in a required installed power for the test case as follows in expression 7.13:

$$P_{BW,inst} = 1608.6\text{kW} \tag{7.13}$$

This is validated with the installed power for the reference vessel at the shipyard. The result from the owner specification is here in the same order of magnitude as the estimated value in 7.13. Consequently, the estimation and rough assumptions are validated for the first design phase. Nevertheless, lateral areas and location of the bow thrusters have to be adjusted again individually in a later step.

System behaviour and calculation results

As described earlier in section 6.1.2, the bow thrusters are only used in the harbour in the hour before mooring and at anchor. In addition, an actual used power of around 50% of the total installed power is usually applied in the common load balance approach in harbour condition. This means, that only one thruster is running in normal conditions while manoeuvring in port. As a consequence and conservative approach, the actual used power is assumed to be at 30% one hour before mooring and 60% of the maximum power in the last 30 minutes, as described in the TDO definition in section 6.1.2. The installed maximum power is used for extreme weather cases, which are not considered in normal conditions in this study.

Having defined that, the maximum occurring power of the bow thruster is at 1610kW for the reference case, as summarized in table 7.2. The fact of having a low average demand during all TDOs of the bow thruster is negligible due to the temporary operation. However, under the made assumptions, the load change of around 500kW occurs after the used time step of 30 minutes. This has to be adjusted by manually adding an even higher immediate load peak, which is expected while manoeuvring. Spontaneous power ramp up and downs are typically for the bow thruster before mooring which can raise up to the maximum power (here 1610kW).
Next to the propulsion demand, the required power for the bow thruster is plotted in the appendix as well in figure D.1b. The peaks in demand are clearly visible right before and after mooring in port, where the main propulsion power goes to zero.

Table 7.2: Characteristics of calculated power demand of bow thrusters for chosen reference vessel

Parameter	Value		In situation
Max. power demand	1610	kW	Max. power manoeuvring
Max. average power demand per day	30	kW	TDO3
Max. load change over 30 min.	483	kW/30min	TDO3 and TDO4; while manoeuvring
Max. peak load (expected)	1610	kW/1-3min.	while manoeuvring
Max. daily energy demand	2606	MJ/day	TDO3

In order to conclude, the main purpose of a bow thruster is to ensure safe manoeuvring in port, consequently a reliable powering of the dynamic power demand is crucial. While the average power and energy demand are negligible, the important fact is having significant high load changes in short period of time.

7.1.3 Propulsion support systems

The propulsion supply systems contain all subsystems which are necessary for reliable operation of the main engines and consist mainly of the pumps for fuel loading, transport and supply. Furthermore, the fuel cleaning (purifiers), lubrication oil pumps and compressed air system are included as well, as discussed earlier on in section 5.1.1.
The systems run constantly and independent of the passenger behaviour or further weather influences. Minor variations due to the speed variation are neglected. Thus, the power is considered to be constant over time.

Prediction model

As a consequence, the prediction model is constructed in a simplified way and only based on the installed propulsion power. Together, all propulsion support systems are assumed to consume 4% of the total installed propulsion power as estimated in section 7.1.1. Only in harbour the consumption differs and is assumed to be 20% of the predicted value.

$$P_{support,i} = \begin{cases} 4\% \cdot P_{B,max} & \text{Sailing condition} \\ 20\% \cdot P_{support,sailing} & \text{Port condition} \end{cases} \tag{7.14}$$

Validation The used percentage is already obtained out of reference vessels in the first design phase, in order to define the percentage in expression 7.14. Consequently, the value would comply with the available data. Other reference data are depending on the definition of the supporting systems and the arrangement of the main engines. However, they are also in the same order of magnitude and might differ only with a few percentage points, e.g. 3% in de Vries [22].

System behaviour and calculation results

The power demand is calculated exemplary for the test case. Based on equation 7.14 and 7.4, it is calculated in 7.15.

$$\begin{aligned} P_{Support} &= 4\% P_{B,max} \\ &= 248\text{kW} \end{aligned} \tag{7.15}$$

Only a reduction of the running support systems is assumed in the port, because of ongoing maintenance and bunkering processes. The power demand is shown in the figure D.2a with its constant value in all time steps and defined TDOs. Consequently, the average demand is normally close to the maximum power demand as well, as shown in table 7.3. A steady increase of power (here 200kW over 30 min) occurs only while running up the engines from harbour to sailing conditions followed by having again a constant load. Thus, no additional significant load changes are expected, which might occur only by starting certain oil pumps or pre-heaters.

Table 7.3: Characteristics of calculated power demand of propulsion support systems for chosen reference vessel

Parameter	Value		In situation
Max. power demand	248	kW	TDO2, TDO3, TDO4 and TDO5; while sailing
Max. average power demand per day	248	kW	TDO2 and TDO5; while sailing
Max. load change over 30 min.	199	kW/30min	TDO3 and TDO4; ramp-up phase after departure
Max. peak load (expected)	20	kW/1-3min.	e.g. pump or pre-heater
Max. daily energy demand	21457	MJ/day	TDO2 and TDO5

In summary, the propulsion support systems are described by a constant load which only differs slightly after departure and running up the engines. After implementing the fuel cell, the contribution might be different due to another system configuration and has to be redefined again in another design review (here out of scope).

7.1.4 Differences to load balance approach

The used predictions for the propulsion and bow thrusters are commonly used approaches in the first design phase to define the order of magnitude of the required power and size of the components. Meanwhile, no additional influence of any dynamic parameters like weather or passengers are expected and considered. Thus, the actual speed is the main driving factor.

The maximum power demand out of the prediction is close to the used value in the load balance for the reference ship with a negligible proportional difference. However, the ship is operating most of the time at off-conditions with a significant lower demand based on typical operational profiles (see TDO3-5).

The propulsion support systems could have been defined more clearly under consideration of the information of the engine manufactures for available engine sizes or fuel and lubrication oil supply and handling. The latter is simplified in this study by applying a proportional rate of the installed propulsion power. However, no accuracy improvements are expected. The order of magnitude for power demand and expectable load changes is obtained, which is the focus of this study towards the implementation of a fuel cell.

As a conclusion, the propulsion systems are having a high power demand in sailing condition and additional high load changes while manoeuvring in port. Meanwhile, coastal operations are usually at lower speeds which reduces the power and energy demand as well.

7.2 Auxiliary systems

The auxiliary systems are taking all remaining systems into account. However, for a cruise vessel, the distinction is made between the auxiliary systems and the additional hotel systems, as mentioned already earlier on in section 5.1.2.
They are subdivided into the following systems as shown in figure 7.4. The deck equipment includes all hydraulic systems like cranes and equipment to handle the additional equipment. Additional hull openings and doors are included as well and described in section 7.2.1. Following this, the survival systems are briefly described in section 7.2.2 including the power demand over time. The third auxiliary system includes all water systems in section 7.2.3, which are offering the supply and handling of the required sea and fresh water as well as the wastewater.

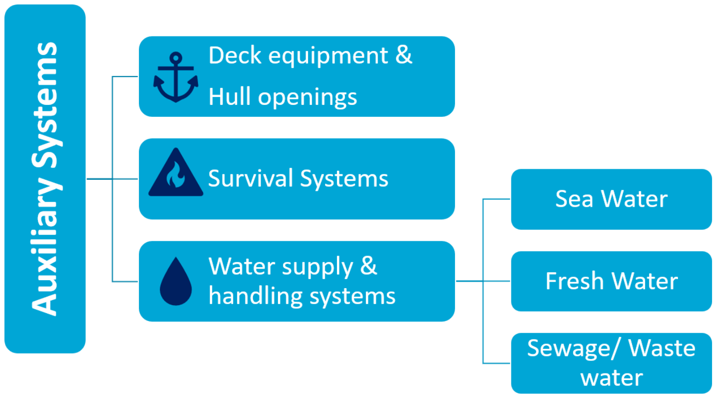


Figure 7.4: System breakdown of auxiliary systems

Influencing factors Looking back to the three main varying operational parameters, the auxiliary systems are independent of the speed variation. Secondly, the number of passengers does play a role by sizing the systems, whereas the daily behaviour on board is less important. Only small variations are considered in the water system. Lastly, the weather season influences the sea water temperature with an impact on the water supply system, while the varying ambient air temperature during the day is not further considered.

7.2.1 Deck equipment and hull openings

The deck equipment is a small part within the overall electric load balance of a cruise ship, as shown in the breakdown in figure 5.2. Especially the cranes and smaller boats are typically a part of the equipment of an expedition cruise ship. The different doors ensure a safe and quick embarkation of the passengers while being moored or at anchor in a bay. This results in a higher installed power for the different components than actually used at the same time.

Prediction model

The required power is assumed to be constant per defined season. In addition, the demand in port is assumed to be higher and twice as high within the hour after arrival (ATA) and before departure (ATD) due to higher activity on board and use of the expedition equipment, cranes and doors. Generally, the exact installed power and number of components are highly depending on the specification of owner and is for the current project predicted by the factor 0.02 kW/gt based on the reference vessel. The used power at a certain time is described by the used proportion u_{DEquip} as defined in table 7.4. The utilization factor is higher in winter due to additional defrosting. Finally, the dynamic power demand is described by the equation 7.16 for every time step *i*.

$$P_{DEquip,i} = \begin{cases} GT \cdot 0.02 \frac{\text{kW}}{\text{gt}} \cdot u_{DEquip,c} & \text{Sailing condition} \\ 2 \cdot GT \cdot 0.02 \frac{\text{kW}}{\text{gt}} \cdot u_{DEquip,c} & \text{After ATA; before ATD} \end{cases} \tag{7.16}$$

Table 7.4: Utilization factor u_{DEquip} of deck equipment

Condition c	**Factor** $u_{DEquip,c}$
Sailing summer	2.5%
Sailing winter	4.5%
Moored in port	6.5%

Validation Not a lot of real-life data is available for the deck equipment. Thus, a validation of the installed power and the individual use over time is difficult to validate and is highly depending on the operation and owner requirements. The defined proportions are obtained by the given reference vessel and are obviously validated for the current case. This brings a certain uncertainty into the model, but on a low level. However, the contribution of the power demand is low and no extensive load peaks or variations are expected, which would be neglected with applied approach.

System behaviour and calculation results

As discussed, the load is assumed to be widely constant over time. For the current case, the installed power is calculated to be 1047kW. However, applying the utilization factors in table 7.4, the actual load is always below 100kW except of the hour after arrival or before departure.
For the used reference vessel, the maximum average power demand per day and energy demand is obtained for the TDO1 while staying all day in port. In addition, the maximum power and highest load changes are expected to be in the hour after arrival and before departure, where all the equipment on board are used and automatic doors and hull openings are in operation as well. However, the expected immediate changes in the power demand within a few minutes are not higher than 80kW. Due to the longer time step in the model, this situation is not considered within the calculation and is now added manually to consider unpredictable operations and local peaks.

Table 7.5: Characteristics of calculated power demand of deck equipment and hull openings for chosen reference vessel

Parameter	Value		In situation
Max. power demand	136	kW	After ATA; before ATD
Max. average power demand per day	71	kW	TDO1, moored in port
Max. load change over 30 min.	110	kW/30min	Summer cond., after ATA; before ATD
Max. peak load (expected)	80	kW/1-3min.	e.g. use of several cranes and doors
Max. daily energy demand	6143	MJ/day	TDO1, moored in port

7.2.2 Survival systems

The survival systems include varies smaller systems to enhance safety and survivability of the ship in different conditions under fulfilment of fire protection or stability regulations. As discussed earlier in section 5.1.2, the hazard prevention systems are part of it including the bilge and ballast water treatment units, separators and pumps, as well as the hazard fighting systems including the fire and deck washing pumps.

Prediction model

Similarly to the previous system, the overall contribution of the electrical consumers is low and assumed to be constant per operational condition (sailing and port). Consequently, the installed power is defined for all components based on the GT applying the factor 0.05kW/gt. The utilization factor is low, because the maximum condition is expected to be in emergency cases, where the emergency generators (not further considered in this study) are providing the energy. The factors in table 7.6 are defined out of reference data, which results in the following equation.

$$P_{Survival,i} = GT \cdot 0.05\frac{\text{kW}}{\text{gt}} \cdot u_{Survival,c} \tag{7.17}$$

Table 7.6: Utilization factor $u_{Survival}$ of survival systems

Condition c	Factor $u_{Survival,c}$
Sailing	5.0%
Moored in port	2.5%

Validation The systems and their power demand can slightly vary depending on their design. Depending on regulations, they are also further combined like the bilge, ballast and firefighting systems. However, the contribution is small and always below 1% for the reference vessel in the considered cases in figure 5.2. Thus, no further variation over the day is implemented and the results are validated with the available data set as origin of the defined factors.

System behaviour and calculation results

As shown in the overview in table 7.7, the power demand is widely constant and always below 50kW for the used case. Next to the low changes in the power demand over one time step, an additional peak in demand is added with 90kW within a few minutes. This is the results of an immediate use of a pump or separator within the bilge system. Other components have a lower power demand. Higher power ramp-ups are expected in an emergency case, where the emergency generators are providing additional power. Thus, these load peaks are not considered for the main power plant.

Table 7.7: Characteristics of calculated power demand of survival systems for chosen reference vessel

Parameter	Value		In situation
Max. power demand	38	kW	While sailing
Max. average power demand per day	38	kW	TDO2, sailing
Max. load change over 30 min.	19	kW/30min	Sailing- to Port-mode
Max. peak load (expected)	90	kW/1-3min.	e.g. bilge water heater or pumps
Max. daily energy demand	3240	MJ/day	TDO2, all day sailing

7.2.3 Water supply and handling systems

The last group of subsystems within the auxiliaries is the water supply and handling systems. It includes all cooling systems, water supply and generation systems and wastewater handling systems. Partly it is depending on the demand of potable water (PW) of the passengers and is consequently also defined as hotel system in other studies as well. However, due to the cooling cycles of fresh water (FW) and sea water (SW) it is considered as a general supply system within the auxiliary systems. Sometimes these subsystems are also connected, which makes a clear distinction even more difficult.

Prediction model

Generally, the electrical power demand of the group of water systems is predicted by the main subsystems as shown in the equation 7.18. The electrical power $P_{HVAC-cooling}$ of the pumps of the cooling water is related to the cooling demand in the HVAC system (see section 7.3.1 later on). The FW and SW cooling water has to be pumped as well for the engine cooling, see $P_{Engine-cooling}$. This is reviewed in a later stage after implementing the fuel cell and probably different heat gains. Furthermore, the potable water has to be generated ($P_{PW-generation}$) by reverse osmosis and distributed on board ($P_{PW-pumps}$), based on the required water volume by the passenger and crew. Lastly, additional pumps have to be powered to handle the wastewater ($P_{WasteWater}$) and additional water volumes to the laundry or between different tanks (considered within P_{Margin}). The more detailed prediction model is elaborated in the Appendix in section D.2.1.

$$P_{Water,i} = P_{HVAC-cooling,i} + P_{Engine-cooling,i} + P_{PW-pumps,i} + P_{PW-generation} + P_{WasteWater} + P_{Margin} \tag{7.18}$$

Validation The values are obtained by using the reference vessel powered by a common diesel-electric configuration. This has to be proven after the fuel cell implementation. Especially the cooling demand is expected to be different and is also connected to the potable water generation and heating as well. Consequently, this system can be seen as validated within the actual scope of the study with an acceptable uncertainty. Even in a different systematic design in a later stage, no extensive power variations or peak loads are expected.

System behaviour and calculation results

Due to the applied approach and rough predictions, the majority of power consumers have a constant power demand over day. Minor load changes are neglected. The dynamic changes are a result of the varying cooling water demand and amount of generated fresh water. Remaining cooling pumps are considered with a lower demand only in port. This results in the maximum power and energy demand for the water systems in summer condition, while sailing (TDO2), see table 7.8. The maximum load change out of the calculation (here 122kW over 30min.) is a result of a lower cooling demand on board. However, no additional immediate load peaks are expected only small ramp-ups by turning on a certain pump, less than 80kW.

Table 7.8: Characteristics of calculated power demand of water supply and handling systems for chosen reference vessel

Parameter	**Value**		**In situation**
Max. power demand	435	kW	TDO2, ISO summer, early morning
Max. average power demand per day	422	kW	TDO2, ISO summer
Max. load change over 30 min.	122	kW/30min	TDO4, ISO summer, after arrival in port
Max. peak load (expected)	80	kW/1-3min.	e.g. cooling pump
Max. daily energy demand	36491	MJ/day	TDO2, ISO standard summer

7.2.4 Differences to load balance approach

The maximum power demand for every system out of all considered TDOs is compared with the predicted value in the commonly used load balance, because this should be usually the design condition. As shown in figure 7.5, the values are comparable in summer (red bars) and winter condition (blue bars). This is partly expected, because the given data (in load balance) was the basis for defining the factors for the first two systems.

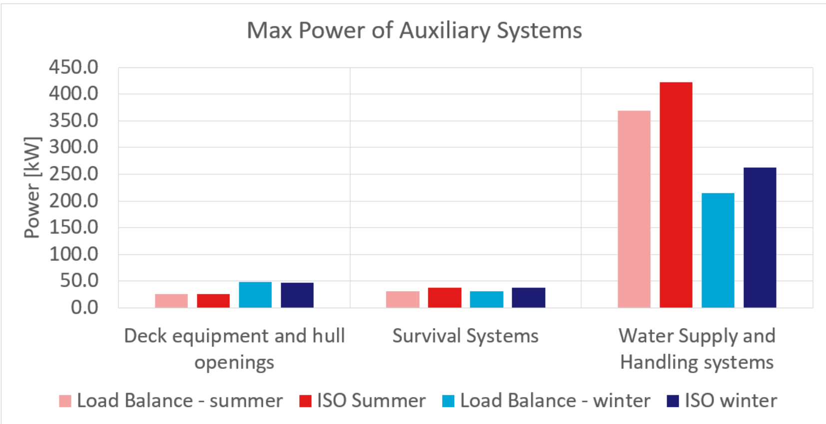


Figure 7.5: Comparison of max. power demand of auxiliary systems between common load balance and calculated values of model, for summer and winter condition

The passenger behaviour and different seasons (water temperature) are considered in the water system prediction and the operational condition (port or sailing) is the only influencing factor for the remaining systems (deck equipment and survival systems). Further environmental variations and the actual speed variation do not have a significant influence on the power demand of the auxiliary systems. This results in major differences between the different operational conditions, while the passenger influence is low, as shown in figure 7.6 (here exemplary for TDO2 and TDO3 in ISO summer condition). Thus, the highest load changes are by changing the operational condition (see right graph in figure 7.6), while in sailing condition (see left graph in figure 7.6) the power demand of all auxiliary systems is nearly constant throughout the day. In contrast, it can be concluded that all load changes are occurring on a low level and the power demand is widely constant by having only small load peaks while using the deck equipment in harbour mode (e.g. see right graph in fig.7.6, turquoise data set, after actual time of arrival (ATA) in the morning).

However, comparing the models, only small differences can be observed in the varying load over time. The constant power demand for harbour and sailing condition of the commonly used load balance is displayed in figure 7.6 as well (broken line). In comparison the predicted systems are slightly overestimated, due to a conservative choice of proportional factors within the estimation, which is acceptable to consider the worst-case condition.

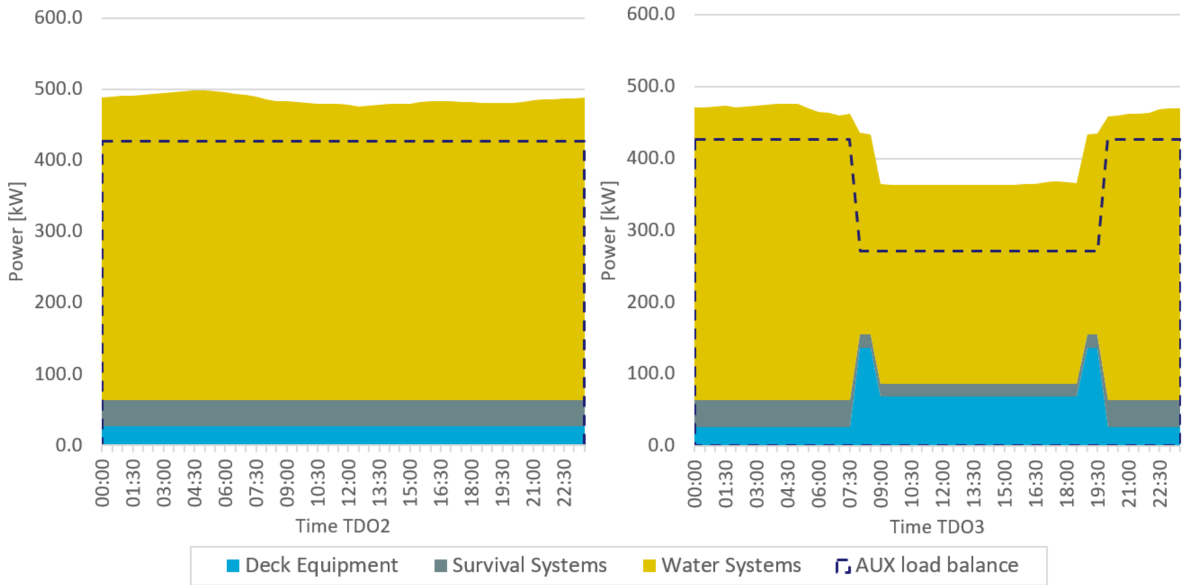


Figure 7.6: Power demand of auxiliary systems over time for defined typical day of operation 2 and 3 in ISO summer condition

7.3 Hotel systems

Lastly, the hotel systems is discussed which are more related to the passenger comfort. The individual configuration of systems and components are always depending on the owner requirements. However, within the scope of an expedition cruise ship, the limited number of outfitting, leisure and entertainment facilities are grouped to enable a rough prediction of the electric energy demand in the first design stage.
Figure 7.7 shows the groups within the hotel systems. The heating, ventilation and air conditioning (HVAC) system and chilled water plant are predicted together under consideration of the various influencing factors in section 7.3.1. Secondly, the varying demand of the galleys and laundries is predicted in the following section 7.3.2. Section 7.3.3 focusses on the lighting system considering mainly the passenger behaviour, while the remaining systems have just a small contribution as shown previously in figure 5.2. Thus, they are described together in section 7.3.4, also referred to as minor systems. As a conclusion, the differences and results of the power demand of the hotel systems are pointed out in the last section 7.3.5.

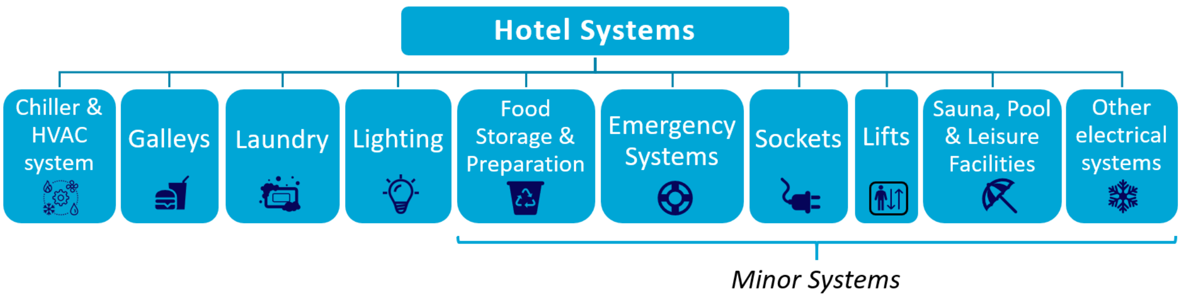


Figure 7.7: System breakdown of hotel systems

7.3.1 HVAC and chilled water plant

The heating, ventilation and air conditioning system is one of the most dynamic energy systems on board of a cruise ship. Under consideration of different regulations, the system has to provide comfortable thermal conditions for occupied areas for passengers and crew. Furthermore, viable conditions are required in working spaces while the prevention of the dispersion of contaminants to any public spaces has to be guaranteed [73]. This holds true for a separate handling of exhaust gases from sanitary spaces and galleys as well. As a consequence, the different areas were already grouped in the appendix A.3 and separate estimations are made for every area.

As mentioned in the system breakdown, the passenger cabins are supplied by local fan coil unit (FCU)s and the public and crew areas by centralized air handling unit (AHU)s. They include the electrical components of fans, cooler, heater and humidifier.

Different investigations are made to increase the efficiency of this system depending on the individual requirement of owner and passengers. However, for the current study, a typical arrangement for cruise ships is used to assess the energy and power demand behaviour under varying conditions. Due to simplicity and possibility of an automated calculation, all defined areas are separately calculated supplied by one central AHU each. The actual size of the module might not exist and would be subdivided into smaller components within the certain area. However, the focus is on the electrical demand of the system and not of the systematic integration of specific available AHU units from manufacturers. The local FCUs in the cabins are controlled separately depending on the demand in the cabin. This results in a higher electrical demand than a centralized system but is based on typical arrangement to fulfil high and individual passenger comfort standards.

Influencing factors

The HVAC is influenced by the environmental condition (see section 6.2) and the passenger and crew behaviour, as discussed in 6.3. Consequently, the ambient air has to be conditioned and heated or cooled depending on the season, which results in a different power demand per time interval. Besides, the ventilation is reduced in unoccupied areas to reduce the power demand. Furthermore, the gained heat (sensible and latent heat) is also related to the number of humans in the room. Additional variations [72] like clothing or activity level are neglected due to complexity of the model and low influence on the final results.
Lastly, every type of area has different requirements regarding inner temperature, fresh air (FA) proportion and number of air changes. The main parameters are defined in table D.2 in the appendix D.3.1 and are based on commonly used values by the owner and advices of classification societies and regulations.

Prediction model

Generally, the prediction is made for every time step (interval of 30 minutes) i and every area j separately. The areas are geometrically defined by the assumptions made in section A.3 in the appendix together with the data in table A.3. In contrast to the main public and crew areas, one standard passenger cabin (see figure A.6) is calculated and multiplied times the number of available cabins. However, the distinction is made between occupied and unoccupied cabins as well as cabins towards the sun considering the additional heat gain (see calculation in appendix D.3.1). The required inner temperature is defined in table D.2 based on current standards and regulations [1, 2, 48]. Varying per time step, the outer environmental conditions are described by the chosen weather condition (constant in ISO summer or winter condition, or as dynamic profile for hot, cold or medium location, see section 6.2.2).
In general, the calculation consists of the following steps:

1. Prediction **heat gain** in cabin or area
2. Obtaining required **number of air changes**
3. Obtaining **fresh air (FA) ratio** of supply air volume
4. Calculation of **intermediate conditions** in fan coil unit (FCU) or air handling unit (AHU), to obtain:
    - Heating demand (in winter), or re-heating after dehumidification (in summer)
    - Cooling demand (mainly in summer)
    - Humidification demand (pump as electrical component)
    - Required air volume for fan power

First of all, the intermediate condition is calculated within the **passenger cabins**. The simplified sketch in figure 7.8 shows the principle of the FCU.
Occupied passenger cabins are supplied by 100% fresh air, while unoccupied cabins are using partly recirculated air as well. The supply air condition is known including the proportion of fresh air (FA) which has to balance the heat gain (or loss) within the cabin. The heat is generated electrically in the FCU as a first step. Afterwards,

the cooler is connected to the chilled water coming from the central chilled water plant in order to be able to cool down the air in summer condition. The cooling demand is the basis for predicting the chillers in a later step, which are connected to the chilled water cycle. The adiabatic humidifiers have to pump a small amount of water to the humidification units contributing a small amount of electric energy. Lastly, the electrical fan provides the required volume flow through the unit.

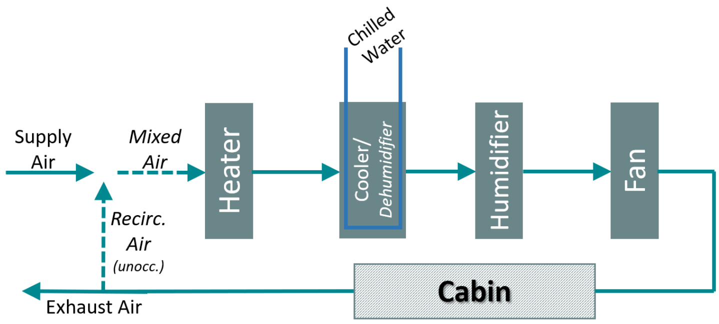


Figure 7.8: Simplified sketch of fan coil unit in passenger cabin with electrical consumers (filters not shown) including heater, cooler, humidifier and fan

Similarly for the AHU within the **public and crew areas**, the electrical consumers are shown in figure 7.9. In contrast to the FCUs, the AHU includes a recovery wheel to transmit heat (cold) from the exhaust air to reduce energy. In addition, the heat is added via a heat exchanger supplied by hot water from the central boiler to reduce electrical energy as well.
The defined areas in table D.2 are all calculated separately for every time step. This can differ from the real case due to missing connections and not using recirculated air from other areas as well, but this approach offers the possibility to calculate the model automatically. In addition, no significant differences are expected for the required level of accuracy.

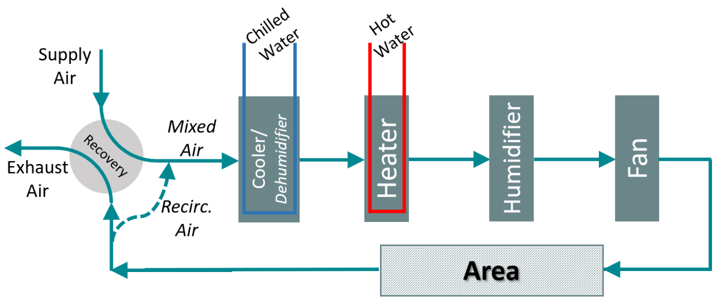


Figure 7.9: Simplified sketch of air handling unit with electrical consumers (filters not shown) including heater, cooler, humidifier, fan and recovery wheel

The calculation is described in more detail in the appendix D.3.1. Out of the prediction of the specific air properties, the heating and cooling demand can be calculated. The cabins are heated individually with the electrical heaters, while the AHUs are supplied by the hot water. A coefficient of performance (COP) includes here the electrical demand within the connected boiler system, while the actual heat is gained mainly from the exhaust heat. Similarly, the cooler are connected to the chilled water, where the applied coefficient of performance (COP) describes the electrical demand within the cooling cycles of the chilled water plant. The humidifier requires only a small amount of energy due to the water pumps. Lastly, the fans are circulating the air through the units into the area and cabins.
Generally, commonly used factors are used for applied efficiencies or fan pressures without considering specific data of manufacturers of individual components, because of a prediction in the first design phase. The whole air conditioning process can be displayed and explained within a Mollier diagram, where the individual air properties are specified. The actual condition within the room or area should be located within the comfort zone as defined by the ASHRAE[93]. Usually, if the supply air has to be heated (cold condition), the air requires some moisture within the humidifier as well. In the other case (summer condition), the water content is being reduced while cooling down the air at the same time, followed by reheating up to the set-point temperature. This

is theoretically the easiest way, but can be improved (see improvements in section 11.1.2) in order to reduce the energy by adjusting the recirculated air volume or using a bypass.

Validation Due to the extensive prediction model under the influence of varies parameters, a reliable validation of the model is only possible by using real life data. The data is currently not available and would require large recordings of data sets of exemplary situations and related conditions. Consequently, the maximum value can be at first compared to the commonly used load balance. The maximum power demand of the HVAC system and chillers (occurs in summer condition) is 5.8% above the predicted value in the load balance, while having a difference of 9.3% in port condition. In both cases, the absolute difference for the reference vessel is therefore below 100kW. Thus, the right order of magnitude is achieved. Larger differences are by comparing the constant value of the load balance with the varying demand over the day in different conditions.

The systematic behaviour is validated by applying the face validation technique [70] to further review the model. Doing that, the conceptual model can be seen as validated, because the prediction method is based on the procedure of Woud and Stapersma [92]. In addition, the system behaviour is reasonable under the defined environmental condition.

System behaviour and calculation results

Summarizing the prediction method, the influence of the weather and passenger behaviour is considered in order to calculate the required cooling and heating demand, which results in a significant electric power demand next to a mostly constantly running fan to circulate the air volume.
Various optimizations can be proven and implemented within the HVAC system and connected chilled water unit, which is out of the current study. This can be investigated in a later design stage under consultation of potential suppliers (see recommendations and outlook of energy saving options in section 11.1.2).

The results reach the required degree of accuracy by comparing the maximum demand of the whole HVAC system and chilled water plant with the corresponding value in the load balance of the reference vessel. The additional variation of the power demand over day is reasonable under the defined reference case conditions (see validation). Similarly to the other systems, the extreme values are displayed in table 7.9.

The **maximum power demand** occurs in sailing condition, in summer early in the morning, when the different areas and cabins have to be cooled during rising heat gain from the sun and humans. Additionally, the highest daily average power demand (also highest energy demand) can be also observed in the same condition (TDO2 in summer). All passengers are on board, while having the highest gained heat caused by radiation and transmission from the outer conditions.

Even if the contribution of the whole HVAC is comparably high, the **load changes** are not as high as in the propulsion system. The highest power variation within one calculated time step is predicted to be 186kW. This occurs in winter condition early in the morning, when the rooms and public areas are heated up to the set point temperature in the night followed by a reduction of heating due to higher heat gains during the day from equipment and humans. In addition, an immediate load change within a few minutes is expected of around (maximal) 200kW. This can occur in situations, where sudden changes in weather or passenger changes in port (including open doors) result for instance in starting another chiller to balance the additional cooling demand.

Table 7.9: Characteristics of calculated power demand of HVAC system and chilled water plant

Parameter	Value		In situation
Max. power demand	1464	kW	TDO2, ISO summer cond., early morning
Max. average power demand per day	1327	kW	TDO2, ISO summer cond.
Max. load change over 30 min.	186	kW/30min	TDO4; cold cond., early morning
Max. peak load (expected)	200	kW/1-3min.	e.g. run up of additional chiller
Max. daily energy demand	114,636	MJ/day	TDO2, ISO summer cond.

Caused by the dynamic system behaviour, the daily maximal power demand differs from the given maximum value in table 7.9 in every environmental and operational condition. Less power is required in cold condition. However, even lower is the power demand in medium condition (here 904kW for Amsterdam summer condition) because no extensive heating or cooling is required.

Looking into the daily variation of the power demand, for instance the following two cases are compared. Figure 7.10 shows the daily varying power demand during a sailing day (TDO2) in constantly warm condition (ISO summer) compared to the varying weather condition in Amsterdam. As mentioned, the lower power demand occurs in medium conditions, where the demand is also more constant throughout the day because of a lower cooling demand in the night in the individually ventilated passenger cabins. At the same time, the heating demand is similar due to reheating after dehumidification and consequently cooling down to a similar temperature. In other words, no humidification is required in summer conditions. Thus, the power demand of the water pumps within the humidification unit is equal to zero. Lastly, the power demand of the fans differs slightly because of different required air volumes within the unoccupied areas. Occupied areas have mostly the same air flows because of the high owner standards (see calculation in appendix).

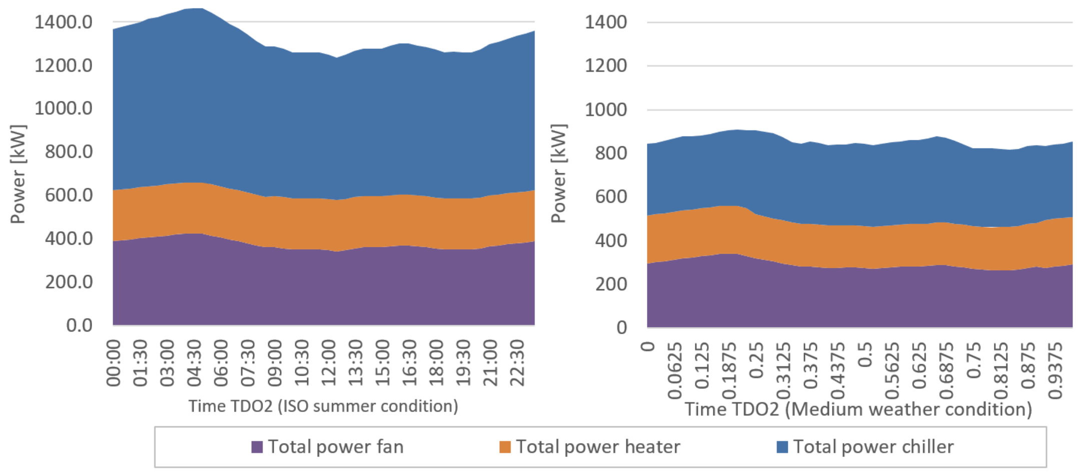


Figure 7.10: Comparison of dynamic power demand of HVAC system during TDO2 in ISO summer and medium weather condition (here in summer no humidification required)

Next to the environmental influence, the differences between the operational days are discussed by comparing the power demand of the HVAC system in TDO2 and TDO4 (case with maximal load change, see table 7.9) in cold condition, in figure 7.11.

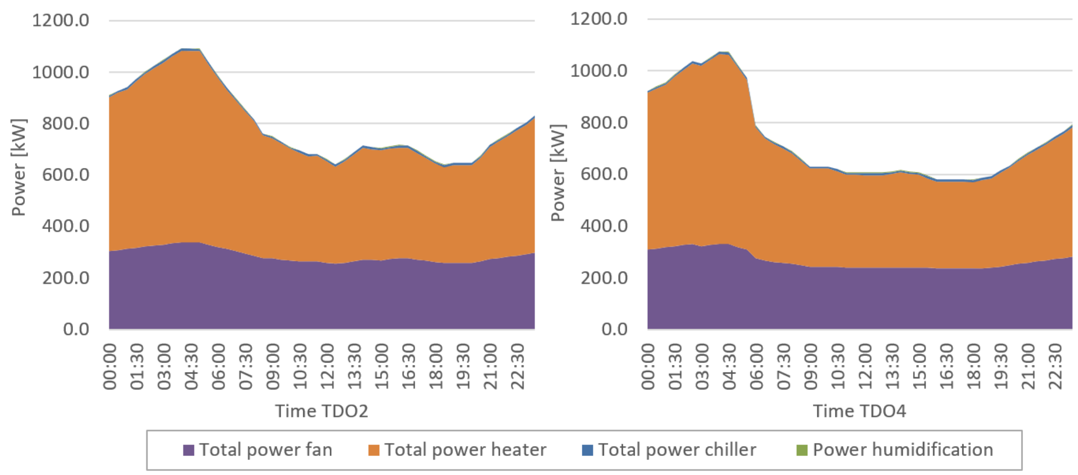


Figure 7.11: Comparison of dynamic power demand of HVAC system (power of chillers and humidification negligibly small) in different operational days in cold condition (weather profile of Resolute Bay)

First, a negligible cooling demand occurs as the ambient air is mostly cold enough, even after mixing it with recirculated air. The power of the fans is again similar even during different operational days, because of the constant ventilation requirements. The varying demand is mainly described by the heating demand. The power demand is higher during the night, while all cabins have to be heated as well as the public areas. During the day, unoccupied rooms can use recirculated and already heated air to reduce the heating demand, resulting in a slightly lower power demand in 4 (see right graph in figure 7.11). Generally, the difference between the two cases is not as high as between different environmental conditions (see above, fig. 7.10). The reduction of heating in the morning is clearly seen in both cases, because of higher heat gains during the day radiated by equipment, humans and the sun, which causes the highest load changes in table 7.9.

As a conclusion, the HVAC system and chilled water plant requires a significant electrical power demand on board, which is influenced by the operational profile and even more by the environmental conditions. More extreme weather conditions (hot or cold) causes higher loads. However, no essential load changes are expected while having the highest demand during the morning due to the individually conditioned passenger cabins, while having a rather constant power demand for the public and crew areas.

7.3.2 Galley and Laundry

The galley and laundry consist of several electrical components. The exact number of installed equipment is mostly defined by the client. However, rough estimations are made under consideration of the typical three mealtimes in the morning, lunch and dinner in the evening.

Influencing factors

Obviously, the use of the galley and laundry are not influenced by the speed of the vessel or the outside weather conditions. However, the passenger behaviour does have an impact, even if the ship is assumed to be fully occupied. The varying power demand is a result of the passenger behaviour throughout the day based on the defined typical day of operation (see section 6.1.2). For instance, the galleys are operating mainly before and within the main mealtimes, while less components are running during the non-mealtimes and while being in a port due to less passengers on board.

Prediction model

Using again the available data from the cooperating shipyard, the reference vessel is the basis for defining the installed power of the components for laundry and galley. Analysing the data, the installed power is related to the number of passengers on board. Therefore, the required installed power for a laundry is defined by 2kW per passenger (PAX) and for a galley by 2.5kW.
In addition, for the actual used power per time step, an utilization ratio is used as shown in the graph in figure D.5 in the Appendix D.3.2. This approach is similar to the common load balance, but uses a varying factor over day to consider load changes. The laundry is usually running within the night to lower the heat and electrical demand during the day as discussed with other engineers. However, the used power is not higher 45% of the installed power due to running components in turns. The average factor over a whole day matches with the used factor within the load balance.
Similarly for the galleys, an utilization factor is defined (see graph in figure D.5), based on the reference vessel. The required power is depending on the main mealtimes during the day. Consequently, a higher demand is expected within during the breakfast and even higher during lunch and dinner due to hot meals. In addition, the demand is lowered by 25% while staying in port, because of less passengers on board. Generally, the average factor for a sailing day is the same as the used factor within the load balance as well.
In summary, the power demand is described with the following equations for the galleys and laundry.

$$P_{Laundry,i} = 2\text{kW/Pers} \cdot PAX \cdot u_{Laundry,i} \tag{7.19}$$

$$P_{Galley,i} = \begin{cases} 2.5\text{kW/Pers} \cdot PAX \cdot u_{Galley,i} & \text{while sailing} \\ 75\% \cdot 2.5\text{kW/Pers} \cdot PAX \cdot u_{Galley,i} & \text{in port} \end{cases} \tag{7.20}$$

Validation Due to the used data, the result is comparable with the reference vessel. The energy demand and the average used power over the day is similar. However, the maximum power demand is higher, because a

dynamic operational profile is applied for the galley and laundry instead of keeping the power demand constant. A constant power demand is not the real case and is an improvement, even though the specific use is also depending on the actual mealtimes and working hours within the laundry. For a proper validation, the result is compared to other studies by calculating the energy demand for the laundry and galley components over one (sailing) day.
Using parameters for an onshore hotel (see prediction in appendix D.3.2) [78], the difference of the daily energy demand of the galley is only 1.1% for the reference vessel. In contrast, the daily energy demand of the laundry is 27% lower for the hotel. However, it is also stated, that off-site facilities are used as well for large-scale hotels. Consequently, the energy demand can be lower than the self-contained cruise ship. In addition, by using the factor for an offshore platform [80], the difference gets smaller to less than 1%. Consequently, the model can be seen as validated for the actual purpose and a first rough prediction.

System behaviour and calculation results

Based on the expected behaviour and considerations implemented in the prediction model, the main driving factor is the passenger behaviour as defined by the utilization factor. The operational day does only have a minor impact on the usage of the galleys, while having less people on board in port. Thus, the used prediction model is also applying an assumed utilization factor as in the load balance, but with a variation over the day.
As shown in the graph in figure D.6 in the appendix, the maximum power demand of the galley occurs in the evening (for reference case 248kW, as shown in table 7.10). Meanwhile, the average power demand gets close to the predicted value in the load balance, which shows the simplification of the common approach by applying a constant demand over the day. Significant load changes are not expected (in prediction of reference case below 70kW, see table) due to the low total power demand compared to other systems.

Table 7.10: Characteristics of calculated power demand of electrical galley components for chosen reference vessel

Parameter	Value		In situation
Max. power demand	248	kW	TDO2, TDO3 and TDO4; dinner time
Max. average power demand per day	152	kW	TDO2; sailing day
Max. load change over 30 min.	62	kW/30min	TDO3 and TDO5; after departure
Max. peak load (expected)	70	kW/1-3min.	e.g. turning on ovens
Max. daily energy demand	13167	MJ/day	TDO2, all day sailing

Figure D.6 shows also the power demand of the laundry, which is the same for every operational day. It alternates only between the working time in night and the lower standby mode during the day. Consequently, the maximum demand occurs in the night, while having the highest load changes only by turning on single components (like tumble dryers).

Table 7.11: Characteristics of calculated power demand of electrical laundry components for chosen reference vessel

Parameter	Value		In situation
Max. power demand	198	kW	every day within the night
Max. average power demand per day	92	kW	within all TDOs
Max. load change over 30 min.	44	kW/30min	day/night within all TDOs
Max. peak load (expected)	80	kW/1-3min.	e.g. turning on tumble dryer
Max. daily energy demand	7920	MJ/day	every day

In order to conclude, a higher demand is expected during the day for the galleys with minor load changes, while the power demand of the electrical components in the laundry are highly depending on the working schedule. However, the daily demand is comparably low for both systems, which might even balance out each other's demand in day and night mode resulting in a constant load.

7.3.3 Lighting

The lighting system involves all components on board to provide the expected illumination for passengers as well as for a safe working environment within the crew areas and machinery spaces. However, it does not belong to the biggest electrical consumers especially while sailing, but is considered separately due to the dynamic demand over the day.

Influencing Factors

Referring to the three main varying parameters in chapter 6, the lighting system is not influenced by the operational profile in terms of the varying speed of the vessel. However, the related passenger behaviour at the different TDOs is considered in the model. If a certain area is occupied, then the light is assumed to be switched on. In addition, the passenger cabin have an additional factor to consider the sunlight. Consequently, if the sun is shining, then normal lighting is reduced to *comfort lighting*. Now, the prediction model is set up.

Prediction model

Generally, except of the passenger cabins, the following equation 7.21 can be used. The obtained area A_j in section A.3 in the appendix is multiplied with the light intensity L_{Int} for every area j. The additional binary factor b_{occ} describes, if the space is occupied by passengers or crew accordingly to the defined behaviour in section 6.3. Thus, if no passengers or crew are for instance in the restaurant, then the lights are turned off. In addition, the outside area has lights only when no sunlight is available.

$$P_{Light,areas} = \sum_j A_j \, L_{Int,j} \, b_{occ} \tag{7.21}$$

The minimum light intensity is advised with a required lumen per square meter in guidelines [1, 2]. This is transferred into power by applying the factor of 100 lumen per watt for LED lights [9]. The values for the different areas are shown in the table D.4 in the appendix D.3.3.

Only the passenger cabins are missing and are predicted under consideration of the different used lights. For example during the night, not all lights are running even if the cabins are occupied. Using the prediction of Nurmi [64], the standard cabin is illuminated by around 105 watts. A lower value of 50 watts is assumed for comfort lighting, which is using only parts of the lights. The defined proportion p for comfort and full cabin lighting is shown in figure D.7 (see appendix D.3.3), which are multiplied with the number of occupied cabins n_{occCab} for every time step i. In summary, the following equation 7.22 is stated for the passenger cabins.

$$P_{Light,cabin,i} = \begin{cases} 105 \, n_{occCab} \, p_{normal} + 50 \, n_{occCab} \, p_{comfort} & \text{no sun} \\ 50 \, n_{occCab} & \text{sun outside} \end{cases} \tag{7.22}$$

In order to conclude, the total power of the lighting system in a certain time step is calculated as a sum of the cabin lighting and the other areas.

$$P_{Light,i} = P_{Light,areas} + P_{Light,cabin,i} \tag{7.23}$$

Validation As expected, the power demand is comparably low and is predicted slightly lower than the system in the load balance by doing an extreme condition test (see graph in appendix in fig. D.8). The dynamic power demand is even lower due to no lighting in unoccupied areas. However, the available reference data is predicted with a low level of accuracy in an early design stage and tends to an oversizing as conservative approach. Thus, the estimation based on square meter describes the system already more detailed and result in a reasonable behaviour (see actual lighting in fig. D.8) and total power demand.

System behaviour and results

As discussed, the lighting system is predicting under consideration of the influencing factors. However, the contribution is comparably low for an expedition cruise ship and might vary more for high-GT vessels with more illuminated entertainment facilities. The power demand variations are mainly driven by weather certain areas

are occupied or not. The sunlight and reduction of lighting is not that significant, because the main areas are lighted throughout the day due to insufficient natural lighting.
The characteristic parameters are summarized in table 7.12. The maximal power demand occurs in summer conditions without significant difference to the average power demand, which results in negligible load changes as well.

Table 7.12: Characteristics of calculated power demand of lighting for chosen reference vessel

Parameter	Value		In situation
Max. power demand	55	kW	TDO2, summer, early morning
Max. average power demand per day	52	kW	TDO2, ISO summer condition
Max. load change over 30 min.	4.3	kW/30min	several situations
Max. peak load (expected)	10	kW/1-3min.	e.g. turning on one lighting area
Max. daily energy demand	4453	MJ/day	TDO2, ISO summer condition

7.3.4 Minor systems

The remaining systems are not modelled separately due to the small contribution to the overall power demand of the cruise ship. Additionally, the power demand is rather constant and is predicted based on indicators. As shown in figure 5.2, the following systems are included:

- Food waste storage and handling
- Emergency systems
- Sockets
- Lifts
- Sauna, wellness and leisure facilities
- Other electrical systems and components (e.g. defrosting, floor heating)

Influencing factors

The minor systems can be seen as constantly running over time. Only some variations are between winter and summer condition while sailing as well as for being moored in a port. For example, the meals are served and cooked (see power of galley) with some variations, however, the waste storage and handling systems, like a shredder or incinerator, are running constantly to recycle any waste. Consequently, the passenger behaviour and speed variation of the vessel is not influencing the energy demand. Only a different temperature in winter results in a slightly higher demand for some systems.

Prediction model

First of all, the installed power is predicted based on available reference vessels, even if this might vary with different specification of different owners especially for leisure facilities while emergency systems are more based on classification rules.
There are two lifts assumed to be installed per 70 passengers with a power demand of 14kW (based on reference data) and a constant utilization rate of 20%. Additional intermediate load peaks are considered later.
The installed power of the emergency system, the sockets and additional components (included in ”other systems”) are related to the GT, while the food waste handling and the leisure facilities are related to the number of passengers on board. The used utilization rate is defined based on available reference data.

With the defined factors in table 7.13, based on reference data, the power demand in every condition (summer, winter or port) is predicted for every minor system k as shown in equation 7.24.

$$P_{k,cond} = \begin{cases} q_k \cdot PAX \cdot u_{cond,k} & \text{if inst. power based on PAX} \\ q_k \cdot GT \cdot u_{cond,k} & \text{if inst. power based on GT} \end{cases} \quad (7.24)$$

Table 7.13: Defined factors for prediction of installed power of minor systems, including corresponding utilization factors $u_{cond,k}$ per condition for every system k

System k	Inst. power q_k	Util. summer $u_{sum,k}$	Util. winter $u_{win,k}$	Util. port $u_{port,k}$
Food waste handling	0.4 kW/Pers	25%	25%	25%
Emergency systems	0.01 kW/gt	65%	65%	50%
Sockets	0.012 kW/gt	30%	30%	15%
Lifts	(2·14) kW/70Pers	20%	20%	20%
Leisure facilities	0.75 kW/Pers	11%	13%	11%
Other elect. systems (e.g. defrosting)	0.02 kW/gt	25%	60%	20%

Validation Due to limited available data, an extensive validation of the defined factors is difficult. The used load balances were the basis for predicting the components. Other vessels can vary from the calculated installed power, if the specifications of the owner differs more from the typical expedition cruise ship. In addition, further behavioural data is not available for a proper data validation [70]. However, the made assumption of neglecting the influence of the passenger behaviour and keeping the power demand widely constant can be seen as conceptually reasonable for the intended purpose of the rough prediction, because the overall contribution is comparably low. Thus, different utilization factors would not even influence the model significantly. All in all, the prediction offers an acceptable order of magnitude to analyse the implementation of a fuel cell.

System behaviour and calculation results

Table 7.14 summarizes the significant characteristics of the power demand of all minor systems. The difference between maximum power and the average demand is negligible, which corresponds to the applied utilization factors. Therefore, no major load changes are expected except of the emergency system (100kW of immediate load change expected, see table). The latter is mainly designed for an emergency case and is only in stand-by mode in normal operation. Thus, the power demand runs up in emergency, while the remaining systems are shut down gracefully, which eventuates in a maximal expected load change of 100kW.

Table 7.14: Characteristics of calculated power demand of minor systems for chosen reference vessel, max. power and energy demand occurs in winter condition within TDO2 (sailing all day)

Parameter	Food Waste	Emergency	Sockets	Lifts	Leisure	Other
Max. power demand [kW]	22.0	97.5	54.0	16.8	21.5	180.0
Max. aver. power demand per day [kW]	22.0	97.5	54.0	16.8	21.5	180.0
Max. load change [kW/30min]	0.0	22.5	27.0	0.0	3.3	120.0
Max. peak load (expected) [kW/1-3min.]	50	100	0	20	10	0
Max. daily energy demand [MJ/day]	1901	8424	4666	1452	1853	15552

All in all, the minor systems do not exceed a total power demand of 400kW together for the reference case, while having an expected constant load over time only with minor load changes.

7.3.5 Differences to load balance approach

Similarly to the auxiliary systems, the maximum power demand of the predicted hotel systems can be compared to the constant demand within the load balance for the reference vessel, in figure 7.12 for summer (red) and winter (blue) condition. The minor systems, laundry, galley and lighting are similar to the values in the load balance, as discussed. Differences can be seen by comparing the chilled water plant and HVAC system, especially in winter condition. The predicted daily maximum value is below the maximum value in the load balance. Consequently, the cooling and reheating demand was estimated lower than in the common approach. This is caused by applying different values for the COP and constant return air flows. On board, the real system is highly complex and optimized for the actual situation by reacting on different heat gains, which is only possible to a limited extent in the prediction model. On the other hand, the load balance implements different utilization factors, which always tend to oversize certain systems due to neglecting dynamic conditions (see recommendations and improvements in section 11.1.2). However, the main influences could have been considered (see discussions in section 7.3.1) to achieve an acceptable level of accuracy.

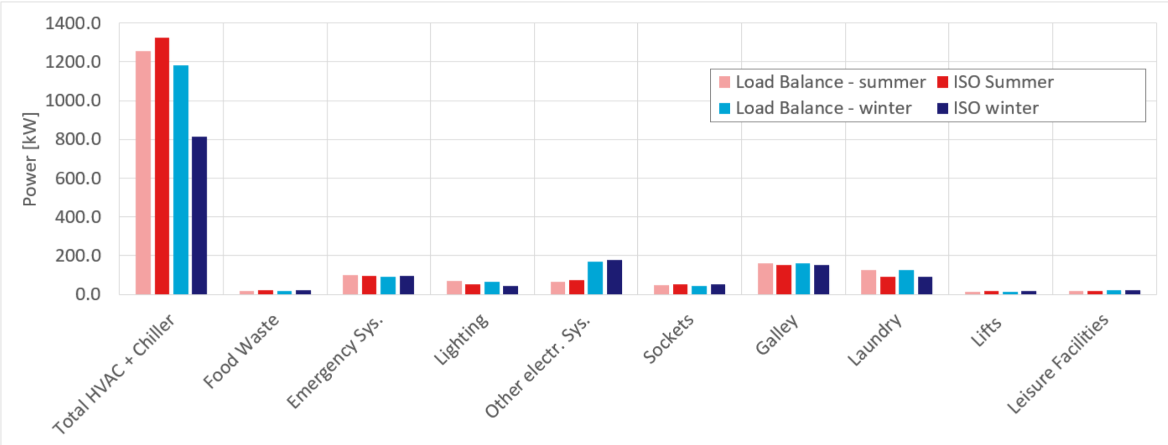


Figure 7.12: Comparison of max. power demand of hotel systems between common load balance and calculated values of model, for summer and winter condition

Going on step further, the varying power demand was not considered in the load balance, while the impact of the passenger behaviour and season can be seen in the prediction model, especially for the HVAC system. The remaining hotel systems are mostly impacted by the operational condition. The power demand of all hotel systems is displayed in figure 7.13 to point out some differences. The typical day of operation (TDO) 2 (sailing day) and TDO3 (half day in port) are shown in winter condition due to the high load changes.

At first, the constant load predicted in the load balance is displayed by the dotted line and is always higher than the estimated value. In varying conditions, the highest load occurs always in the morning, while a lower demand is expected during the day. As expected, the HVAC system is the highest consuming system with the highest dynamic load behaviour as well.

Secondly, the load changes are clearly visible in winter condition, while having a more constant demand for instance in medium condition (not shown in figure). However, changing the operational mode (e.g. arriving in port) causes the main differences, as shown in the second graph in figure 7.13. Less passengers resulting in a lower power demand of some systems due to a lower actual comfort level and less hotel services (e.g. galley).

All in all, by sizing a power plant or for instance a fuel cell for the hotel systems, the power demand throughout the day is more constant than the propulsion system even in different operational days. Changing the operational day leads to higher variation of the load behaviour (see comparison 7.13), while changing the environmental condition mainly influences the HVAC system resulting in a different level of required power (see comparison 7.10).

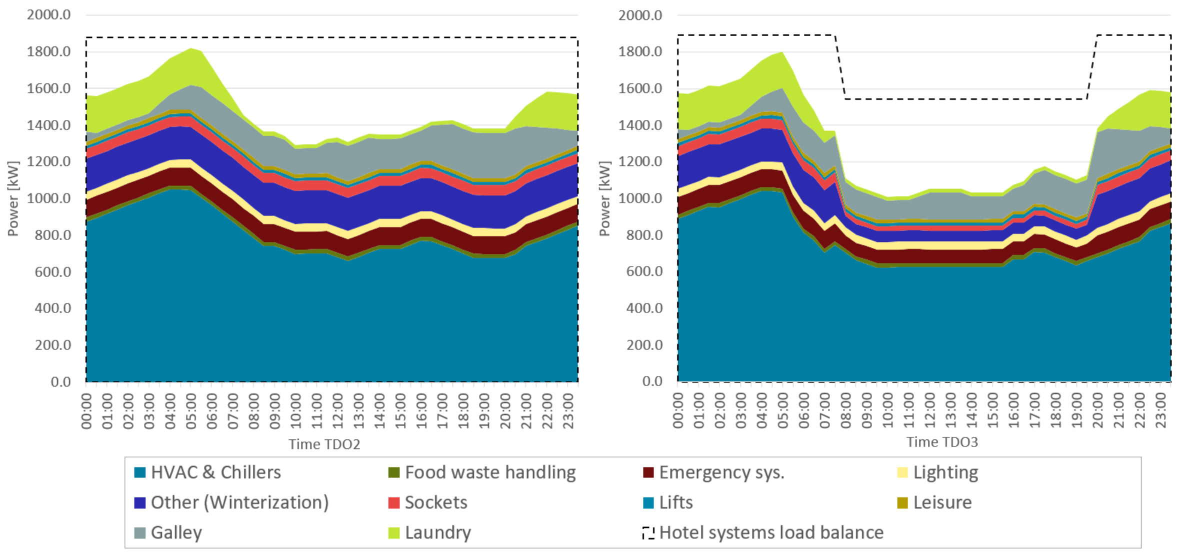


Figure 7.13: Power demand of hotel systems over time for defined typical day of operation in ISO winter condition; comparison of sailing day (TDO2) and day incl. port call (TDO3)

7.4 Total power demand

The prediction of the power demand is the basis for sizing the fuel cell (or power plant) on board. Using an estimation under dynamic operational conditions provides different insights in the demand of the whole cruise vessel after calculating the load of the individual systems in the previous sections. Not only the maximum power demand is predicted, but also the average and base load can be seen as well (section 7.4.1). In addition, the load changes and power fluctuations (section 7.4.2) can be pointed out, which are crucial to consider due to the specific operational characteristics of a fuel cell (as discussed earlier in section 2.1.1). Together with the analysis of the energy demand in the following chapter, the fuel cell can be finally designed for specific systems.

7.4.1 Power demand

It is important to differentiate between the maximum power load and the base load. The base load describes the minimum amount of power needed over the day and is significantly lower than the maximum load, which occurs only temporarily. The base load can be beneficial for an efficient implementation of a fuel cell in a hybrid configuration. Part loads can be supplied by fuel cells in order to avoid critical load changes.

Maximum power demand The highest power is required by the main propulsion in sailing mode (see left graph in figure 7.14). However, expedition cruise ships are operating often at lower speeds below the design conditions, which results in a considerably lower demand (see right graph in figure 7.14). In contrast, the power demand of the auxiliary systems is rather constant at its maximum load in sailing condition. The maximal load of the hotel systems occurs always in the morning, when all passengers are on board and several components ramp up from the lower night mode. In general, the power demand is higher in summer followed by winter condition. The medium weather condition results in the lowest hotel power demand because of no extreme cooling or heating mode of the HVAC systems. The remaining and smaller systems are negligibly impacted by the environmental conditions.

Base load Comparing the daily average power demand shows, that in all typical operational days (except of TDO2 sailing) the average demand is lower than 50% of the demand in sailing condition (TDO2). This means, that a power plant would run most of the time below their maximal operational point. Figure 7.14 shows, that the total predicted demand in sailing condition at design speed is close to the value predicted in the load balance (LB). Bigger differences are in intermediate conditions driven by a different actual speed (e.g. right graph in fig. 7.14 in the morning). In harbour mode, the total demand is again comparable to the LB approach and at its minimum load. This describes the base load of the electric power.

In port condition, the propulsion power tends to zero and the hotel and auxiliary systems are running only with minor fluctuations. Consequently, they are describing the base load due to the more constant load throughout the day, even in port condition.

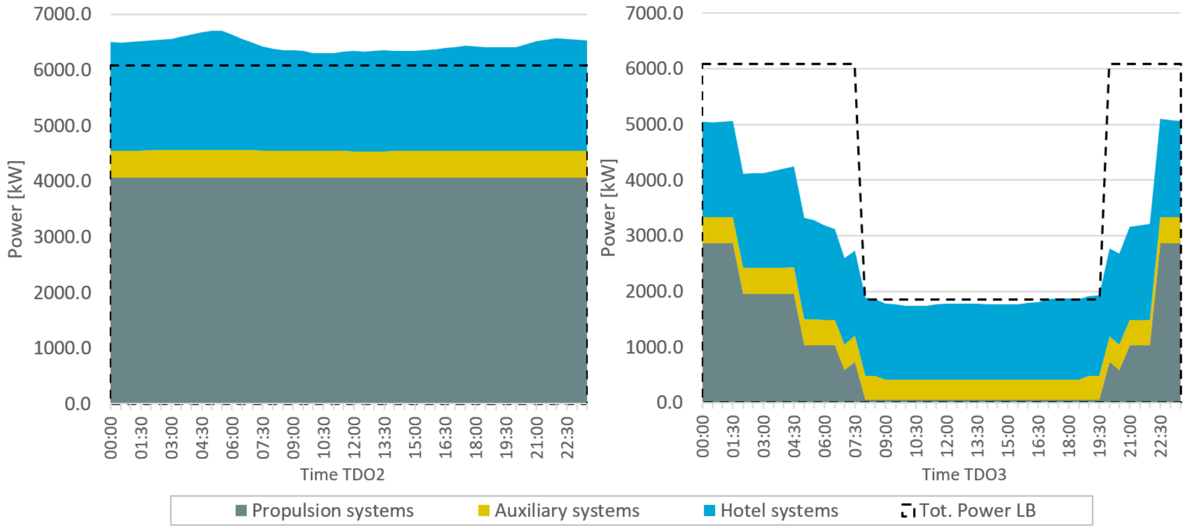


Figure 7.14: Power demand of propulsion, auxiliary and hotel systems over time for defined typical day of operation 2 and 3 in ISO summer condition, compared to load balance approach

7.4.2 Load change

Looking further into the power fluctuations, it is important to consider the load changes during the day as well as additional immediate peak loads in a short period of time, as added manually in the prediction.

As mentioned, the propulsion systems are driven by the actual speed. Thus, the highest load changes result from adjusting the speed as well. Additional peak loads occur while manoeuvring in port, which are not considered by the used time step in the dynamic prediction and are added manually (e.g. see table 7.2 for bow thruster).
In contrast, the power demand of the auxiliary systems is relatively constant close to its maximum load in sailing condition. Only gradual load changes occur by changing the operational mode for example from sailing to port condition. Comparably low peak loads are expected for example after arrival in port, when the deck equipment is used.
The power variations within the hotel systems are mainly driven by the passenger behaviour. As soon as the passengers are disembarking in port, the load decreases. Compared to the propulsion power fluctuation, it occurs on a comparably low level and does not even exceed 300 to 400 kW over 30 minutes. Additional immediate load changes are expected only as a result of single components which are returning from their stand-by mode.

7.4.3 Simultaneity of electrical consumers and systems

The dynamic power prediction could consider the influences of environmental conditions, passenger behaviour and speed. The running systems could be directly linked to the actual demand without applying a constant utilization factor throughout one operational mode like in the load balance approach. Thus, the previously assigned factor to consider the simultaneity (see equation 2.1) is now replaced.
Systems with a larger electrical load are calculated more detailed for the actual conditions, like the propulsion and HVAC system. The minor systems (see section 7.3.4) are still related to a utilization factor due to their small power contribution. Going further into the power fluctuations of these systems would not significantly improve the model due to widely constant operating systems. Thus, the applied factor is also called as loading factor and refers to the predicted installed power.

Displaying the total demand (see fig. 7.14) shows that the sum of the individual loads of the systems under dynamic conditions is comparable with the load balance approach in sailing and port condition. Larger differences are while sailing at lower speeds mainly caused by the propulsion system. Meanwhile, the hotel and auxiliary

loads seem to be affected only by small fluctuations throughout the days.
The main advantage of the dynamic prediction have a visible effect by analysing the load behaviour of the individual systems. In the overall view, some load changes are even balancing out each other, in example the galleys and laundry. Looking into the systems separately, the load changes and immediate peak loads can be pointed out which also have to be supplied by a reliable power plant component, like a fuel cell.

7.5 Conclusion

The daily variations and maximum load of the dynamic power demand could be analysed with the dynamic prediction model. The load profile is affected by fluctuations which has to be powered by a reliable power plant later on.
Generally, the different environmental conditions impact mainly the hotel power demand by having the highest load in summer condition. The impact of the varying passenger behaviour results in higher power fluctuations of the hotel systems throughout the day (see figures in 7.14). The operational condition in terms of speed has a significant influence on the propulsion power, so that sailing in coastal operation (TDO3,4 and 5) causes a significant lower electrical demand, as expected in section 4.2. The auxiliary systems have mostly a constant load, which only changes by modifying the operational condition.
The highest load changes result from adjusting the speed. In addition, high peak loads occur in manoeuvring condition. Comparing the total power demand shows that the load changes caused by the hotel systems gets smaller in relation to the changes within the propulsion system. However, disembarking in port causes the highest changes within the hotel load due to a lower actual utilization in port condition of several systems that normally ensure the high passenger comfort.

Chapter 8

Energy consumption of operating ship

After having predicted the power demand of the individual systems under dynamic conditions, the energy demand can now be calculated for the whole cruise ship under defined operational conditions.
As summarized in figure 8.1, the *power* demand was calculated in the previous chapter for all subsystems. This is the basis for sizing the power plant consisting of the fuel cells and optional diesel engines as well as further balance of plant component (BOP) like batteries. Adding now the time variable, the *energy* demand is predictable for the individual typical day of operation (TDO) in the first section. A typical coastal operational profile can be assembled in section 8.2 by adding different TDO in accordance with the obtained typical speed profile in section 6.1.1. The impact on the energy demand of an expedition cruise ship can be proven to size the fuel tanks sufficiently for mixed operation. Generally, the driving factors of the energy demand (see fourth research question, sec. 3.3.3) can be analysed to keep the tanks as small as possible considering the lower energy densities of alternative fuels. The following chapter can build on the crucial findings within the power and energy demand to elaborate on the options and limits for an efficient fuel cell implementation.

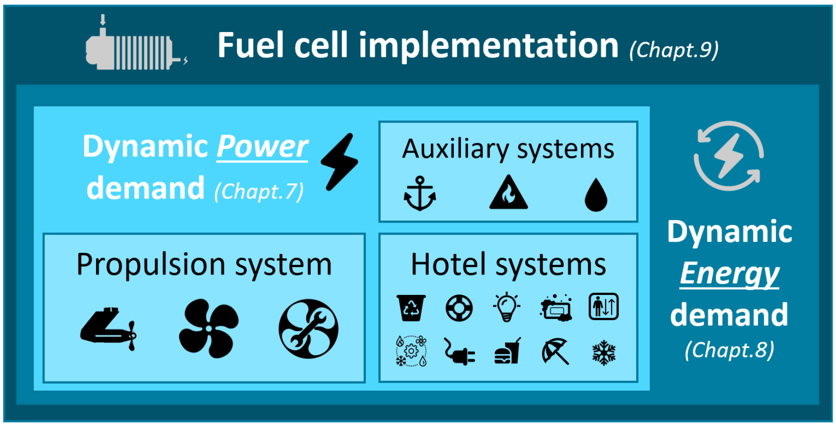


Figure 8.1: Starting at individual dynamic power prediction via dynamic energy demand towards implementation of a fuel cell system

8.1 Energy demand of typical days of operation

First, the energy demand is calculated for the different typical day of operation (TDO), as defined in section 6.1.2. The dynamic power demand over the specific days has been predicted in the previous chapter. Thus, the energy demand can directly be calculated. In addition, the corresponding energy demand based on the load balance (LB) is displayed as well. Only the sailing (at design speed in summer and winter) and port condition is a considered operation in the LB. Consequently, the defined hours of harbour mode in the TDOs (see figure B.4) define the operating time in harbour and remaining time in sailing condition (based on equation D.25 in appendix).

Sailing and port condition The energy demand of staying a whole day in port (TDO1) and sailing at design speed (TDO2) is shown in figure 8.2, for the different weather condition. The stacked bars for the propulsion,

auxiliary and hotel systems show the predicted demand for the reference vessel compared to the commonly used load balance approach (dashed line).
The energy demand of the auxiliary systems is considered widely constant throughout the different days and seasons with gradually changing needs driven by the operational mode, due to a constant power demand in sailing and port mode(see previous chapter). The hotel systems need slightly less energy per day in winter and medium condition than in summer condition. No extensive cooling or heating is required in medium weather condition and results in a lower load. In addition, the demand is slightly lower for the day in port due to less people on board. The electrical demand of the hotel systems, which are related to the passenger comfort, is partly reduced at that time.
The main difference can be seen between the propulsion energy demand, which is basically non-existent while staying in port in relation to the energy demand in design speed condition (TDO2).
The predicted total energy demand is close to the LB value in summer condition and is only slightly lower in medium and cold condition. This is a result of the lower predicted cooling system (see figure 7.12 in section 7.3.5) and can be proven in a later design stage, if necessary. Generally, the energy demand is close to the estimated value based on the LB data, except of minor variations between the seasons due to the variable running hotel systems.

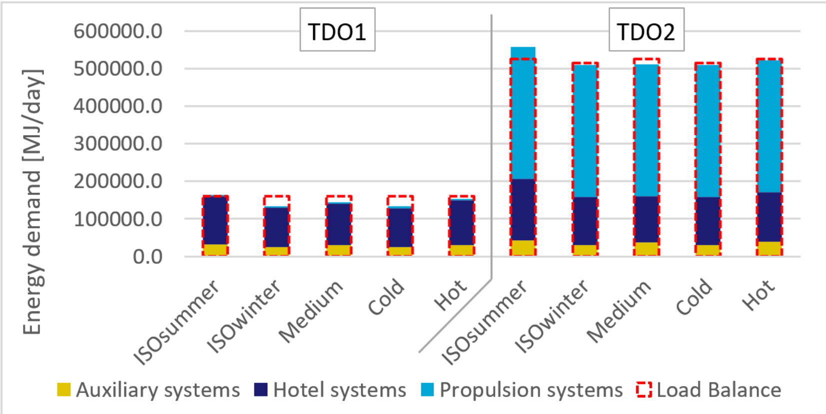


Figure 8.2: Energy demand of propulsion, auxiliaries and hotel systems for TDO1 and TDO2 compared to commonly used load balance

Sailing days including port call More significant differences can be seen by comparing the typical days of operation 3,4 and 5 in figure 8.3, also considered as mixed operations. The predicted energy demand is between 20% (TDO3) and up to 45% (TDO5) lower than using the data in the load balance for the reference vessel. As longer the ship is mooring in port as lower gets the daily energy demand and smaller the difference to the LB based estimation.
Looking into the proportional demand, it can be shown that the daily propulsion energy demand is equal or even lower than the energy demand of the remaining systems. This is in contrast with the allocation of the power demand in sailing condition. Thus, the assumption of two-thirds for the propulsion and one-third for the remaining systems (see conventional approach in section 2.2.1) is not untenable for these mixed operation.
The auxiliary systems are negligibly impacted by the time spend at port and different speeds. Minor variations can be seen between the seasons. In winter, the energy demand is around 25% lower than the summer condition due to a lower need of cooling water and corresponding pumps.
The difference in the energy demand of the hotel systems between the mixed operational days (TDO3,4 and 5) is low and about a few percent. The majority of systems are running in port as well, so that the length of port call in the current cases is not significant. Only the weather lowers the demand in medium and cold condition by up to 15%, similarly to the first and second TDO.

Summarizing the energy demand of the different TDOs, the driving factor of a reduction is mainly the speed. The power fluctuations within the hotel and auxiliary systems, as discussed in the previous chapter, have a lower impact on the energy demand. They are averaged out due to partly higher and partly lower loads during the day.

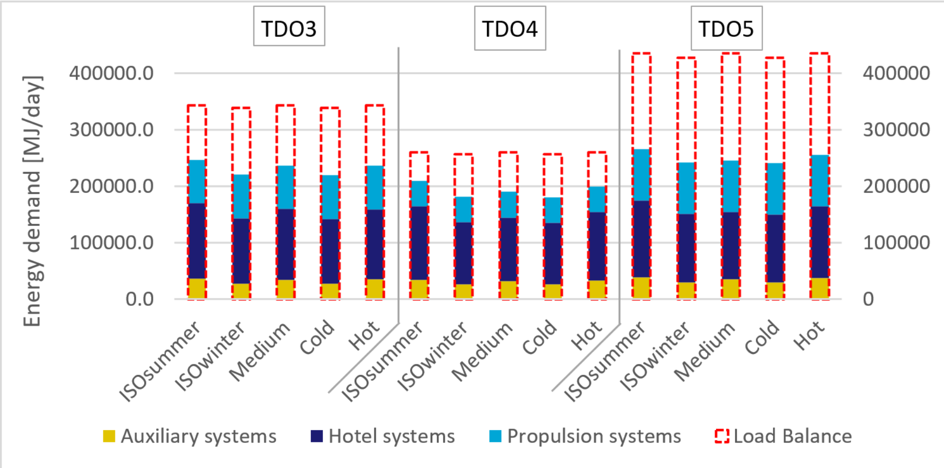


Figure 8.3: Energy demand of propulsion, auxiliaries and hotel systems for TDO3, TDO4 and TDO5 compared to commonly used load balance

8.2 Assembling operational profile

Going one step further, the energy demand of the operational profile can be calculated, which is the basis for the required size of tanks. Usually, shipping companies defines a range of minimum 6000 nautical miles between refuelling to cross the ocean at service speed and an additional margin left in the tank. This corresponds to around two and a half up to three weeks for the endurance.
Considering the lower demand within mixed condition (TDO3-5), the energy demand could be significantly lowered and consequently the fuel tanks as well. This means, that in typical coastal operations (see speed profile in section 6.1.1) of a cruise ship, the large tanks are not needed and are mainly designed for the rarely operated transit condition.

The defined TDO is now used to predict the energy demand of a typically used transit profile and an alternative coastal profile of the same endurance of 3 weeks under dynamic operational conditions. The profile in transit condition is assembled by adding 21 sailing days. Secondly, it can be proven, to what extend the energy can be reduced by applying a typical speed profile as determined in section 6.1.1, so called as coastal operational profile. The *ISO summer* condition is used, because it could have been pointed out as condition with the highest energy demand in the previous section 8.1.

An exemplary 21-days cruise is used as case study based on a planned trip of an expedition cruise vessel of HAPAG-Lloyd Cruises[38] (see case in appendix B.1.3), simplified by using the defined typical day of operation (TDO) (see simplification of itinerary in table B.1). The simplified coastal profile consist of 4 days sailing (TDO2), 6 days half a day in port (TDO3), 3 days of a longer stay in port (TDO4) and 8 days partly lying at anchor (TDO5). It does not follow a weekly round trip and sails to small harbours or even remote areas to lie on anchor. Looking in the underlying speed profile, the used case represents a typical speed profile of an expedition cruise ship. The proportional amount of spent time at a certain speed range is similar to the obtained speed profile of several reference vessel (see table B.2), as obtained out of the AIS data in section 6.1.1.

Figure 8.4 clearly shows the obtainable energy savings if the coastal profile (see appendix) is used as maximum range between refuellings instead of 3 weeks sailing constantly at design speed. The total energy demand is reduced by around 40% for the reference vessel, mainly because of the reduction of propulsion energy (60%).
This results in a considerable option to reduce the tank sizes of the alternative fuels to power the fuel cell, which are affected by low energy densities (as discussed earlier, see table 2.2). Longer ocean crossings could be powered by conventional, more energy dense systems and fuels, outside any restricted Emission Control Areas (ECA)s.

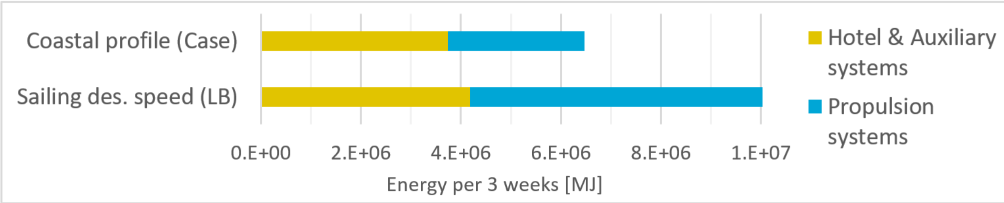


Figure 8.4: Energy demand of 3-week operational profile by sailing at design speed compared to coastal operational profile considering different TDO

8.3 Conclusion

The energy demand could be analysed for the individual operational days as well as for a whole operational profile. Based on that, the fuel tanks can be sized. The demand is comparable with the results out of the commonly used load balance (LB) approach for sailing and port condition. In mixed operations, the driving factor is the speed, which results in higher differences to the LB. The passenger behaviour and changing weather condition causes power fluctuations, with no significant impact on the energy demand per operational day for the hotel and auxiliary systems. They are averaged out due to partly higher and partly lower loads during the day. In other words, the replaced constant simultaneity factors in the LB approach result in higher power fluctuations in specific systems. Lowering the energy demand is mainly achieved by reducing the speed or adjusting the operational profile as basis for the fuel tanks. In these mixed conditions, the daily propulsion energy demand becomes equal or even lower than the remaining systems, which are not affected by the varying speed.

Chapter 9

Fuel Cell Implementation

The power prediction in chapter 7 points out some important findings, which has to be considered by designing a reliable and efficient power plant including fuel cells under consideration of its operational characteristics. The same holds true for the energy demand for the operational days in chapter 8. The crucial findings are summarized in the first section 9.1 and are related to the operational characteristics and limits of a fuel cell (see fifth research question, sec.3.3.5).

Operational strategies are formulated in section 9.2 by referring to the labelled findings out of the power and energy analysis. Afterwards, the different strategies can be briefly assessed in section 9.3. In the actual development stage of fuel cells, the focus is on feasibility and reliability, while the costs are hardly predictable due to ongoing developments and the rising technology readiness level (TRL). However, the fuel cell and fuel storing volume, weight and costs are briefly discussed to see the impact of the improved energy demand prediction model.

9.1 Crucial findings out of dynamic energy model

Power demand In order to implement fuel cells on board, the operational limits have to be considered, as mentioned in the theoretical background in section 2.1.1. Without designing the whole power supply side, the following considerable cases in table 9.1 are summarized for an exemplary low- and high-temperature fuel cell out of the analysis in chapter 7. The low temperature-proton exchange membrane fuel cell (LT-PEMFC) and solid oxide fuel cell (SOFC) has been chosen as most promising options due to the comparably high technology readiness level (TRL) and better gravimetric and volumetric power densities, in accordance with the obtained data in table 2.1. The comparably low power fluctuations within the total power demand of the auxiliary and hotel systems can be considered as a widely constant load over time (case P1). This minimal load, also referred to as base load, is more favourable for fuel cell systems due to no extensive peak loads, where the system has to heat up immediately to cover the load (mainly SOFC).

The second case (P2) describes the high electrical power demand of the propulsion system as it occurs in sailing condition above the design speed. This would result in large fuel cell modules resulting in high investment costs. In addition, currently no project is in use of such an upscaled fuel cell system to power these loads. The reference vessel would require more than 4.5MW (see TRL of fuel cells in section 2.1.1). Thus, it is considered as a technically impracticable solution in the current development stage, due to the additional required volume and weight of the fuel cells and tanks (briefly assessed in section 9.3) on board and available sizes of fuel cell modules.

The following case (P3) of operating often below 50% of the maximal load would result in an oversized system during normal coastal operation. Additional high peak loads can occur while manoeuvring in a short period of time (case P4), because of the power ramp ups of the thrusters. Covering these high immediate loads with a low temperature fuel cell has to be proven with the manufacturer or can be supported by additional balance of plant component (BOP) like batteries. Covering the loads only with a high temperature fuel cell is impossible within a few minutes, because of the long starting time (see background theory).

Table 9.1: Significant cases out of *power* prediction to be considered within fuel cell implementation *(Symbolization: [+]favourable, [o]technically impracticable, [-]technically impossible)*

Index	Case	LT-PEMFC	SOFC	*Comments*
P1	Widely constant hotel and aux demand	+	+	*Constant load favourable for FC*
P2	High max. power of main prop. system	o	o	*Requires large fuel cells, not feasible at current TRL*
P3	Often operating in off-design condition with significant lower propulsion power	o	o	*Tends to oversized system*
P4	High peak loads within propulsion systems	o	-	*SOFC impossible, PEMFC has to be proven*

Energy demand Additional findings are formulated in table 9.2 out of the energy prediction in chapter 8, which have to be considered while implementing a tank size of the alternative fuels. The LT-PEMFC is exemplary listed with pure hydrogen to avoid an additional fuel reforming, next to the more cost-competitive and energy dense hydrocarbon fuel LNG. The latter is also considered as promising option for the SOFC due to the rising availability. Pure hydrogen would not result in an efficient high temperature fuel cell system, like SOFC, and is neglected in the study. It would not make use of the main advantage of the high tolerance to fuel impurity.

First of all, in sailing condition, the high main propulsion demand leads to a significant energy demand which is highly depending on the actual speed (fact *E1*). The low energy density of the alternative fuels would result in an extreme rise in tank size and consequently in loss of available inner volume of the ship. LNG is already used in combustion engines and would more than double the required tank size. Storing enough pure hydrogen for full operation seems highly impracticable, because of its volumetric density of less than on sixth in relation to MGO.

Using different operational days leads to a lower energy demand (fact *E2*). The computed coastal operational profile in section 8.2 describes normal operations of a cruise ship with speeds often below the sailing condition. The energy demand of the propulsion systems are significantly lower, while the hotel and auxiliary systems are relatively constant, as a consequence of the fact P1 (see previous section). Designing the tanks for the lower energy demand in coastal operation would result in a more favourable solution of the less energy dense LNG, but still technically and economically impracticable hydrogen tank sizes.

Lastly, the most constant and lowest energy demand is obtained by the auxiliary systems (fact *E3*). The demand is below 10% of the total maximal energy demand. Powering these systems with fuel cells would not oversize the fuel tanks even in coastal operation. The hotel systems have minor variations in the daily energy demand, depending on passenger and environmental conditions, while consuming around one fourth of the total energy during a sailing day. The tanks can be kept comparably small and designed for the widely constant demand throughout different operational conditions, which is favourable for all alternative fuels.

Table 9.2: Significant cases out of *energy* prediction to be considered within fuel cell implementation *(Symbolization: [+]favourable, [o]technically impracticable, [-]technically impossible)*

Index	Case	LT-PEMFC H_2	LT-PEMFC LNG	SOFC LNG	*Comments*
E1	Sailing condition (TDO2) driven by high energy demand of main prop. system	o/-	o	o	*Technically possible, but tends to highly impractical tank sizes*
E2	Significant lower energy demand in coastal operation	o	+/o	+/o	*Results in lower tank size in coastal operation*
E3	Lowest, most constant energy demand of aux. systems	+	+	+	*Avoids oversized fuel tanks throughout operation*

9.2 Operational strategies

The operational strategies in table 9.3 are possible options to handle the critical cases as pointed out in the previous section (table 9.1 and 9.2). Later, the impact on weight, volume and cost is briefly assessed compared to the conventional powering with a diesel generator set (indicated with *S0*). The operational profile or further energy saving strategies are not applied in order to only adapt the dynamic prediction model to some exemplary powering options which can be further developed and optimized in other studies.

The first strategy (*S1*) considers the fully fuel cell driven expedition cruise ship by eliminating all emissions, using hydrogen, or the major part by using the alternative hydrogen carrying fuels (here LNG). This would mean, that the fuel cells would have to be designed for the maximum power demand including the high propulsion power. In addition, sufficient fuel has to be stored in the tanks to ensure the endurance of 3 weeks constantly sailing at design speed, which results in a highly impracticable solution for a cruise ship in terms of weight, volume and costs(see results in following section 9.3). It is expected that the high temperature fuel cells can not handle the high load changes (especially while manoeuvring) due to the long starting (or heat up) and transient time, without using any additional balance of plant component (BOP) like batteries. It has to be investigated more detailed for low temperature fuel cells. In addition, it would be faced by high alternating loads, where a reliable fuel supply and transfer through the membrane has to be ensured as well.

In order to consider the critical peak loads, the second strategy (*S2*) could eliminate the high peak loads while manoeuvring (see P4 in table 9.1). Additional diesel generator sets (or BOP) could be implemented on board in a hybrid configuration. However, the power ramp-ups while changing the speed would remain and seems to be still highly critical at least for a high temperature fuel cell (here SOFC). Furthermore, the emissions would rise especially in mostly restricted port areas.

Improving the size of the fuel cell and tanks even further, all propulsion systems could be powered by additional diesel generators (*S3*). The fuel cells could be designed for a significantly lower maximum load, because the main consumers are taken out (see findings P2 and E1). The same holds true for lowering the tank size due to a lower energy demand. In addition, lower load changes can be expected during a more constant power demand throughout different operational conditions (see findings P1 and E3). This would lead to a more efficient operation of a fuel cell, which is now designed for the highest efficiency by keeping the fuel cell as small as possible. However, keeping a diesel generator for the propulsion would not eliminate the major part of the emissions while sailing, which was the main motivation of implementing fuel cells.

This brings up the last strategy under consideration of the alternative coastal operational profile (see section 8.2). The cruise ship could be fully powered by a fuel cell close to shore while cruising between different ports, which areas are mostly regulated by stricter emission limits. Longer transit cruising across the ocean could be powered mainly by additional diesel engines. The fuel cells would be still designed for the maximal occurring power demand and has to handle the high load changes (impossible for SOFC without BOP). Next to a large fuel cell system, the additional power source (e.g. diesel generator and tanks) are also designed for maximum sailing conditions, which would result in a spacious solution. Thus, the low emissions in coastal operation remain as main advantage next to the technically more favourable tank size for alternative fuels.

Additional balance of plant component (BOP) like batteries or the more dynamic operable supercapacitors are not considered in detail in this study. Later, it could be proven, if this option can be efficiently used instead of diesel generator sets even if the weight and costs are significantly higher.

Table 9.3: Operational strategy options to handle operational limits of fuel cells using (partly) diesel genset (DG) or BOP (e.g. Batteries or supercapacitors), considering cases of power and energy prediction in table 9.1 and 9.2; *(Symbolization: Technically favourable/ improved[+], unpracticable/not really unimproved[o] or impossible/unimproved[-] fuel cell (FC) system, tank size, and handling of load changes)*

Operational strategy		Emissions	FC size (Power)	Tank size (Energy)	Load changes		DG required (or BOP)	Handled case (See table 9.1 & 9.2)
					LT-PEMFC	SOFC		
S0	*Conventional powering*	*N/A*	*N/A*	*N/A*	*N/A*	*N/A*	*yes, DG used*	*initial case*
S1	Full FC driven	+	o/-	o/-	o	-	no (yes for load changes)	N/A
S2	No manoeuvring	o/-	o/-	o/-	+/o	o/-	yes, for peaks	*P4*
S3	No Prop systems	o/-	+	+	+	+	yes, Prop. Sys.	*P1, P2, E1, E3*
S4	No long transit cond.	+/o	o/-	+/o	o	o/-	yes, for transit	*P3, E1, E2*

9.3 Impact on volume, weight and cost of fuel cell system

Finally, the obtained predictions for power and energy demand are transferred into a required fuel cell size per operational strategy (indexing refers to table 9.3) compared to a powering by a conventional diesel genset (DG) (Strategy S0) exemplary for the used reference case. The following figures show the weight, volume and costs of the whole full cell system, storage system of the fuel as well as the diesel generator sets (if necessary as additional power source, here for strategy 2-4). The comparison is computed by using the parameters per installed power (basis for fuel cell size) and energy (basis for fuel storage size) in table 2.2 and 2.1 in chapter 2.1, for the low temperature PEM fuel cell and the more efficient solid oxide fuel cell (SOFC) by using LNG and pure hydrogen (H_2).

Volume and weight Generally, the volumetric and gravimetric density of the conventional MGO is higher than any of the alternative fuels for the fuel cell, which results in a significant lower weight and volume as soon as the required power of a DG gets proportionally higher (e.g. operational strategy S3). The dashed line in figure 9.1 shows the volume and weight for a fully DG driven cruise ship as conventional configuration fuelled by MGO.

First, the implemented fuel cells would have to be designed for the maximum required power (sailing at design speed) in strategy S1, S2 and S4, while the third strategy (propulsion systems via DG) results in the lowest required power (around 60% less) considering only the supplied hotel and auxiliary systems. Together with the DG for the remaining propulsion system, the whole power plant would have the lowest volume (blue bars in left graph in figure 9.1). Using a SOFC fuelled by LNG, the volume would be around 3% of the total volume of the vessel.
The additional tanks and larger fuel cells for the coastal operation leads to a higher volume in strategy S4 (red bars). The first two strategies are volumetrically larger especially by using pure hydrogen due to the high amount of energy. Strategy two leads to the highest volume by having just small differences to strategy one, because of the additional DG for manoeuvring. The volume would be already around 12% of the total enclosed volume for the reference vessel. The figure shows also the significant higher volume by using pure hydrogen for a LT-PEMFC which is at least twice as high as the conventional configuration. In addition, using the same fuel (here LNG), the power plant becomes slightly larger by using a high temperature fuel cell (here SOFC) due to the lower volumetric density in relation to the LT-PEMFC.

Comparing the weight of the different options in figure 9.1 (right graph), shows major differences for a low temperature fuel cell and using pure hydrogen (see bars in middle). The weight is significantly higher than other options as well as the conventional DG driven option, because of the low gravimetric density for the storage system. The proportional eight of around 10% for a conventional configuration would rise to 18% (S3) up to 30% (S1 and S2) of the total weight of the vessel using a LT-PEMFC fuelled by H_2.
Even if the volume of the hybrid configuration is higher, a lower gravimetric density of the fuel cell itself and higher fuel efficiencies lead to a comparable weight by using LNG in relation to the fully DG driven cruise ship (see grouped bars on left and right side). Furthermore, there are only minor weight differences between the operational strategies fuelled by LNG. The heavy storage system of the insulated and cryogenic hydrogen tanks is the driving factor of a rising weight as soon as the FC power supply rises proportionally (e.g. LT-PEMFC and H_2 in strategy S3 in relation to higher contribution in strategy S1 and S2).

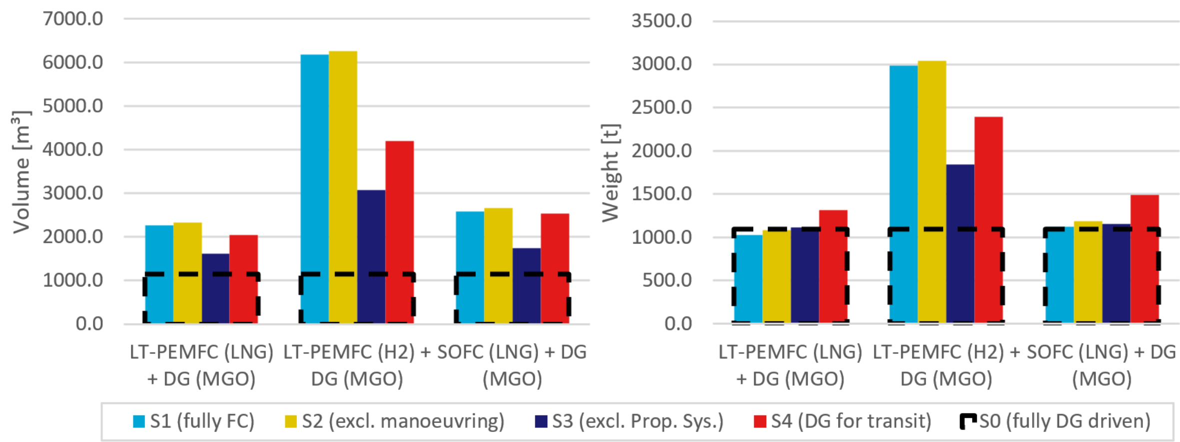


Figure 9.1: Comparison of considered fuel cell (FC) systems (incl. additional diesel genset (DG)) in terms of weight and volume (additional engine room volume excluded) for different operational strategies (see table 9.3), compared to conventional powering by diesel generator sets (dashed line), for used reference vessel; obtained parameters for weight and volume used as shown in tab.2.1 for fuel cells, tab.2.2 and fig.2.2 for fuel types

Costs As mentioned earlier, the costs are usually the main decision factor for any investment decision. However, the financial perspective is not of high importance in the actual study, because a feasible configuration has to be designed first which operates reliable and most efficiently throughout the lifetime. Secondly, the costs of fuel cells and the alternative fuels are highly varying due to ongoing developments and rising availability of fuel worldwide as well as fuel cell modules.

Based on actual parameters (see obtained factors in theoretical background in table 2.1 and 2.2), the different configurations are briefly assessed to give an idea of the actual order of magnitude. Figure 9.2 compares the capital expenditures (CAPEX) of the different configurations as far as considered earlier. It can be clearly seen that the driving factor is the fuel cell cost. The currently available small SOFC modules would result in high investment costs for a large-scale order like a cruise ship. LT-PEMFCs are already cheaper due to more developments within the automotive industry (see higher TRL), which currently can not even compensate the lower efficiencies. The high costs of a SOFC including the required fuel tanks and potential DGs (as displayed in fig.9.2) can be compared to the total building costs of a fully DG driven cruise ship. In operational strategy S1,S2 or S4, the whole power plant would nearly reach 70% of the total costs of the reference vessel with a conventional configuration. Strategy S3 can lower it to around 30%.
As a result, it would be currently not economically beneficial to design the maximal load per operational strategy on the more efficient operational point of the FC. The additional costs for a lager fuel cell system could not compensate the fuel savings over its lifetime, even for strategy S3 with an average demand close to the maximal demand.
The costs of the tanks and further storage equipment is significantly higher for the pressurized and insulated tanks of hydrogen. Nowadays, LNG is already used for combustion engines on board of ships, which could lower the prize already. However, the liquefied gas requires special tanks and is economically not directly competitive to the conventional MGO in terms of storing costs. In contrast, MeOH (here not displayed) becomes more competitive in this category due to lower requirements and consequently lower costs for the tanks (see table

2.2). Generally, the additional installation costs of the DG seem to be nearly negligible in comparison with the total costs of a hybrid concept. Thus, also the fully DG driven (conventional) strategy costs only a fraction of the cheapest hybrid configuration. The latter would cost around 10% of the total building costs of a DG driven vessel instead of 2% of the conventional DG power plant (strategy S0).

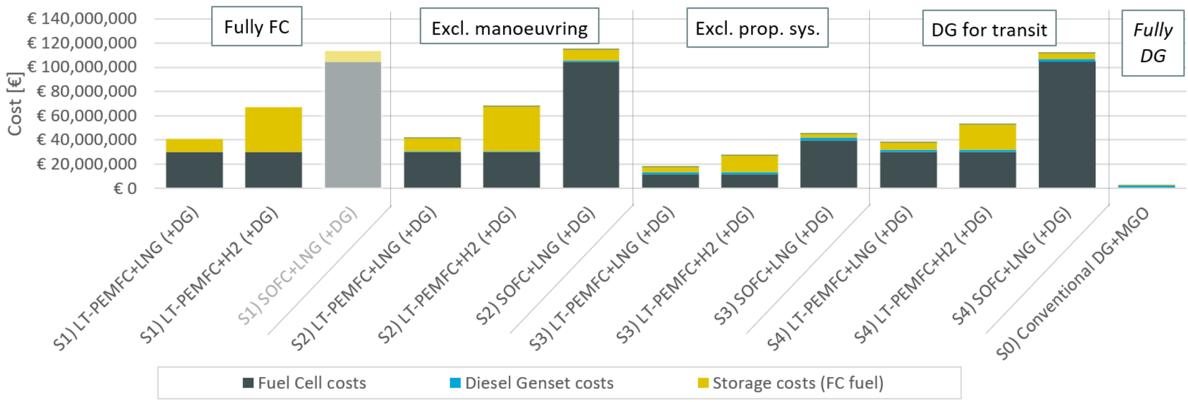


Figure 9.2: Comparison of considered fuel cell (FC) systems and required storage equipment (incl. additional diesel genset (DG)) in terms of costs for different operational strategies (see table 9.3; *Strategy 1 powered by SOFC technically impossible*), compared to conventional powering by diesel generator sets (Case 0), for used reference vessel; obtained parameters used out of table 2.1 and 2.2

Further optimizations The operational strategies can be optimized and analysed in more detail in additional studies using more specific data of manufacturers of specific modules. The varying efficiency of the fuel cells can be considered, while especially the high temperature fuel cells would have higher efficiencies at part loads. Alternatively, the average power demand could be matched with the most efficient operating point (e.g. strategy 3 with more constant load). The current high fuel cell costs can not compensate the comparably low fuel cost savings, but this can change in the future.
Secondly, the short investigation is performed by using a DG. Alternatively, the additional (more energy dense) combustion engine as power source could be also fuelled by LNG, which would simply the fuel storage and supply system.

Lastly, the implementation of balance of plant component (BOP) (like batteries or supercapacitors) can be proven, as mentioned earlier. They can be used either as additional power source (*boost function* or *load levelling* e.g. peak loads at high speed) to lower the maximum power demand and fuel cell size or as *ramp support* to reduce drastic load changes. For example in strategy 2, additional temporary power (while manoeuvring) could be supplied, while no further emissions are emitted. However, the components have to be charged in port from an external grid or directly by the fuel cells. Generally, it would result in a significant increase of volume, weight and cost in relation to the DG. The dynamic energy prediction can help to investigate the operational time, when the load is lower and the BOP could be charged by the fuel cells. However, the whole study of an efficient and reliable implementation of such a hybrid configuration is out of the scope of this study. The additional costs, weight and volume of required BOP are also not considered in the brief impact analysis.

9.4 Conclusion

As a conclusion of this chapter, the findings out of the power and energy prediction could be linked to the operational characteristics of fuel cell systems. Different operational strategies can be formulated to handle the significant findings out of the dynamic power behaviour as well as the energy prediction.
High loads of the propulsion system lead to a large fuel cell system and fuel tanks, because of the lower volumetric and gravimetric densities. The high peak loads while manoeuvring are critical for the fuel cells (S2) or even impossible to cover by the long starting time of high temperature fuel cells without any BOP components. If the whole propulsion system would not be powered by fuel cells (S3), the size of FC modules and fuel tanks could be significantly lowered. In addition, the remaining systems would run with less power fluctuations, which results in a more efficient operation. The last option (S4) could reduce the emissions in more restricted coastal

areas, by running only on fuel cells. Additional BOP components are essential to cover load peaks next to more energy dense diesel gensets for the longer transit condition at a high sailing speed. The defined typical days of operation can be used to assess common itineraries of an expedition cruise ship in mixed operational conditions and varying loads.

All in all, the dynamic prediction method can support an efficient and reliable implementation of a fuel cell by pointing out critical operational conditions like high energy demands, power fluctuations and additional peak loads. The following multi-criteria decision analysis on the power supply side can build up on the required energy and power demand of a certain part load to design the hybrid concept. Especially the impact on weight, volume and costs has to be considered. The required fuel cell size can be quantified based on the estimated maximal load and the fuel tanks by considering the predicted energy demand of the specific group of systems or operations.

Chapter 10

Conclusions and Discussion

The following chapter summarizes the research project by focussing on the main conclusions in the first section. The second part discusses the implications of the results and dynamic prediction method.

10.1 Conclusion

In order to conclude the research project, the stated research questions can be reviewed. The following part reassesses the expected results as stated in the literature review.

10.1.1 Research questions

First of all, the research objectives, as stated in section 3.3, are reviewed by summarizing the corresponding key findings, in order to solve the following problem statement.

> *Powering certain loads or operational conditions by a fuel cell system can only be assessed with a systematic bottom-up approach to consider the dynamic energy demand of certain systems in different conditions over time.*

First question - Main consumers

> *What are the main energy consumers on board and how can they be grouped?*

The main consumers are clearly identified for an expedition cruise ship. Generally, the following main groups of systems are described, like the propulsion (sec. 7.1), auxiliary (sec. 7.2) and hotel systems (sec. 7.3). Starting with the commonly used load balance (LB) approach and reference vessels, the main consumers could be analysed and grouped based on mainly three considerations.

At first, if a specific system or component contributes a higher proportion to the overall power demand, temporarily or constantly over time, then it should be modelled with a higher degree of detail. For example, the main propulsion system with its azimuth propellers is the main power consumer in sailing condition while having high load changes in port as well. Thus, a more detailed investigation can point out the temporarily high loads of the thrusters while having the speed as driving factor for the varying load in sailing condition.

Secondly, components or systems are modelled together, if they are highly dependent on each other. For example, the HVAC system is modelled together with the chilled water plant even if both systems are consuming a significant amount of energy. The cooling demand by the HVAC system is supplied by the chilled water plant and can not be kept separately.

In contrast, the emergency systems are described separated as part of the hotel systems even if the power demand is comparably low. In this case, the expected peak load occurs only in emergency situation while operating at a lower stand-by mode in normal operation. Consequently, this results in the third consideration of taking the operating conditions into account. If the grouped systems are operating in different conditions, then they should be modelled separately as well.

Second question - Simultaneity

How can the simultaneity and variable use of systems be modelled?

It is crucial to understand the dynamic power demand of every system especially in a hybrid power configuration of a cruise ship. The fuel cells and other potential powering components (e.g. DG or batteries) can be specifically designed for the power demand of a specific system or operation without taking the risk of overshooting.
The previously used constant utilization factors per operation (sailing and port) could be replaced by a dynamic prediction model considering the varying speed, passenger behaviour and weather condition. The power fluctuations of the main consumers can be pointed out. Changing loads result in a certain load change per time interval, which would be averaged out by using constant utilization factors. However, factors are still applied for minor systems, where only low gradual load changes are expected, which are neglected to reduce the computation time.

The predicted power demand of the LB approach in constant sailing condition (at design speed) is comparable, but does not consider any variations as soon as the operational condition changes. The dynamic model could consider the either simultaneous or partly running loads of the individual systems. Using typical days of operation consider all normal operations where significant changing loads of the running systems can be expected.

Third question - Driving factors of energy demand and peak loads

What are the driving factors of the energy demand of a cruise vessel and their peak loads?

First of all, the driving factors of the (installed) power demand of an expedition cruise ship are mainly the speed as well as the number of passengers and the size of the vessel (GT), which are also related to each other via the luxury level (see equation 4.1). The actual power demand is varying per operational condition, which results in a different energy demand in mixed conditions.

The energy demand of the propulsion systems is highly influenced by the speed. Lowering the speed can significantly reduce the required energy. The remaining systems are mainly depending on passenger behaviour and weather condition. However, both influencing factors do not reduce the daily energy demand by more than 10% of the total demand.
Looking into the underlying dynamic power behaviour, temporary peak loads and load changes could be identified. The manoeuvring condition results in high peak loads which can even fluctuate in a short period of time. The passenger behaviour causes load changes within the hotel systems, which are related to the actual required passenger comfort. The peak load are expected in the morning. Then the high load decreases slowly up to 40% in port condition to its minimum. The weather condition impacts the power demand of the hotel systems by less than 10%, while no significant immediate load changes are expected.

Fourth question - Localization of peak loads

Where are the peak loads during normal operation and does it hold true for different operational days?

The normal operational conditions are described by the defined typical days of operation (TDO). The mixed operational conditions (TDO3-5) describe typical schedules on a cruise ship. Temporary peak loads are identified under consideration of the varying influencing factors. The highest immediate peak occurs while manoeuvring in port. The remaining systems generate gradually changing loads with less significant peak loads. Only single electric components are starting up out of standby mode, which results in negligible peaks in the overall power demand.

Fifth question - options and limits for fuel cells

What are the options and limits of powering a cruise ship by fuel cells under the dynamic energy behaviour?

The energy demand is the driving factor for sizing the fuel tanks sufficiently. The high energy demand in sailing condition leads to large impracticable tank sizes. Hybrid configurations can reduce the energy demand by using

partly more energy dense power suppliers in specific operations or group of systems. The dynamic prediction model can be used for the identification of more favourable part load conditions or specific systems.
The immediate peak loads, mainly while manoeuvring, are critical due to the start-up time of the fuel cell modules or even impossible to cover by the long starting time of high temperature fuel cells without any BOP component.
The size of the fuel cell module can be reduced, if only systems with low load changes are supplied by the FC system. In addition, the costs would be reduced and the FC system could constantly run at a more efficient operational point. The economical perspective is the driving factor in the final implementation of any FC modules, but is out of the scope of this study due to high uncertainties and focus on the development on a feasible solution.

Main research question Bringing the individual systems together, the total power and energy demand could be analysed to answer the main research questions.

> *How can a systematic bottom-up approach be built up in the first design stage to assess the potential loads or operations to be powered by a fuel cell system under consideration of its specific operational characteristics?*

The dynamic prediction method could consider the main influencing factors, like the varying speed, passenger behaviour and the different weather condition. The situations are modelled in five typical days of operations, which present all usual operational modes of an expedition cruise ship. As a result, not only static operational modes are predicted.

The following dynamic prediction shows the varying power demand of the individual systems under varying operational conditions, while the total energy demand is still mainly driven by the variation of speed. Looking only into the auxiliary systems including the hotel functions, the fluctuating load is influenced by the passenger behaviour and the operating mode, like port or sailing condition. The different weather season impacts the level of the actual electric load, while the daily varying temperature has a lower influence.
The load behaviour of the remaining hotel and auxiliary systems is more constant and results in a less varying energy demand per day even in different operational conditions. The total load changes only gradually over time, because the demand does not change immediately. The additional peak loads are comparably low and only result from power ramp ups of individual electrical components.

As a conclusion, the method supports a well-founded decision on the power supply configuration, if it comes to hybrid systems including different power supply components and their operational characteristics. The individual load of systems can be quantified including expectable power fluctuations, which limits the serviceability of fuel cells for certain loads. In addition, the corresponding fuel tanks can be sized for an energy demand of certain systems and operating time windows considering different operational profiles such as ocean-crossing or coastal operations in more sensitive areas. The commonly used approaches with its static utilization factors for specific operational modes lead to an overprediction of the power plant components. This gets intensified for fuel cells considering lower volumetric and gravimetric energy densities in relation to conventional diesel-based solutions. The maximum condition is only reached temporarily. Especially cruise vessels are mostly running in part load conditions, for which a hybrid system can be optimized by using the proposed dynamic prediction method.

10.1.2 Proving expected results

Looking back into section 4.2, the expected results are reviewed. It could be proven, that the highest load occurs in sailing condition, where all passengers are on board, in extreme cold or warm weather conditions. Next to the propulsion system, also the hotel systems are running on a high load to offer the required passenger comfort in all areas. The number of passengers on board are the driving factor of the actual power demand of the hotel systems, which results in a lower demand in port mode. However, the peak load occurs in the morning, where the majority of the passengers are in the cabins and especially the HVAC system runs up to its maximum to ensure the required comfort level. It is the most consuming hotel system and is mainly responsible for the gradual load changes during the day. High comfort standards are defined for occupied areas. Thus, the owner specifications are the driving factor of the specific load, as expected, but also for the load behaviour during the day.
Lastly, the passenger behaviour and weather condition could be considered but have a lower impact on the total

demand than the influence of the speed. Only by focussing on part loads, the individual system behaviour can be better assessed including temporary peak loads.

10.2 Discussion

Having concluded the main findings, the prediction method and improvements are discussed. The implication is related back to the initiated problem. The following sections elaborate on the final application of the method and its limits.

10.2.1 Event validity

The prediction is based on predefined operational weather conditions. Three seasons could be used with a typical temperature profile for a cold, medium and hot location. Temporarily changing extreme weather conditions are neglected due to no added value of improving the estimation. The impact of environmental conditions on the electrical demand can be sufficiently assessed with its comparably low impact on the total energy demand.

The operational days have a wider impact on the power fluctuations. The speed profile is directly related to the propulsion demand with the highest load of all systems. The resulting energy demand of a typical coastal operational profile is based on the obtained speed profile for some reference vessels. Thus, it is important to consider, that even if the ship is not constantly sailing at design speed condition, the varying coastal profile can still slightly differ from the displayed values as soon as operational days are not entirely coincidental with the defined typical day of operation (TDO).

The defined passenger behaviour on board is also related to the operational days and based on expected movements and activities of all humans. The same holds true for the definition of the crew behaviour and working hours. In both cases, real life data and investigations on board could justify these made behavioural assumptions. The time period of higher loads can slightly differ, because of other passenger volumes in certain areas. However, the made assumptions are based on typical movements of all humans in normal operations and schedules on board.

Generally, the prediction method is made for an early design stage and is capable to point out the critical points of the power and energy demand throughout the operation, which has to be covered by a reliable power supply most likely as hybrid configuration. An event validity would result in an additional extensive data processing by increasing the level of accuracy only to a limited extent for the aimed design stage.

10.2.2 General validity and transferability of results

Reducing emission by using fuel cells is being discussed for several type of vessels in different operational profiles. The prediction was performed explicitly for expedition cruise ships as conceptual study for an early design stage. As a consequence, several parameters, the space geometry and made assumptions for typical operations are made for this type. The definition of the vessel is described in section 4.1.1 as boundary condition for the project.
In the report, a reference vessel is used to quantify the dynamic prediction. Within the mentioned limits, the main dimensions and further input data can be changed. The underlying parameters are referring to the given data (e.g. gross tonnage) and the demand can be analysed for another ship as well. Larger high-GT vessels (significantly higher than 50,000GT) are usually considered as destination itself and are equipped with more entertainment facilities, like theatres or cinemas. A proportional higher electric demand can be expected for the hotel systems, even if the number of passengers increases as well, as described by other studies as well (see fig.A.1). The model is not validated for these large vessels and only trends could be pointed out. Based on the definition, the auxiliary systems would scale mainly with the GT, while the hotel systems are more related to the number of passenger. The propulsion system load is based on the GT and the defined maximum speed.

Completely different types of vessels, like commercial vessels as containerships, are following different guidelines and regulations, which would lead to wrong results. The distinction between hotel and auxiliary system would become unnecessary, because of less passenger related systems. The whole power plant can be designed

for more static operational points, especially for long distance liners. The added value of a dynamic prediction is lower in this case, so that the load balance approach might be sufficient for the few operational modes.
Ferries could make use of the general idea of using predefined TDOs. The typical days can directly describe the regularly recurring operational days between the desired destinations. The dynamic speed profile is widely known as well as the passenger behaviour or further environmental influences. Although the impact in the latter case might be comparably low.

10.2.3 Computation time of dynamic prediction

The developed approach of assessing the power and energy demand under dynamic operational conditions provides more detailed insights into the individual behaviour of every system. The analysis looked into different weather condition each for different typical operational days, which results in several predictions. Consequently, different data sets have to be analysed to point out the extreme loads and load changes which have to be covered by a reliable power supply. In addition, only by doing an in-depth study of the complex HVAC system, the power fluctuations over the day can be pointed out. Together, this increases the computation and analysis time to properly assess the results.
At this point, a static approach seems to be easier to calculate the maximum load of the individual systems and components. However, the power fluctuations would be not considered, which results in insufficient results for larger dynamically operating ships. In contrast, the predefined operational days and passenger behaviour in the dynamic model can now be used for further projects to speed up a first conceptual study. Further adjustments of specific parameters can be done in a later stage, so that the method can be used with a limited set of required input data at the beginning.

10.2.4 Financial impact

Section 9.3 assesses an efficient implementation of fuel cells only briefly in terms of volume, weight and costs. A dynamic prediction model is here the basis for the potential savings and optimizations, as a result out of different operational strategies. However, the specific value is highly depending on the underlying parameters per power or energy unit. Especially the costs are depending on highly varying parameters due to ongoing developments and rising availability. As soon as more efficient fuel cells become available for large-scale projects together with an improved fuel availability worldwide, the technology would become more competitive as well. Then, the limiting factors of the operational strategies would differ, and the dynamic prediction could be fully used to identify only the operational limits. At that point, focussing on peak loads and load behaviour is of higher importance than optimizing the size of fuel cell in terms of financial limitations.

10.3 Final advices

The lower energy dense fuel cell systems and available sizes limits a practically feasible implementation of fuel cells on board of expedition cruise ships. As a consequence, the fuel cells are implemented most likely in hybrid configurations together with commonly used diesel generators for high loads or additional BOP for balancing out temporarily higher power demands. The most efficient operational condition has to be identified under dynamic conditions.

At this point, the dynamic prediction method analyses the individual behaviour of the systems. The previously used simultaneity (included in the utilization factor) averages out peak loads and the different load levels in part load condition. The driving factor of the total power demand is the speed of the vessel. The resulting fuel cell size can be reduced by focussing on the more constant load of the hotel and auxiliary systems. The baseload could be reliably supplied by a fuel cell system, which is currently the most efficient option in terms of volume, weight and costs.

Finally, the corresponding power supply side can be analysed and optimized in a multiple-criteria decision analysis building on the dynamic prediction. Further improvements and next steps are described in the following chapter.

Chapter 11

Outlook

The last chapter describes further suggested research which can build on the findings of the actual research project. In addition, the final outlook brings the topic in a broader framework and ongoing debates beyond the technical aspects.

11.1 Recommendation and further research

Simplifications are made within the power prediction, which leads to further room of improvements. Some recommendations for further research studies are presented in the following section.

11.1.1 Thermal balance

The actual study focussed on the electrical demand of a cruise ship as a basis for a sufficient power supply. Fuel cells could replace the commonly used diesel-powered systems. At this point, it is important to consider further thermomechanical consequences as well.
The heat in the exhaust, produced by the combustion process, is normally used by the exhaust gas boiler, heating up water directly or any other heat recovery system. The required heat in these other systems has to be balanced by fuel cells or potentially additional electric heaters or boilers. Lower exhaust temperatures are expected for some fuel cell types, while additional heat could be taken out of the produced water after the chemical process in the stacks.
On the other hand, the liquefied chilled fuels (e.g. H_2 and LNG) have to be preheated as well before bringing them into the fuel cell membrane. This requires additional heat in relation to the commonly used MGO in the liquid phase in ambient condition. Meanwhile, the fuel cell modules require less cooling while operating. The reduction of cooling water and additional ventilation can further be optimized.
All together, a thermal load balance under dynamic condition should be performed as well to prove the heat balance on board. Alternatively, additional heat has to be produced, for example electrically impacting the electric power prediction.

11.1.2 Energy saving devices and strategies

The main part of the study was the power prediction for every system on board. Assumptions could simplify the estimation based on common configurations. However, a variety of energy saving strategies can be proven on board by using new technologies or improving the internal operating point and efficiencies. The total power demand could be lowered and load changes further reduced. Some options are briefly discussed.

Propulsion system The used efficiencies within the propulsion chain are used like for a conventional configuration with diesel gensets. In following studies, the impact of additional fuel cells can be proven. Optionally, the cruise ship could be run completely on electric energy. Only a transformation would be necessary at the azimuth thruster directly to mechanical energy. The possibility and impact of having less voltage transformation has to be reviewed.

In addition, the fuel cell modules could be also distributed on board to have the power source right at the location. Long transmission and more transformations including their losses would not be required anymore, on condition that a sufficient fuel supply is provided. However, the impact has to be further investigated.
Generally, a hybrid concept with various power sources can be driven on different configurations, where the efficiency is depending on the actual load. Together with the corresponding charging time of batteries, the whole operational profile has to be kept in mind to reach the best overall efficiency.

Water systems The usage of water is reducing the electric power demand in several ways. Less water reduces the to be produced fresh water as well as the wastewater system demand. In addition, reduction of warm water requires less heat as well, which can be used by other systems, if the exhaust heat is used.
Especially the required water in cabins can be optimized. The flow rate of water in showers can nowadays reduced by using pressurized mist. The atomized water can increase the covered surface without a significant loss of comfort for the passenger. Together with potential recirculation of water (e.g. in laundry), the total required volume can be reduced to lower the electric energy demand.
The immediate use of the produced water by the fuel cell has to be proven as well. After adding minerals, the water quality could be raised to potable water quality.

HVAC The complex HVAC system prediction makes use of many commonly used parameters as usually defined by the owner specifications. High comfort standards are typically applied for more luxurious expedition cruise ships. However, adjusting the design parameters can have a significant impact of the consumed energy.
The calculations in section 7.3.1 show, that the hourly air changes are mostly driven by the fixed rates set by the owner. Lowering the air change rate would reduce the power of running fans and heating or cooling elements. Together with a higher recirculation rate, the heating (or cooling) demand could be significantly lowered. CO2 sensors in the room could be linked to a more efficient HVAC system.
Furthermore, the electric heaters are generally a cheap option to install, but during its lifetime related to higher operational costs. Using warm water can make use of exhaust heat by increasing the total efficiency. Less electrical power would be used by the locally installed heaters.
Cooling is the main power consumer during the summer season. Further investigations of the gained heat by the sun can reduce the required cooling in the room. The length of the balcony or improved shading of the window glasses can lower the demand. Ultrasonic humidifiers could further increase the efficiency of dispensing the mist in the air by means of high frequency vibrating dishes. The energy savings coming along with currently higher installation costs.

A broader analysis of the whole operational lifetime can also survey the design point of the HVAC system. It can be expected, that the system and its components are running most of the time below the optimal design point. The rare extreme weather conditions are the reason for installing large components [72]. Alternative design point could lower the consumed energy. Consequently, the high comfort level (e.g. temperature) could only not be hold in some single extreme conditions.

Lighting The illumination is of high importance for a cruise ship and part of the interior design not only practically, but also as part of bringing the right atmosphere and comfort into the areas.
New cruise ships making use of LED lighting, which can significantly reduce the electric demand. The majority of lights are running throughout the day in public areas independent of the actual occupancy. This could be improved by using additional sensors. In addition, the option of using more natural lighting could be proven. Recently, suppliers and ship operators are investigating the idea of using light domes or tunnels to bring the sunlight into the rooms. Together with mirrors, the light can be transferred even further in inner areas. However, the potential savings are comparably low in relation to other systems.

11.1.3 Real-life validation

As partly discussed in section 10.2.1, especially the operational day and the corresponding passenger behaviour and speed variation is assumed based on typical operations. A real-life assessment could validate the made assumptions by tracking passenger movements throughout the day and the individual usage of all facilities. The processed data could be further used for energy-saving strategies, as previously mentioned. Systems could run temporarily to fulfil the actual passengers demand.

11.1.4 Matching power demand and supply efficiently

After having looked into the power demand side, the supply side has to be designed as well. As briefly mentioned earlier, different options are available for a hybrid configuration. Next to the conventional combustion engines, batteries are already in use in the maritime industry to balance immediate peak loads on smaller ferries. A reliable power plant can be optimized in terms of different parameters like volume, weight or costs. The different power sources have to be considered with their different advantages. For example, batteries are comparably heavy and expensive, which limits the application. Next to the CAPEX, the expected OPEX over its lifetime have to be considered as well. Thus, the right combination has to be analysed for the specific ship in a multiple-criteria decision analysis supported by the proposed dynamic prediction method of the energy demand.

Life Cycle Assessment

It is important to consider also further OPEX costs as a consequence of required replacements of the fuel cells or batteries in the end of their lifetime. Usually, the modules has to be replaced, while the vessels lifetime is at least twice as high. The whole life cycle assessment rises also further questions in terms of emissions. Not only the FC modules have to be produced, but also the alternative fuel should be sustainably obtained.
For example, pure hydrogen (H_2) is currently mostly produced by energy-intensive production methods(e.g. electrolysis). In addition, the availability worldwide has to be improved to avoid further required distribution by tankers or trucks on shore emitting even more greenhouse gases. Thus, a life cycle assessment can properly evaluate the potential reduction of emissions within the whole supply chain.

11.2 Outlook

In the last 20 to 30 years, some developments within the cruise industry could have been observed. Starting in the nineties, the cruise ships began to be part of the mass tourism. The number of ships and the total volume started to increase massively. Yearly high rates of passenger increase resulted in lowering the expenses per person to make it affordable for everyone in a competitive market.
In the last years, the cruise industry is also impacted by the rising ecological awareness while it is still considered to be one of the most polluting types of holiday. The focus became more on fuel saving strategies and rising operational efficiencies not only out of the economic perspective. It is even part of the marketing strategy towards a greener industry. More money could be spent on investigations of reducing the fuel consumption and developing new technologies.

Recently, the number of smaller expedition cruise ships increases, as described at the beginning. More remote or restricted areas are within the itineraries and require more efficient and sustainable technologies on board. The lower energy demand of smaller ships enables even more the implementation of fuel cells as promising solution.
The global corona pandemic in 2020 faces the cruise industry nowadays with other challenges and upsets any plans at the moment's notice. The consequences can not be foreseen with the impact on ongoing technological developments. On the one hand, smaller ships might be more required, which are commonly considered as more spacious per individual passenger. Otherwise the market is saturated with ships in the market and already placed orders for the next years. Thus, any higher capital investments of new technologies are even more critical.

On a long-term basis, fuel cells are a promising option to comply with upcoming regulations for new expedition cruise ships. In the meantime, a comprehensive bunkering network has to be ensured. The raising availability of LNG leads already to an increased utilization of gas driven combustion engines. This network could be also used for LNG driven fuel cells in the first stage. Pure hydrogen has to be produced by more sustainable methods first, before considering it as promising emission-free alternative.

All in all, a dynamic prediction method of the total electrical demand on board of ships becomes crucial in any case. Ships are going to be build and refitted to comply with rising number of regulations and local restrictions. The dynamic assessment of the on board systems can raise the efficiency and lower the fuel consumption by keeping the costs, additional required volume and weight as small as possible.

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Appendix A

General definitions and supplementary information

A.1 Supplementary information literature study

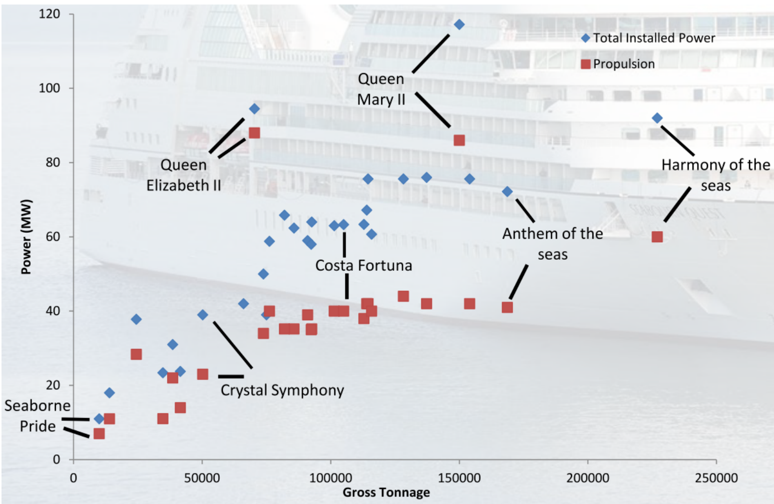


Figure A.1: Total Installed Power and Propulsion Power for different GT cruise ships built between 1988 and 2016 [88]

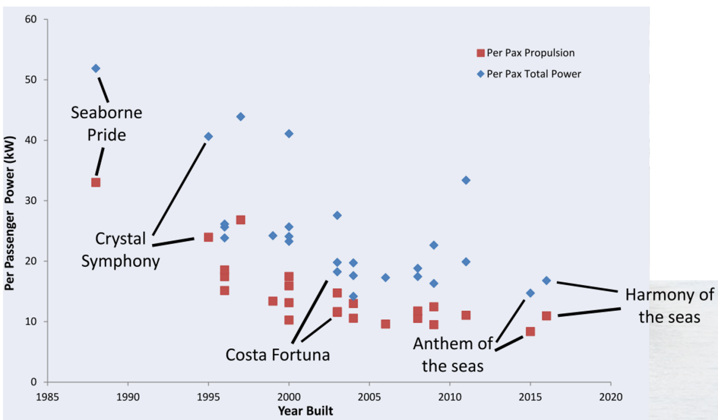


Figure A.2: Per passenger power versus year built for cruise ships built between 1988 and 2016 [88]

A.2 Regression data main dimensions

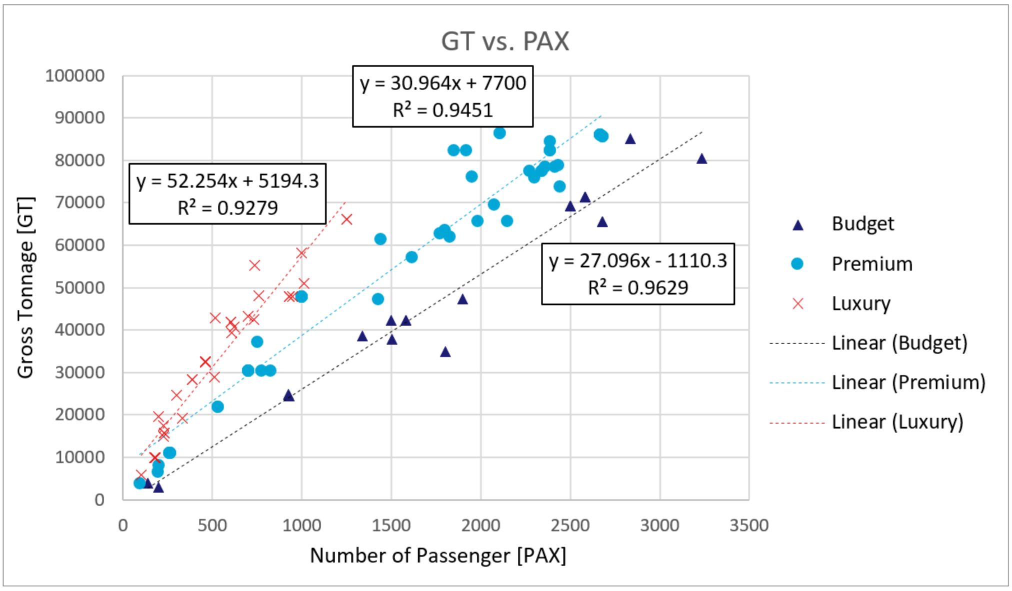


Figure A.3: gross tonnage over passenger, data obtained from internal database of shipyard for built cruise ships with less than 90,000GT

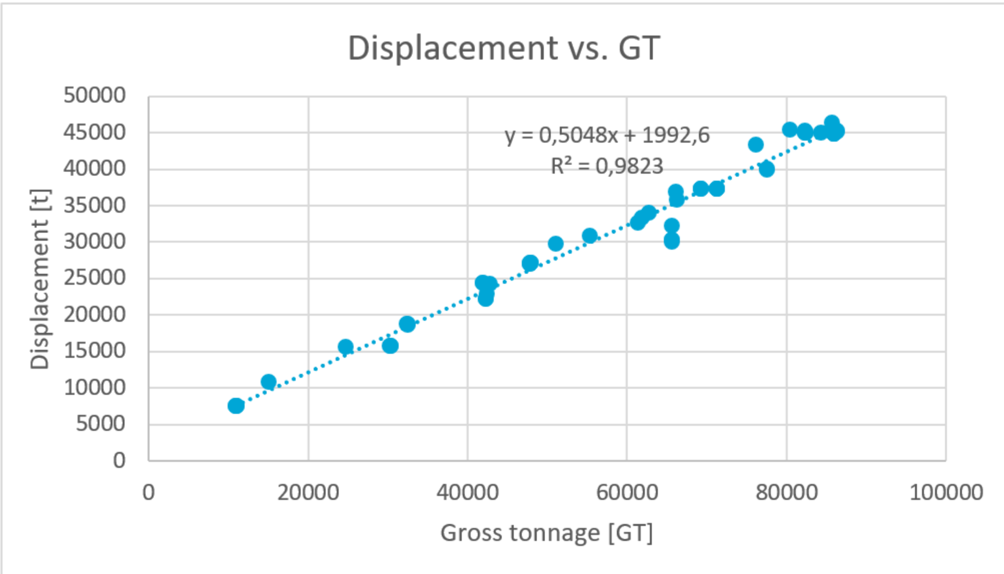


Figure A.4: Displacement over GT, data obtained from internal database of shipyard for built cruise ships with less than 90,000GT

A.3 Types of areas

A distinction has to be made between the different types of areas, which usually have a different design of the HVAC system or different comfort requirements and regulation standards. Based on the reference vessel, provided by the shipyard can be grouped based on different regulations[48] and common owner standards. This simplified overview is shown in the graph in figure A.5 with the corresponding percentages.

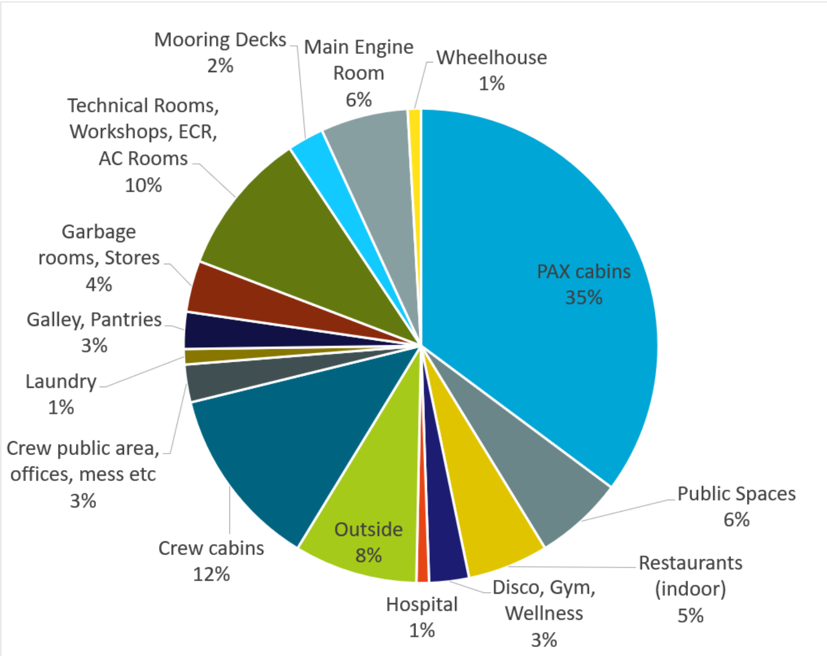


Figure A.5: Percentage of different types areas out of overall area on board of reference vessel, data provided by shipyard

Obviously, shipping companies would like to extend the number of cabins as much as possible in order to accommodate more passengers during operation. In the current case, 35% of all areas on board are used for cabins. Considering the luxury level, the proportion of the different areas can differ between different projects. For example, the area of the cabin block would be proportionally larger for ships with a lower luxury level and consequently with a lower space-to-passenger ratio.
The crew area (15%) includes the crew cabins, mess and further offices. The 6% of public spaces in figure A.5 involves lobbies, shops and lounges. The restaurants are implemented separately with 5%. However, only indoor restaurants are considered. Recreation areas (3%) include additional areas like the nightclub, gymnasium and wellness-areas. Even if the air in the outside areas (8%) is not further conditioned, it is included due to the additional lighting in these spaces. The hospital as well as the laundry and galleys are considered separately due to the specific regulations[48] for handling the exhaust air. Different types of areas are defined for the operational rooms for the power plant components. Technical rooms and workshops (10%) are summed up in one group and contain all engine workshops, the engine control room (ECR), AC rooms and additional stores for further equipment. The mooring deck is usually open to the ambient air and uses around 2% of the whole area. The engine and propulsion rooms of 6% have to handle big air flows for the engine and is examined separately as well. Lastly, the wheelhouse has a proportional area together of around 4%.

The defined areas on board can now be allocated by using the reference data of the shipyard. Floor space factors floor space factor (FSF) are defined to obtain a parametric model which is scalable for further projects. The accuracy of this approach can be adjusted and improved in a later design stage, where more data and drawings are available. Generally, the hotel spaces are scaled based on the number of PAX, the crew spaces per crew member, the general service spaces per person on board (POB) and the machinery spaces per installed brake power. Obviously in the latter case, the propulsion calculation has to be done before this step to gain the installed brake power (see equation 7.4). This is possible, because the propulsion system is independent of the current space allocation. The obtained FSFs are shown in table A.1. Only the cabins are a standardised size and will be scaled per required number of cabins(see following paragraph).

The actual volume of the spaces can now be obtained by multiplying the areas by the deck height, which is defined by 3 metres per deck in this early design stage. This considers the inner room height and the additional upper space above ceiling for the required steel structure, pipes and cables.

Table A.1: Obtained FSFs for space allocation

Room/Area	FSF	
PAX cabins	*see below, expression A.1*	
Corridors	10.0	m^2/PAX
Public spaces	5.5	m^2/PAX
Restaurants (indoor)	3.7	m^2/PAX
Disco, gym, wellness	2.1	m^2/PAX
Hospital	0.6	m^2/PAX
Outside	5.6	m^2/PAX
Crew cabins	11.8	m^2/crew
Crew public area, offices, mess	2.5	m^2/crew
Laundry	0.5	m^2/POB
Galley, Pantries	0.9	m^2/POB
Garbage rooms, Stores	1.3	m^2/POB
Technical Rooms, Workshops, ECR, AC rooms	230.0	m^2/MW
Mooring Decks	50.0	m^2/MW
Main Engine Room	115.0	m^2/MW
Wheelhouse	16.0	m^2/MW

A.3.1 Definition of standard cabin

In order to simplify the different sizes of cabins on board, one standard cabin can be defined. The size can be scaled depending on the actual luxury factor of the vessel. The higher the luxury factor, the higher is the average size of passenger cabin. This standardised cabin can then be multiplied by the number of passenger. This is based on different reference vessels which are fulfilling the definition of an expedition cruise vessel in section 4.1.1. The ten chosen vessels have less than 50,000gt and are operating in the premium or luxury market (see definition in table 4.1). The obtained data for cabin sizes is shown in table A.2. The weighted average cabin size can be compared with the commonest size of the available cabins on board. In the latter case, less cabins of larger and smaller sizes are usually on board.

Table A.2: Cabin sizes of selected reference vessels

Cruise Ship	Gross tonnage [gt]	Luxury level [gt/Pers]	Weighted average size [m^2]	Commonest available size [m^2]
Europa 2	42830	77	31.53	28.00
Europa	28890	64	28.45	27.00
Silver Wind	17235	48	26.86	22.00
World Explorer	9271	53	22.57	22.50
Le Laperouse	9976	54	29.46	19.00
Roald Amundsen	20890	35	22.84	22.00
Scenic Eclipse	22498	72	44.68	32.00
Seabourn Quest	32346	60	32.23	28.00
Sea Dream I	4333	39	21.83	18.00

The weighted average size of the available cabins can be calculated and is the basis for the graph in figure A.6. A linear relationship is concluded between the weighted average size of cabin over the luxury level. Thus, the equation A.1 can be used to calculate the standard cabin for a cruise ship under consideration of the luxury level. In addition to the FSFs in table A.1, the cabin block can now be calculated by accommodating 2 passengers in one cabin.

$$FSF_{Cabin} = 0.327 \frac{GT}{PAX_{ALB}} + 9.56 \qquad [m^2/cabin] \tag{A.1}$$

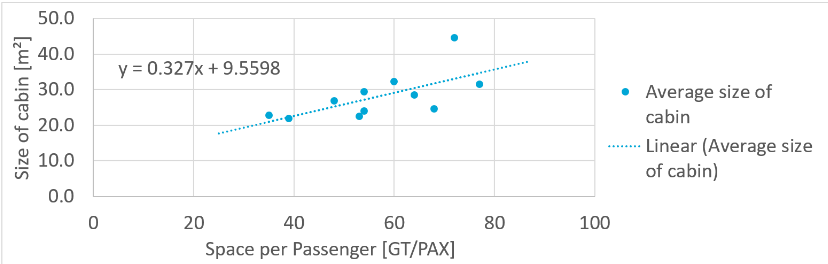


Figure A.6: Displacement over GT, data obtained from internal database of shipyard for built cruise ships with less than 90,000GT

A.3.2 Space geometry

Lastly, the wall and window areas are required as a rough approximation for assessing the gained heat and resulting power demand of the HVAC system in a later step, even if a general arrangement or alternative drawings are not available in this stage. However, the degree of accuracy of this approximation is low, but sufficient to consider additional heat gains in a later step. The different groups of spaces and corresponding areas are defined and can now be linked to a ratio of width over the length of the rooms by assuming a rectangular shape. Thus, the room dimensions are now defined.

In the next step, the assumed proportion of outer walls brings up the length of inner walls and walls towards the ambient air. In the end, the proportion of windows defines the glazing area in the outer walls for considering additional heat gains. The described basic procedure is shown in the sketch in figure A.7. The assumed ratios are based on general arrangement plans of reference vessels and are listed in the table A.3.

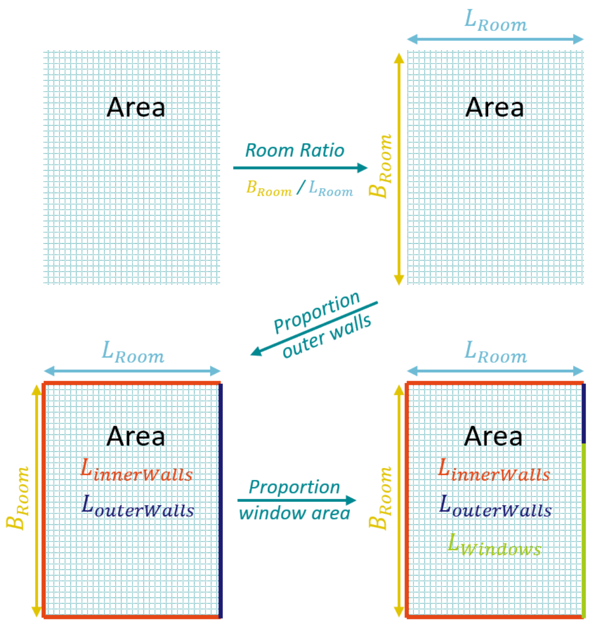


Figure A.7: Simplified procedure to define lengths of inner and outer walls as well as windows in early design stage

Similarly to the mentioned approach above, the standardized cabin is also assigned to a Width/Length-ratio, here equal to 2.5, see figure A.8. Additionally, the outer wall consists mainly of a window (green) bordered by a wall (80cm, according to regulations for minimum required steel structure [26]). A balcony is located in front of every cabin.

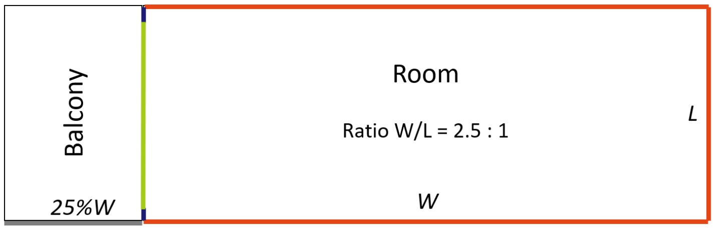


Figure A.8: Definition of lengths of inner and outer walls as well as windows in early design stage for standardized cabin

Table A.3: Ratios for room dimensions, proportion of outer walls and windows

Area	Ratio B/L of area	Propor. outer walls	Propor. windows of out. walls
Public Spaces	4	40%	50%
Restaurants	1.5	25%	70%
Disco, Gym, Wellness	1.5	25%	70%
Hospital	1.5	0%	0%
Crew cabins	2	15%	10%
Crew public area, offices, mess	1.5	15%	10%
Laundry	1.5	0%	0%
Galley, Pantries	1.5	0%	0%
Garbage rooms, Stores	1.5	0%	0%
Technical Rooms, Workshops, ECR	1.5	0%	0%
Main Engine Room	1.5	0%	0%
Wheelhouse	5	60%	60%

Appendix B

Operational conditions

B.1 Operational profile

B.1.1 Speed Profile

In order to analyse and define a typical operational profile of an expedition cruise ship, the following reference data can be used, in accordance with section 6.1.1. Before displaying the obtained data, some incidents have to be considered which occurred for some of the used cruise vessels.

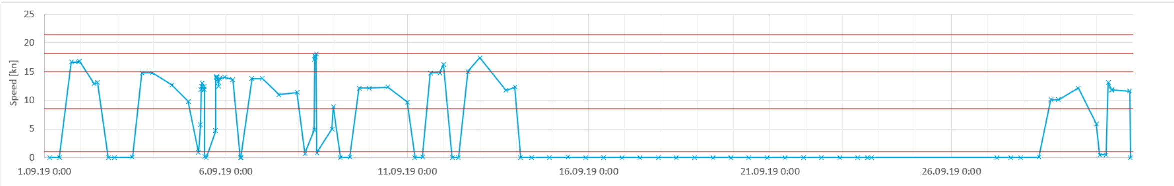
Europa 2 The ship was in the dock in Hamburg for around 2 weeks in September 2019, as shown in figure B.1a.

Hanseatic Nature No data is recorded for the vessel in the first part of January 2020.

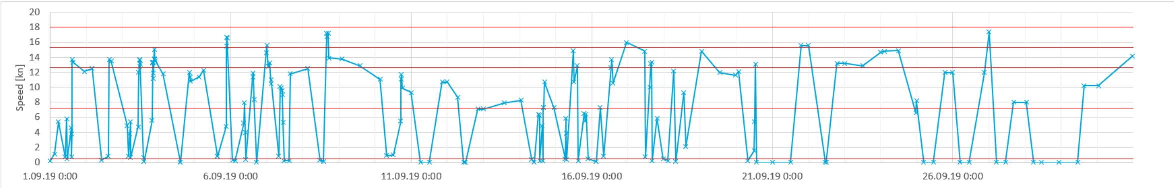
Roald Amundsen The expedition vessel *Roald Amundsen* of the shipping company Hurtigruten was built in 2019 and launched after September. Consequently no data is available for the September 2019 in figure B.3a.

Silver Wind The Atlantic was crossed between the 5th and 11th of September 2019 and can be seen in the graph with constant speed within the assumed design speeds.

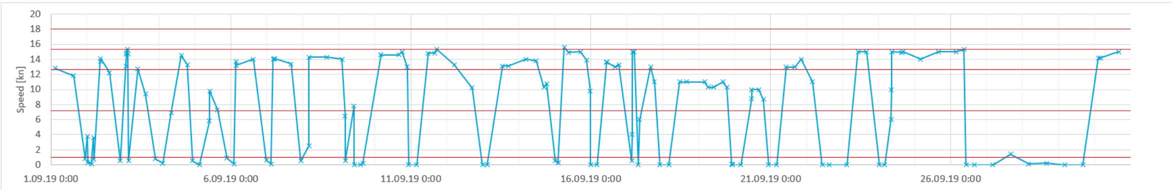
The following speed profiles can be obtained in figure B.1 and B.2 from the maritime intelligence provider *MarineTraffic* [59].



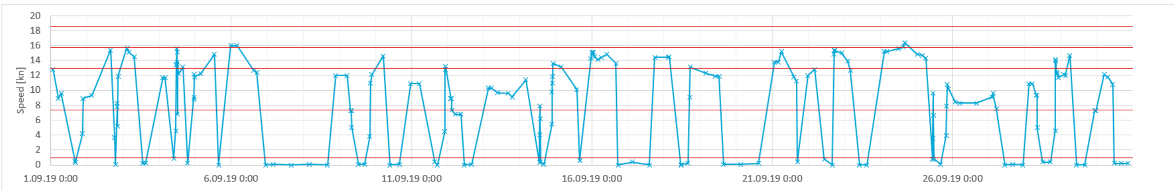
(a) *Operational Profile Europa 2*



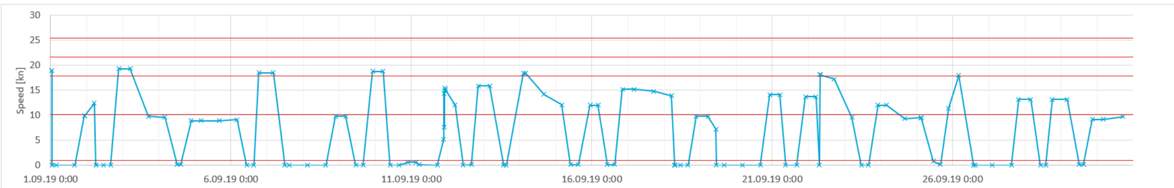
(b) *Operational Profile Hanseatic Nature*



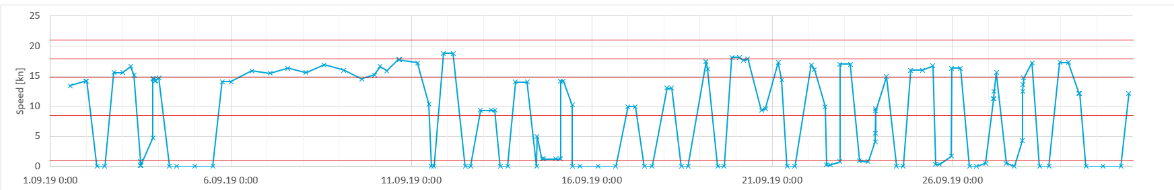
(c) *Operational Profile Le Laperouse*



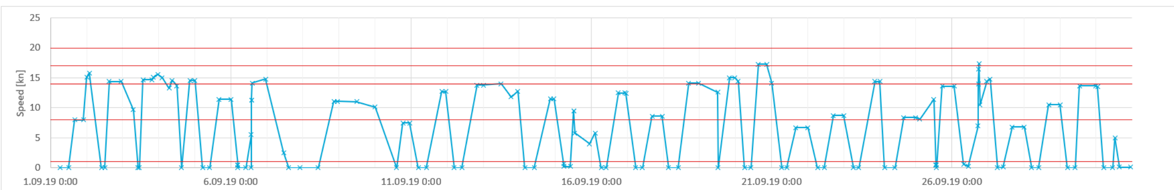
(d) *Operational Profile Scenic Eclipse*



(e) *Operational Profile Seabourn Quest*

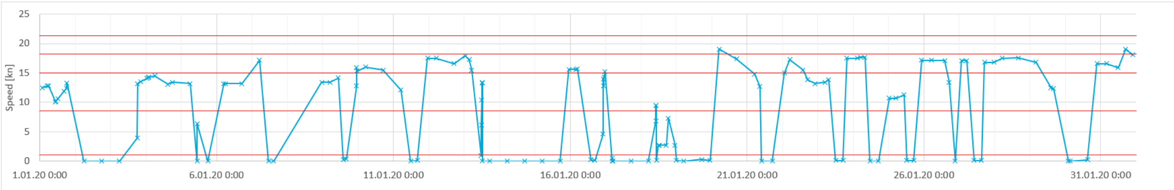


(f) *Operational Profile Silver Wind*

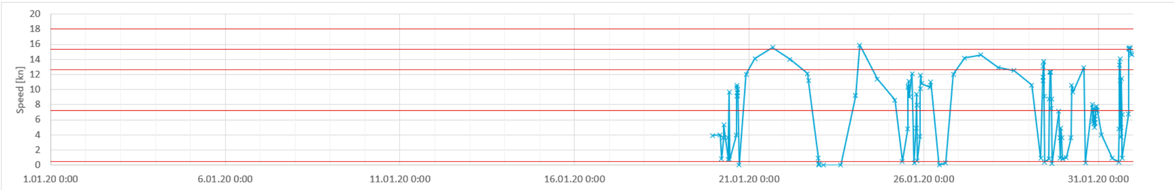


(g) *Operational Profile World Explore*

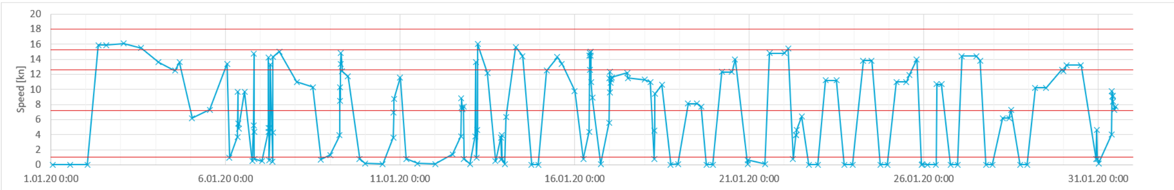
Figure B.1: Operational Profiles of selected expedition cruise vessels in September 2019 [59] (Speed ranges marked in red as defined in table 6.2)



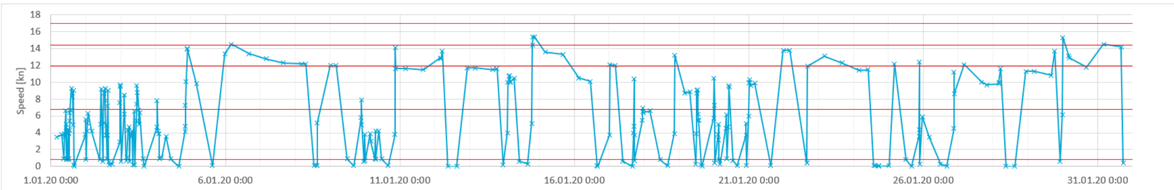
(a) *Operational Profile Europa 2*



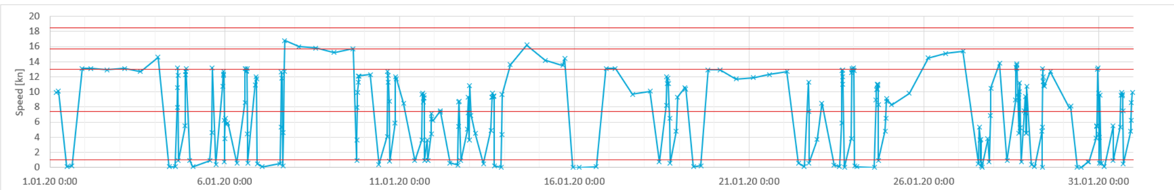
(b) *Operational Profile Hanseatic Nature*



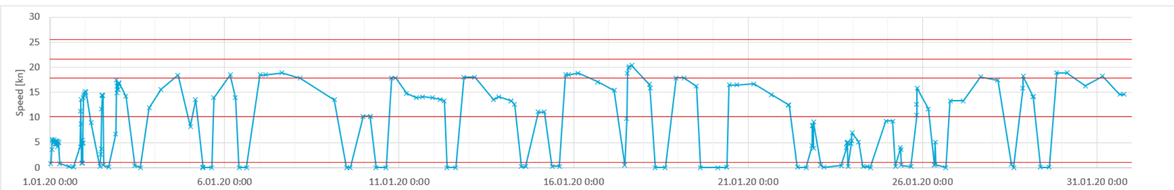
(c) *Operational Profile Le Laperouse*



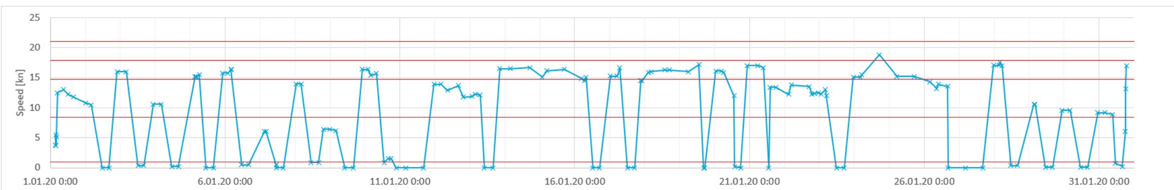
(d) *Operational Profile Roald Amundsen*



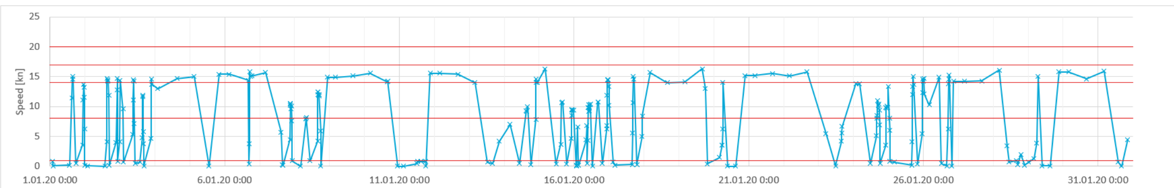
(e) *Operational Profile Scenic Eclipse*



(f) *Operational Profile Seabourn Quest*



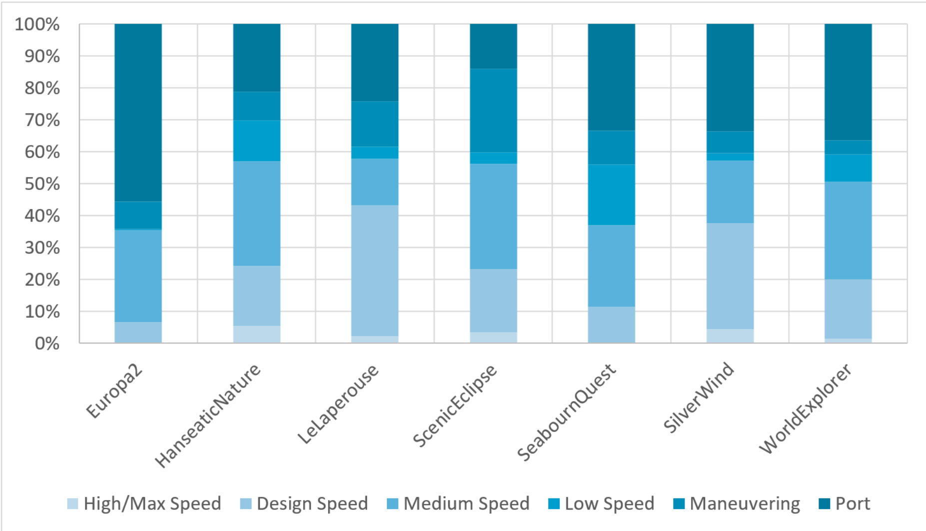
(g) *Operational Profile Silver Wind*



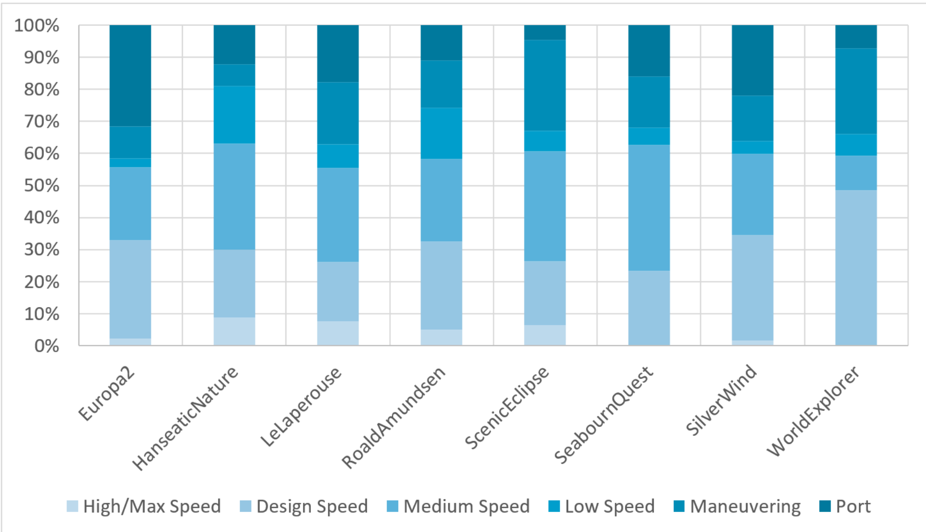
(h) *Operational Profile World Explore*

Figure B.2: Operational Profiles of selected expedition cruise vessels in January 2020 [59] (Speed ranges marked in red as defined in table 6.2)

Processing the data, the following figure B.3 shows the time spent at a certain speed range per ship.



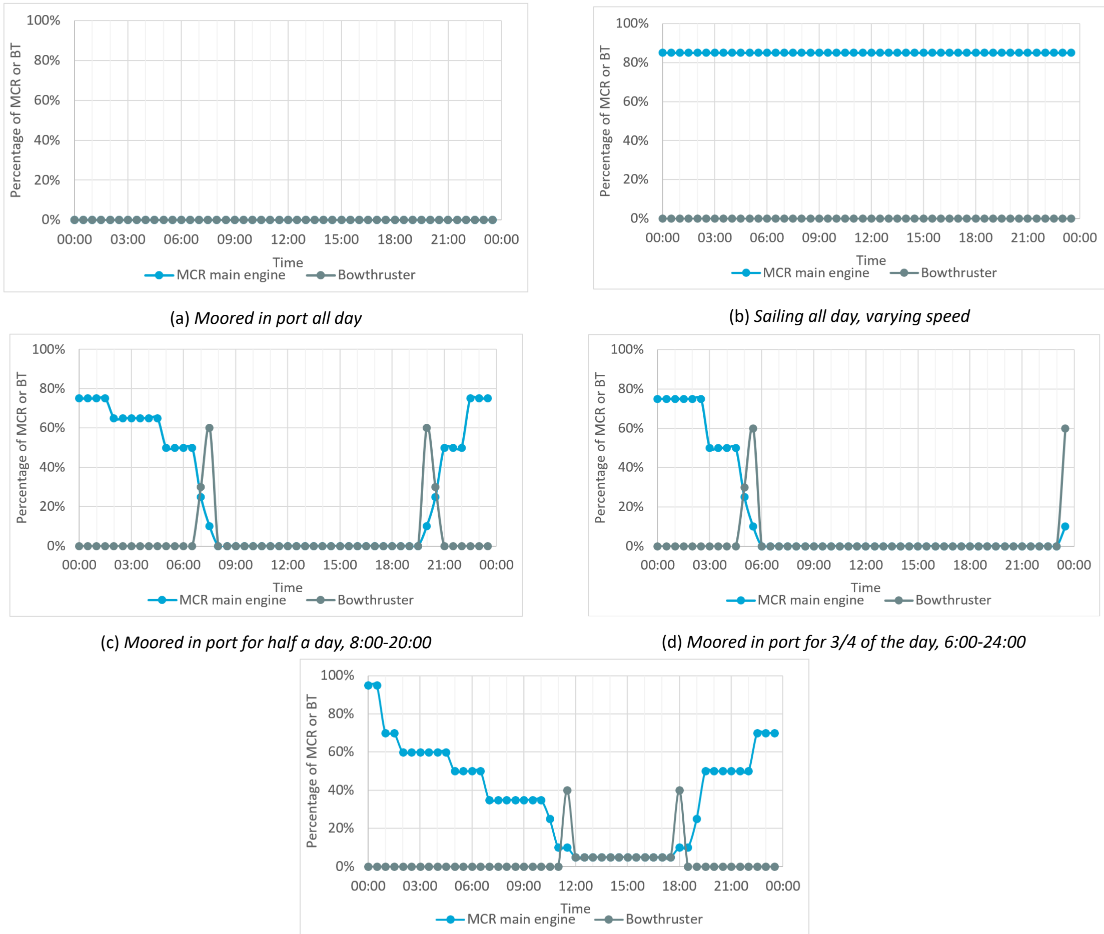
(a) *September 2019*



(b) *January 2020*

Figure B.3: Speed Condition of reference ships

B.1.2 Defined speed profile for TDOs



(a) *Moored in port all day*

(b) *Sailing all day, varying speed*

(c) *Moored in port for half a day, 8:00-20:00*

(d) *Moored in port for 3/4 of the day, 6:00-24:00*

(e) *Slow speed sailing and anchoring for half a day, 12:00-18:00*

Figure B.4: Definition of speed profile within defined typical days of operation (TDOs)

B.1.3 Case study - operational profile

The following operational profile is used for the case study in section 8.2. A typical expedition cruise vessel (see definition in section 4.1.1) is chosen with a gross tonnage of 15,651gt operating in the luxury class with 68gt/PAX (see luxury level in table 4.1). The used *Hanseatic inspiration* is the same class as the reference vessel *Hanseatic nature* operated by HAPAG-Lloyd cruises in section 6.1. The following 21-days operational profile is used as case study based on a planned cruise, simplified by using the defined typical day of operation (TDO) (see itinerary in table B.1), as defined earlier in section 6.1.2. It represents a typical schedule of expedition cruise ships. It does not follow a weekly round trip and sails to small harbours or even remote areas to lie on anchor.

Figure B.5: Map of planned cruise by *Hanseatic inspiration*, used as case study, obtained by operating cruise line HAPAG-Lloyd [38]

Table B.1: Itinerary (obtained by operating cruise line HAPAG-Lloyd [38]) of planned cruise by *Hanseatic inspiration*, used as case study, including simplification using defined TDOs

Day	**Destination[38]**	Simplified by TDO	
Day 1	Anchorage, departure 17.00 hrs	TDO3	1/2-day in Port
Day 2	Relaxation at sea	TDO2	Sailing day
Day 3	Unga Island/Aleutian Islands/Alaska	TDO5	1/4-day at Anchor
Day 4	Relaxation at sea	TDO2	Sailing day
Day 5	Aleutian Islands (Seguam)	TDO5	1/4-day at Anchor
Day 6	Aleutian Islands (Tanaga Island)	TDO5	1/4-day at Anchor
Day 7	Aleutian Islands (Attu Island)	TDO5	1/4-day at Anchor
Day 8	Relaxation at sea	TDO2	Sailing day
Day 9	Kamchatka/Russia (Petropavlovsk)	TDO3	1/2-day in Port
Day 10	Kamchatka/Russia (Petropavlovsk)	TDO4	3/4-day in Port
Day 11	Kamchatka/Russia (Zhupanova)	TDO5	1/4-day at Anchor
Day 12	Kamchatka/Russia (Russkaya Bay)	TDO5	1/4-day at Anchor
Day 13	Kamchatka/Russia (Cape Kerkyrnyi)	TDO5	1/4-day at Anchor
Day 14	Kuril Islands (Ptichiy Islands)	TDO3	1/2-day in Port
Day 15	Kuril Islands (Atlasova)	TDO3	1/2-day in Port
Day 16	Kuril Islands (Yankicho (Ushishir))	TDO3	1/2-day in Port
Day 17	Sakhalin (Tyuleny)	TDO5	1/4-day at Anchor
Day 18	Sakhalin (Korsakov)	TDO3	1/2-day in Port
Day 19	Japan (Rishiri)	TDO4	3/4-day in Port
Day 20	Japan (Teuri)	TDO4	3/4-day in Port
Day 21	Relaxation at sea	TDO2	Sailing day
Day 22/Day 1	*Kanazawa/Japan, arrival/next cruise*	*next cruise*	

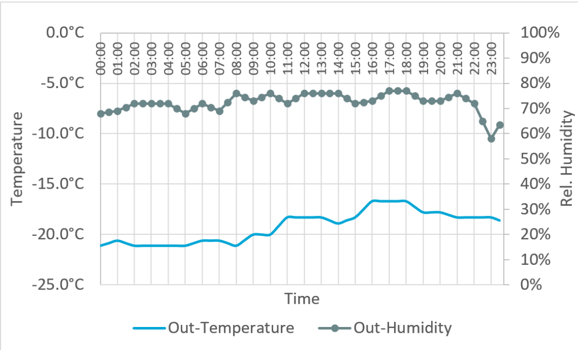
Operating time in certain speed range compared to typical profile, as obtained out of the AIS data in section 6.1.1

Table B.2: Proportion of operations in certain speed ranges as obtained out of AIS data (reprinted from table 6.3) and for used case of 21-day cruise

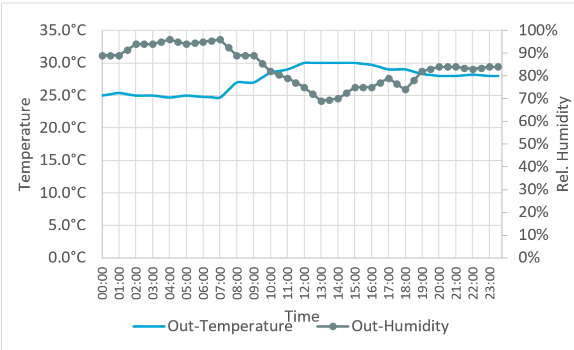
Speed Range	% of max. Speed	Proportion summer	Case
Port/Anchor & Manoeuvring	<1kn	42%	39%
Low Speed	1kn-40%	8%	9%
Medium Speed	40-70%	27%	26%
Design Speed	70-85%	25%	25%
High Speed	85-100%	4%	2%

B.2 Weather Profile

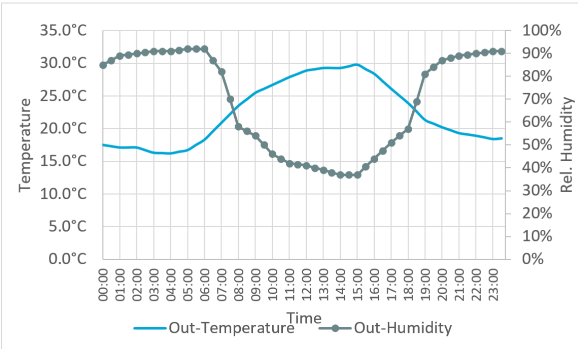
Used data for defining environmental condition in section 6.2.2.



(a) *Resolute Bay in Canada in winter (referred to as cold condition)*



(b) *Singapore in summer (referred to as hot condition)*

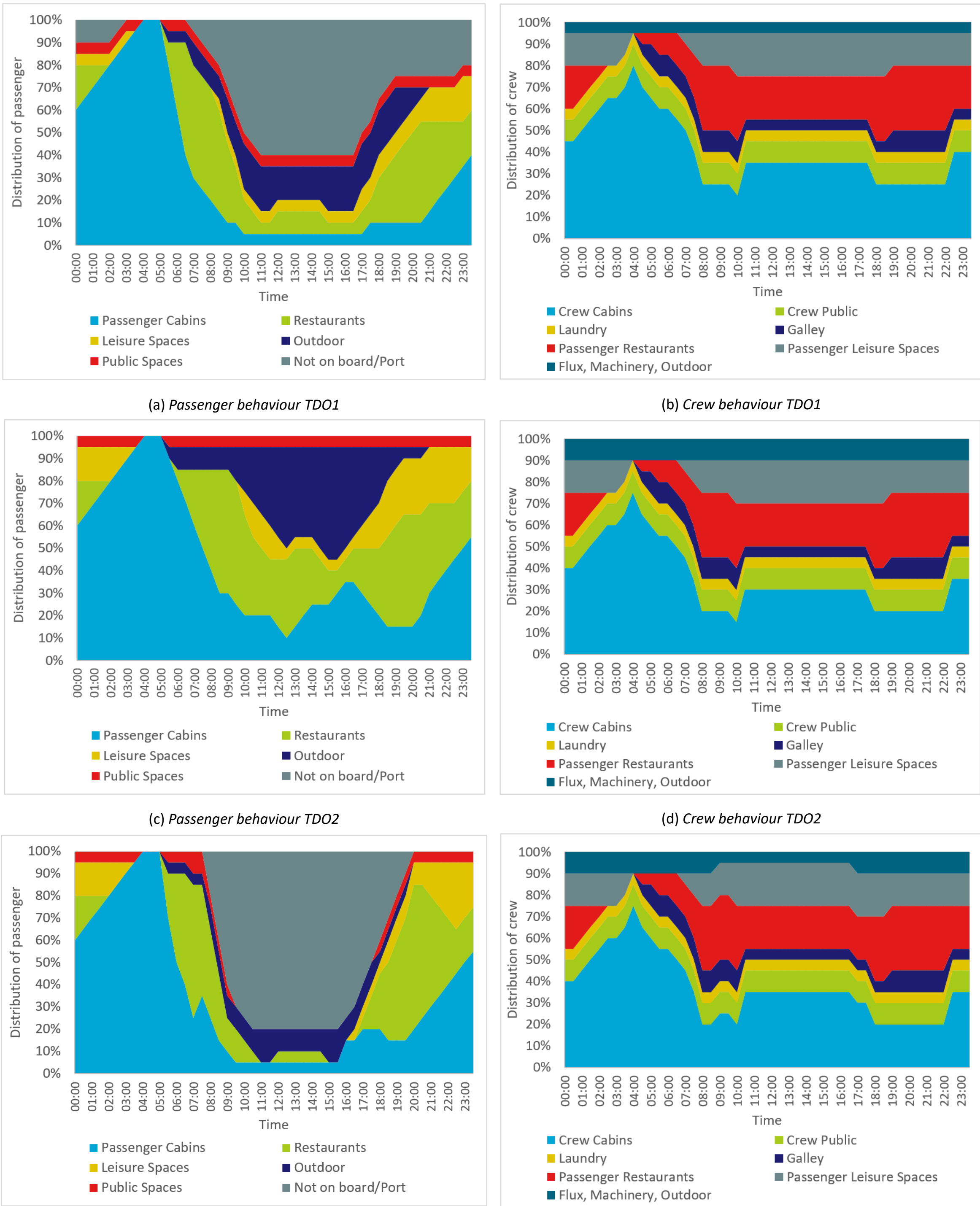


(c) *Amsterdam in the Netherlands in summer (referred to as medium condition)*

Figure B.6: Weather Profiles of selected cities, obtained by *EnergyPlus* database [32]

B.3 Passenger and crew behaviour

Definition of passenger and crew behaviour, as discussed in section 6.3.



(a) *Passenger behaviour TDO1*

(b) *Crew behaviour TDO1*

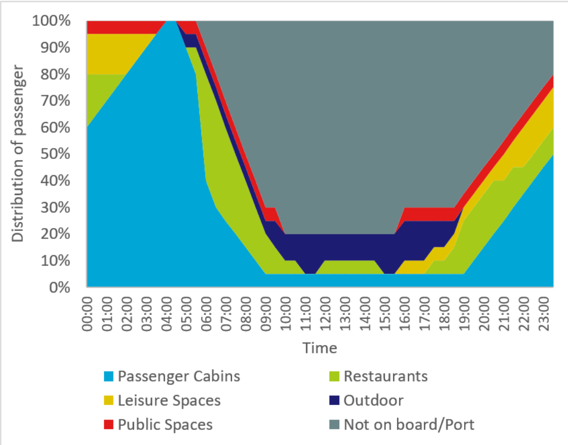
(c) *Passenger behaviour TDO2*

(d) *Crew behaviour TDO2*

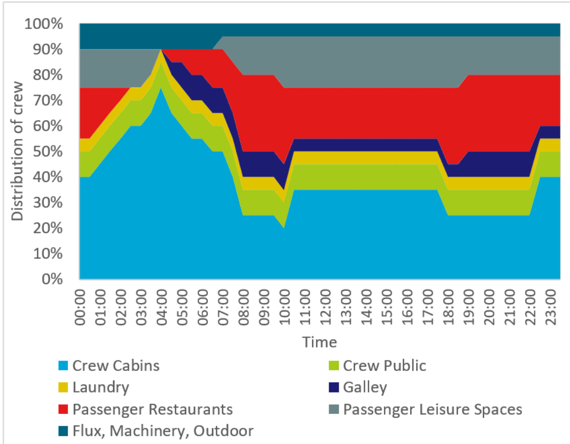
(e) *Passenger behaviour TDO3*

(f) *Crew behaviour TDO3*

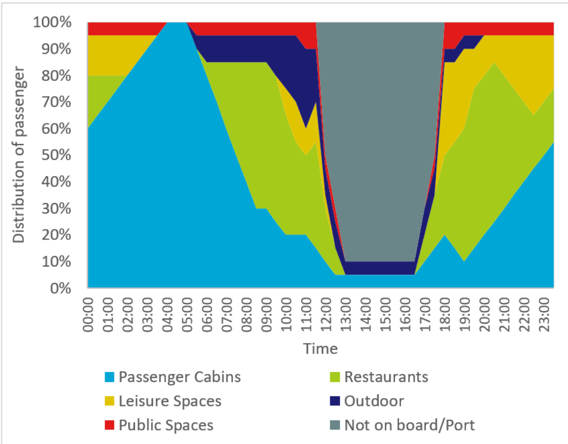
Figure B.7: Defined passenger and crew behaviour for TDOs, part 1



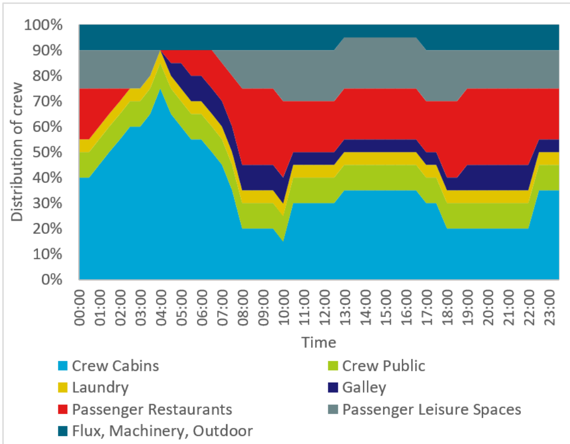
(a) *Passenger behaviour TDO4*



(b) *Crew behaviour TDO4*



(c) *Passenger behaviour TDO5*



(d) *Crew behaviour TDO5*

Figure B.8: Defined passenger and crew behaviour for TDOs, part 2

Appendix C

Resistance and Power Prediction

C.1 Holtrop & Mennen calculation

The resistance and power prediction for the propulsion system in section 7.1.1 based on the theory of Holtrop and Mennen [39]. The total resistance is calculated with the following equation.

$$R_T = R_F\,(1 + k_1) + R_{APP} + R_W + R_B + R_{TR} + R_A \qquad \text{(ref. 7.1)}$$

The total resistance consists of the frictional resistance R_F and the form factor $(1 + k_1)$, appendage resistance R_{APP}, wave resistance R_W, additional pressure resistance of bulbous bow R_B, additional pressure resistance of immersed transom stern R_{TR}, and model-ship correlation resistance R_A. The following formulas can be used:

$$R_F = \frac{1}{2}\,\rho_{SW}\,C_F\,S_{BH}\,v_s^2 \qquad \text{(C.1)}$$

$$R_{APP} = \frac{1}{2}\,\rho_{SW}\,C_F\,S_{APP}\,v_s^2\,(1 + k_2)_{eq} \qquad \text{(C.2)}$$

$$R_W = \rho_{SW}\,g\,\nabla\,C_1\,C_2\,C_5\,e^{m_1\,F_n^d + m_4\,\cos(\lambda\,F_n^{-2})} \qquad \text{(C.3)}$$

$$R_B = 0.11\,e^{-3P_B^{-2}}\,F_{ni}^2\,A_{BT}^{1.5}\,\rho\,g\,/\,(1 + F_{ni}^2) \qquad \text{(C.4)}$$

$$R_{TR} = \frac{1}{2}\,\rho_{SW}\,C_6\,A_T\,v_s^2 \qquad \text{(C.5)}$$

$$R_A = \frac{1}{2}\,\rho_{SW}\,C_A\,S_{BH}\,v_s^2 \qquad \text{(C.6)}$$

(C.7)

Vessel dimensions Additional basic dimensions of the vessel has to be defined in addition to the lengths, width and draft in section 4.1.1.

The length of the run can be obtained out of the following expression:

$$\frac{L_R}{L_{WL}} = \frac{1 - C_P + 0.06\,C_P\,lcb}{4\,C_P - 1} \qquad \text{(C.8)}$$

The form factor $(1 + k_2)$ is obtained by considering two Azimuth thrusters and 2 stabilizer fins and the corresponding factors together with the assumed wetted surface area in C.12.

$$(1+k_1) = 0.93 + 0.487118\, C_{14} \left(\frac{B}{L_{WL}}\right)^{1.06806} \left(\frac{T}{L_{WL}}\right)^{0.46106} \left(\frac{L_{WL}}{L_R}\right)^{0.121563} \left(\frac{L_{WL}^3}{\nabla}\right)^{0.36486} (1-C_P)^{-0.60247} \tag{C.9}$$

$$(1+k_2) = \frac{\sum S_{App,i}\,(1+k_2)_i}{\sum S_{App,i}} = 2.14 \tag{C.10}$$

The wetted surface area of the bare hull S_{BH} can be calculated as well as the area of appendages A_{App} with assumed areas for the azimuth thruster and stabilizer fins. A_M represents the immersed part of the transverse sectional area of transom at AP at zero speed.

$$S_{BH} = L_{WL}\,(2\,T + B)\sqrt{C_M}\left(0.4530 + 0.4425\, C_B - 0.2862\, C_M - 0.003467\frac{B}{T} + 0.3696\, C_{WP}\right) + 2.38\,\frac{A_{BT}}{C_B} \tag{C.11}$$

$$A_{App} = n_{POD}\, A_{POD} + n_{Fin}\, A_{Fin} = 2 \cdot 100m^2 + 2 \cdot 20m^2 = 240m^2 \tag{C.12}$$

$$A_{BT} = A_M\, C_{ABT} \tag{C.13}$$

$$A_M = B\,T\,C_M \tag{C.14}$$

$$h_B = 3.0m \qquad \textit{(assumed)} \tag{C.15}$$

The coefficients are:

$$C_1 = 2223105\, c_7^{3.78613} \left(\frac{T}{B}\right)^{1.07961} (90 - i_E)^{-1.37565} \tag{C.16}$$

$$C_2 = e^{-1.89\sqrt{C_3}} \tag{C.17}$$

$$C_3 = \frac{0.56\, A_{BT}^{1.5}}{B\,T\,\left(0.31\sqrt{A_{BT}} + T_F - h_B\right)} \tag{C.18}$$

$$C_4 = \frac{T}{L_{WL}} \tag{C.19}$$

$$C_5 = 1 - 0.8\, A_T\, \frac{1}{B\,T\,C_M} \tag{C.20}$$

$$C_6 = 0.2\,(1 - 0.2\, Fn_t) \tag{C.21}$$

$$C_7 = \frac{B}{L_{WL}} \qquad \text{when } 0.11 \le B/L_{WL} < 0.25 \tag{C.22}$$

$$C_{12} = 48.2\left(\frac{T}{L} - 0.02\right)^{2.078} + 0.479948 \tag{C.23}$$

$$C_{14} = 1 + 0.011\, C_{stern} \tag{C.24}$$

$$C_{15} = -1.69385 + \frac{\left(\frac{L}{\tau^{1/3}} - 8.0\right)}{2.36} \tag{C.25}$$

$$C_A = 0.006\,(L_{WL} + 100)^{-0.16} - 0.00205 + 0.003\sqrt{\frac{L_{WL}}{7.5}}\, C_B^4\, C_2\,(0.04 - C_4) \tag{C.26}$$

The form coefficients are:

$$C_{ABT} = 0.075 \tag{C.27}$$
$$C_B = 0.7 + 0.125\ \tan^{-1} \frac{23 - 100\,Fn}{4} \tag{C.28}$$
$$C_F = \frac{0.075}{\left(\log_{10} Rn - 2\right)^2} \tag{C.29}$$
$$C_M = 0.8 + 0.21\,C_B \tag{C.30}$$
$$C_{WP} = \frac{2}{3}\,C_B + \frac{1}{3} \tag{C.31}$$
$$C_P = \frac{\nabla}{L_{WL}\,A_M} \tag{C.32}$$
$$C_{Stern} = +10 \tag{C.33}$$
$$\lambda = 1.446\,C_P - 0.03\,\frac{L_{WL}}{N} \tag{C.34}$$

Froude number and additional parameters are:

$$Fn = \frac{v_s}{\sqrt{g\,L_{WL}}} \tag{C.35}$$
$$Fn_i = \frac{v_s}{\sqrt{g\,\left(T - h_b - 0.25\,\sqrt{A_{BT}}\right) + 0.15\,v_s^2}} \tag{C.36}$$
$$Fn_t = \frac{v_s}{\frac{2\,g\,A_T}{B + B\,C_{WP}}} \tag{C.37}$$
$$R_B = \frac{L_{WL}\,v_s}{\nu} \tag{C.38}$$

Constants used

$$\rho = 1025\frac{kg}{m^3} \tag{C.39}$$
$$g = 9.81 \tag{C.40}$$
$$\mu = 0.00108 \tag{C.41}$$

Propulsion chain efficiencies:

Table C.1: Parts of transmission efficiencies along the propulsion power line

Subsystem/ Component	Symbol	Efficiency
Generator	η_{Gen}	96.5%
Transformer	η_{Tr}	98.5%
Drive	η_{Dr}	98%
E-Motor	η_M	96.5%
Cable	η_{Cab}	99.5%

C.1.1 Thrust force bow thruster

In addition to section 7.1.2, the thrust force can be obtained under consideration of the wind force as stated in expression C.42 [14].

$$F_{Wind} = \frac{1}{2}\,\rho_{Air}\,v_{air}^2\,A_L\,C_{D,wind} \tag{C.42}$$

The lateral plane side area of the vessel A_L above waterline is simplified with the following estimation in C.43, obtained out of drawings. It can vary depending on the individual design of the deckhouse, but is assumed for the first design phase based on the length of the waterline and the height of the highest deck h_{maxD} above waterline and the form factor C_{LA} of 0.7.

$$A_L = L_{OA}\,h_{maxD}\,C_{LA} \tag{C.43}$$

The additional coefficients and parameter are listed in table C.2.

Table C.2: Coefficients and parameters for wind force

Coefficient/Parameter	Symbol	Value		Reference/Comment
Density air	ρ_{air}	1.2	kg/m^3	assumed for ambient air
Wind speed	v_{air}	17	m/s	for max. Bft. 7, <35kn , <17m/s
Transverse wind drag coeff.	$C_{D,wind}$	0.9		[12]

The turning moment is calculated by multiplying the wind force times half of the length L_{pp}. Thereby, the pivot point is located at the azimuth thrusters while manoeuvring, whereas the wind force is assumed to act at the middle of the ship. The latter depends normally on the design of the lateral plane side area of the cruise vessel above waterline and can slightly vary in the design process later on.
The counteracting force of the bow thrusters is assumed to be 8% of L_{pp} behind the forward perpendicular, as shown in figure C.1. The thrust force for the worst case weather condition can now be calculated in equation C.1.

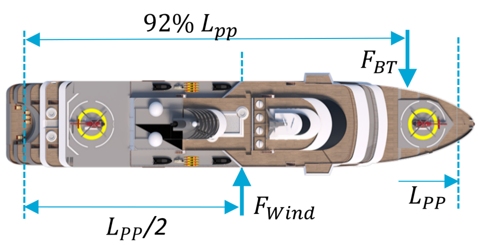


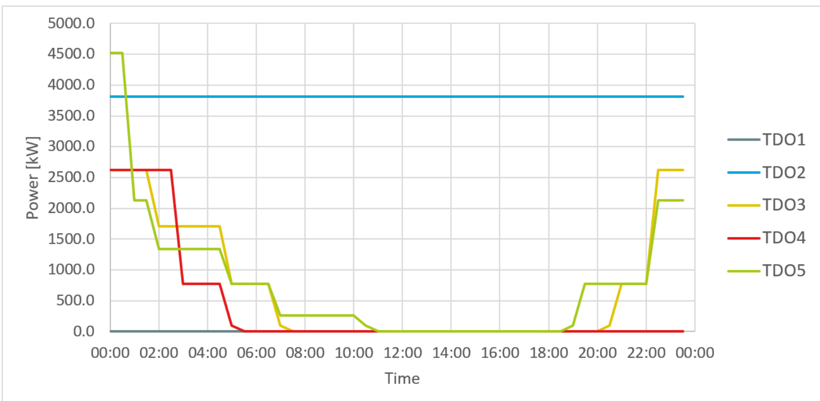
Figure C.1: Sketch of acting forces while manoeuvring

Appendix D

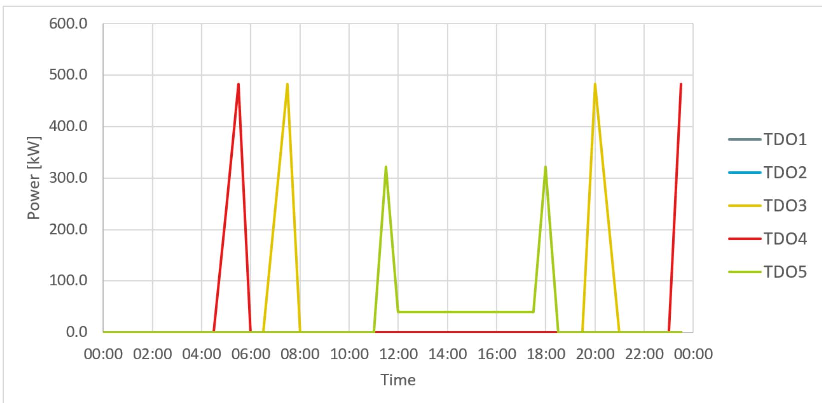
Power and energy demand of systems

The applied prediction models are described partly in more detail in the following sections next to additional graphs of obtained results in accordance with the discussion and analysis in chapter 7. Similarly, additional information is provided for the energy prediction in section D.4 in accordance with section 8.

D.1 Propulsion Systems

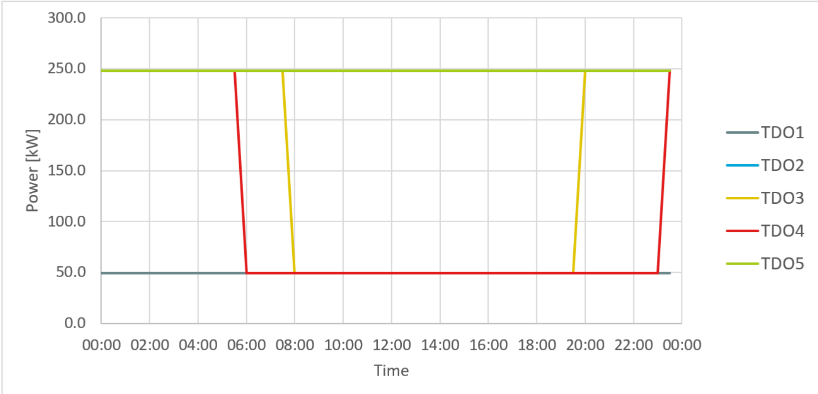


(a) *Main propulsion*



(b) *Bow thruster*

Figure D.1: Power demand of propulsion systems during pre-defined TDO1, TDO, TDO3, TDO4 and TDO5; *Part 1*



(a) *Propulsion support system*

Figure D.2: Power demand of propulsion systems during pre-defined TDO1, TDO, TDO3, TDO4 and TDO5; *Part 2*

D.2 Auxiliary Systems

D.2.1 Water supply and handling systems

In accordance with the discussion in section 7.2.3, the following prediction is made for the water supply and handling systems.
The cooling demand, obtained by the HVAC system (see Appendix D.3.1), is supplied with chilled water which has to be pumped through the cooling units. Due to the uncertain design ob the whole system in this design stage, the cooling demand is multiplied by a factor (see equation D.1) to consider the electric power demand of the water pumps. The factors are based on the reference vessels of the cooperating shipyard. In winter condition, the cooling demand is lower, but also the proportional factor as a consequence of the cooling demand only in lower decks. The water does not have to be pumped up that high.

$$P_{HVAC-cooling,i} = \begin{cases} 15\% \cdot Q_{c,i} & \text{Summer condition} \\ 10\% \cdot Q_{c,i} & \text{Winter condition} \end{cases} \tag{D.1}$$

The sea and fresh water cooler is responsible for an appropriate cooling of the machinery. The fresh water is within the inner cycle directly cooling the machinery systems, while extracted heat is transferred via the heat exchanger to the sea water cooling cycle. Even if the cooling demand and consequently the demand of cooling water with its flow rate can be related to the engine speed, the electrical demand of the pumps are simplified by applying a constant power demand over time. While sailing, a higher cooling demand is expected while it is lower in port due to the low speed of the diesel engines. In summer, a higher flow rate is expected due to warmer sea water to obtain similar cooling in the heat exchanger. The values are obtained by the reference vessel powered by a common diesel-electric configuration. Consequently, this has to be improved anyway after the implementation of the fuel cells (see comment in section 7.2.3 as well). The following equation can be stated for the cooling pumps.

$$P_{Engine-cooling,i} = P_{SW-cooling,i} + P_{FW-cooling,i} = \begin{cases} 100\text{kW} + 100\text{kW} & \text{Sailing in summer} \\ 60\text{kW} + 85\text{kW} & \text{Sailing in winter} \\ 50\text{kW} + 50\text{kW} & \text{Moored in port} \end{cases} \quad \text{(D.2)}$$

The potable water has to be generated out sea water. Nowadays this is done by reverse osmosis, where the sea water is treated and filtered under pressure by specific membranes. For the electrical demand of the reverse osmosis fresh water plant, the factor of 3.5 kW per produced cubic metre of fresh water [64] can be used. The demand is obtained by usual values for person on board within the shipyard as well as in the literature [93]. Following that, 200L per crew member and 300L per passenger can be expected per day. As shown in figure D.3, usually a higher demand can be expected in the morning and evening due to a more extensive usage of the showers by the passengers, while the remaining part for passengers and crew is distributed equally over the day. Lastly, an additional factor is implemented to consider the fresh water production only while sailing. Usually, the water is not generated in harbour, which results in a power demand $P_{PW-generation}$ reduced to 20% in port and while sailing increased to 200%. As a results, it can be stated:

$$P_{PW-generation,i} = \begin{cases} 3.5\text{kW/m}^3 \cdot P_{FW} \cdot 200\% & \text{Sailing} \\ 3.5\text{kW/m}^3 \cdot P_{FW} \cdot 20\% & \text{Moored in port} \end{cases} \quad \text{(D.3)}$$

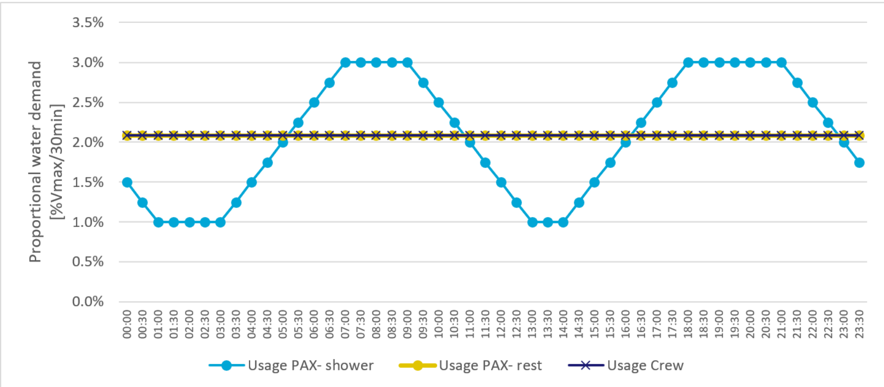


Figure D.3: Proportional water demand of maximum required water per day within time step of 30 min.

The circulation pumps for distributing the potable water on boards are considered with a constant power demand $P_{PW-pumps}$ of 40kW. No variation is considered, because the water has to be circulated based on regulations and to avoid any legionella occurrence [47]. Similarly, the waste water $P_{WasteWater}$ is considered with a constant load of 40kW as well. Even if the sewage is also collected by using the gravity, smaller pumps are at different locations to transport the whole contaminated water and constituents. Additional laundry and transfer pumps are considered in the margin P_{Margin} constantly at 20kW.
The total electrical power demand of the water systems can now be calculated for every time step as stated in equation 7.18.

D.3 Hotel Systems

D.3.1 HVAC system and chilled water plant

The prediction model of the HVAC system and related chilled water plant is described in this section in more detail, following the general approach and steps in section 7.3.1. The prediction is made for every time step (interval of 30 minutes) *i* and every area *j* separately.

Heat gain

The heat gain in a certain area *j* per time step *i* consist of the heat transmission via the walls and windows $\dot{Q}_{Transmission}$, the radiated heat of the sun $\dot{Q}_{Sun}$, the sensible heat $\dot{Q}_{Human}$ of all persons in the area and the heat of the equipment and lighting $\dot{Q}_{Lights}$ and is described in equation D.4.

$$\dot{Q}_{sens,i,j} = \dot{Q}_{Transmission,i,j} + \dot{Q}_{HumanS,i,j} + \dot{Q}_{Sun,i,j} + \dot{Q}_{Lights,i,j} \tag{D.4}$$

Transmission heat load The transmitted heat can be calculated by the obtained areas for the different areas or cabin considering the different inner or outer wall and window areas. Based on ISO norm 7547 [48], the transmission factor K_s can be defined as shown in the table D.1. The defined temperature differences are shown as well, while the difference for outer walls is depending on the individual environmental conditions in the certain time step.

Table D.1: Heat transmission factor and temperature differences for walls, windows and floor [48]

Area	Transmission factor [W/(m^2·K)]	Δ Temperature [K]
Ceiling	0.6	5
Outer walls	0.6	$T_{out} - T_{in}$
Floor	0.6	5
Inner walls	2.5	2
Windows	3.5	$T_{out} - T_{in}$

Now the transmitted heat via the boundary surfaces s (see table D.1) can be calculated per area *j* and time step i.

$$\dot{Q}_{Transmission,i,j} = \sum_{s} A_s\, K_s\, \Delta T_{i,j,s} \tag{D.5}$$

Human heat load The gained heat of the passenger and crew members in the specific area is calculated by an assumed sensible heat of 70W and latent heat of 50W per person[48]. The number of person in the area results from the defined behaviour (see section 6.3 and distribution in Appendix B.3). An occupied passenger cabin has two person.

$$\dot{Q}_{HumanS,i,j} = (n_{Pass,i,j} + n_{Crew,i,j})\ 70\text{W/Pers} \tag{D.6}$$

$$\dot{Q}_{HumanL,i,j} = (n_{Pass,i,j} + n_{Crew,i,j})\ 50\text{W/Pers} \tag{D.7}$$

Solar heat gain The influence of the sun has to be considered in addition to the transmission heat due to the additional heat radiation via walls and windows. It can be calculated by equation D.8. The solar radiation consists of the lighted surface (assumed to be constant of 30% of outer surface considering shadowing, see sketch in D.4) of the outer walls $A_{outer,j,s}$ and windows $A_{window,j,s}$ for the specific area j during the day (binary factor $c_{sun,i}$ for sun/no sun). Given in regulations [48], the total heat transfer coefficient k can be defined as well as the excess temperature T_r caused by solar radiation for vertical light surfaces. The heat gain from glass surfaces G_s is defined for clear glass surfaces with interior shading.

$$\begin{aligned}\dot{Q}_{Sun,i,j} &= p_{lighted}\, c_{sun,i} \left(\sum_s k\, \Delta T_r\, A_{outer,j,s} + \sum_s G_s\, A_{window,j,s} \right) \\ &= 30\%\, c_{sun,i} \left(\sum_s 0.6\mathrm{W/m^2K} \cdot 12\mathrm{K} \cdot A_{outer,j,s} + \sum_s 240\mathrm{W/m^2} \cdot A_{window,j,s} \right) \end{aligned} \tag{D.8}$$

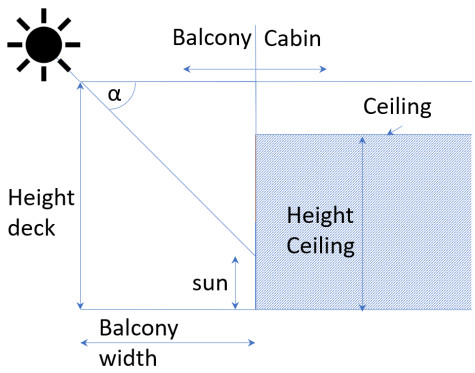


Figure D.4: Solar radiation on lighted wall and window to define proportion of lighted surface $p_{lighted}$

Heat load equipment and lighting Lastly, also the equipment and lights are producing heat. Assuming LED lighting, the gained heat is defined per square metres in the ISO standard (values for LED lighting assumed to be equal to Fluorescent) and is set for the different areas as shown in table D.2. Similarly for equipment, the values are assumed per square metres under consultation of different experienced engineers and other research studies [64], as the ISO regulation does not define gained heat parameters for the equipment, because it is usually low for other commercial vessels. In addition, for the occupied passenger cabins, the heat gain is assumed to be 8kW per square metres for lighting and 200kW for the equipment (60kW in stand-by mode for unoccupied cabins). Together, the heat load is defined per area and time step:

$$\begin{aligned}\dot{Q}_{Lights,i,j} &= \dot{Q}_{Light,i,j} + \dot{Q}_{Equip,i,j} \\ &= q_{Light,i,j} \cdot A_j + \dot{Q}_{Equip,i,j}\end{aligned} \tag{D.9}$$

Table D.2: Design parameters of HVAC system for the heat gain of equipment and lights as well as the required min. air changes per hour and the fresh air (FA) proportion, based on typical owner specifications and international standards [1, 2, 48, 64]

Area	Heat lights [W/m^2]	Heat equip. [W/m^2]	Air changes -/h	FA proportion [%]	Inside Temp. [°C]
Corridors	10	0.5	6	50%	22
Public Spaces	10	1	12	40%	22
Restaurants (indoor)	10	3	10	50%	22
Disco, Gym, Wellness	20	2	12	100%	22
Hospital	20	2	10	100%	22
Crew cabins	8	3	6	30%	22
Crew public area, offices, mess	10	2	10	40%	22
Laundry	20	3	20	30%	22
Galley, Pantries	20	4	25	100%	22
Garbage rooms, Stores	10	3	60	30%	-5
Tech. Rooms, Workshops, ECR, AC Rooms	10	4	20	100%	25
Main Engine Room	10	80	15	100%	*Summer:* 27 *Winter:* 22
Wheelhouse	10	4	20	30%	22

Number of air changes

After calculating the heat load in the certain time step, the minimum number of air changes can be predicted under consideration of different requirements. Consequently, the supply air volume can be predicted.

$$N_{AC,i,j} = \min\left\{N_{Heat}, N_{Owner}, N_{Spec}\right\} \tag{D.10}$$

$$\rightarrow \dot{V}_{SupplyAir,i,j} = N_{AC,i,j} \cdot V_j \tag{D.11}$$

Heat load First of all, the previously calculated heat gain has to be balanced by the supplied air. The cooling air should not has a temperature difference of more than 10°C, while the delta should reach a maximum of 8°C while heating [48].

$$N_{Heat,i,j} = \frac{\dot{V}_{SupplyAir-Heat,i,j}}{V_j} = \frac{\dot{Q}_{sens,i,j}}{c_{p,a}\,\Delta T\,\rho_{Air}\,V_j} \tag{D.12}$$

Owner specification Usually the owner or client is defining a minimum of number of air changes N_{Owner}, which exceeds the required value in most of the cases. An optimization is out of the scope of the current study even if the energy demand could be reduced significantly. Typically, for expedition cruise ships a number of air changes is set to be 8 times per hour for occupied passenger cabins (zero is assumed for unoccupied cabins) and for the remaining areas as specified in table D.2. This based on a typical design as discussed with experienced engineers and suppliers.

Regulations In addition another minimum N_{Spec} of 6 air changes per hour is set by the Maritime Labour Convention (MLC) to ensure a safe working environment as well as in the American Bureau of Shipping (ABS) guide for passenger comfort [6].

Fresh air ratio

The proportion of fresh air (FA) within the supplied air can now be predicted. The maximum value has to be chosen to fulfil the maximum CO_2-level, the ISO standard and the owner specification, even if a lower FA ratio can reduce the energy demand by reusing the air volume due to recirculation.

$$F_{FA,i,j} = \max\left\{F_{CO2,i,j}, F_{ISO,i,j}, F_{Owner,j}\right\} \tag{D.13}$$

CO_2-level The CO_2-level can be only controlled by using FA because the CO_2 content is rising within the room due to the person. The maximum CO_2-level in the room is 0.1% and the assumed proportion for the FA is equal to 0.035% [93]. Together with the new supplied air volume $\dot{V}_{SupplyAir,i,j}$ out of equation D.11, the minimum required FA proportion can be calculated.

$$F_{CO2,i,j} = \frac{\dot{V}_{FA-CO2,i,j}}{\dot{V}_{SupplyAir,i,j}} = \frac{\dot{V}_{CO2,i,j}}{\left(y_{CO2,room} - y_{CO2,FA}\right)\dot{V}_{SupplyAir,i,j}} \tag{D.14}$$

ISO minimum The ISO regulations [48] providing another minimum FA proportion of 0.008m^3/(s·Pers.), which has to be fulfilled as well in all conditions.

$$F_{ISO,i,j} = \frac{0.008\left(n_{Pass,i,j} + n_{Crew,i,j}\right)}{\dot{V}_{SupplyAir,i,j}} \tag{D.15}$$

Owner specification Lastly and usually the highest value is given by the owner specification (here $F_{Owner,j}$). For expedition cruise ships it can be set to 100% FA for all passenger cabins. The proportion for the remaining areas is given in the table D.2.

Intermediate condition

In addition to the figures 7.9 and 7.8 in section 7.3.1, the calculation and made assumptions can be explained in more detail to obtain the electrical power demand within the cooling, heating process as well as the humidification and ventilation for the cabins and remaining areas. The prediction model is based on the procedures of Woud and Stapersma [93] by using the Mollier diagram for identifying the thermodynamic properties (like temperature $T_{i,j}$, enthalpy $h_{i,j}$, relative $\phi_{i,j}$ and absolute humidity $x_{i,j}$) of a certain situation. Thus, if to parameters are known, the other two properties can be read within the diagram.

The procedure can be briefly described following an automatic loop for every time step to obtain the dynamic power demand as basis for the energy demand for a whole day. Based on the defined inside condition, the "blow-in"-condition can be calculated under consideration of the maximum allowed temperature difference (10°C while cooling and 8°C while heating) to balance the gained heat (or loss) within the room with the new obtained air volume flow (see equation D.11).

$$\Delta T_{supply,i,j} = \frac{\dot{Q}_{HeatRoom,i,j}}{\dot{m}_{supply,i,j}\, c_{p,a}} \tag{D.16}$$

Calculating backwards, the added heat of the fan can be subtracted.

$$\Delta T_{Fan,i,j} = \frac{\dot{P}_{Fan,i,j}}{\dot{m}_{supply,i,j}\, c_{p,a}} \tag{D.17}$$

In summer, no humidification is required, while in winter, no sensible heat is added in the humidifier only water vapour. However, the absolute humidity difference can be obtained. In addition, the enthalpy difference can be calculated with the evaporation of water r_W and the specific heat at constant pressure of water vapour $c_{p,v}$, at an assumed temperature of 100°C due to the vapour, as shown in the equation D.18.

$$\Delta h_{Hum,i,j} = \Delta x_{Hum,i,j} \left(r_W + c_{p,v} \, T_{Vapour} \right) \tag{D.18}$$

Further backwards, the cooler is mostly used only in summer condition. Thus, in winter condition, the required properties can be obtained out of the previous steps for the condition after the heater. Similarly in summer condition, the required temperature is known for the condition after the cooler. In addition, the relative humidity can be assumed to be at 90% after the cooler and simultaneous condensation to define the other properties [93].
Looking from the other direction, the ambient air condition is known. Considering the recirculated air (if applicable for certain area j), the mixed air properties are obtainable (see fresh air ratio). For the passenger cabins (with local FCUs), the required heat in winter can now be calculated (see below) as well as the cooling demand considering the enthalpy difference.

The prediction model is similar for the central AHUs. However, the cooler is located before the heater in order to provide the possibility of reheating the air in summer. Often the air has to be cooled and dehumidified which is below the acceptable supply temperature. Thus the heater can add some heat afterwards by using the hot water from the boiler.
As whon in figure 7.9, a heat recovery unit can be also included within the AHU. Consequently the latent and sensible heat can be transmitted from the recirculated air to the fresh air with an efficiency of 75%.

$$T_{Rec} = T_{FA} + (T_{Recirc} - T_{FA}) \cdot \eta_{Rec} \tag{D.19}$$

$$x_{Rec} = x_{FA} + (x_{Recirc} - x_{FA}) \cdot \eta_{Rec} \tag{D.20}$$

With the calculated intermediate air properties, the required electrical heat for heating, cooling, ventilation and humidification can be calculated as described below.

Fan power The fan ensures a sufficient air volume flow and is powered by electrical energy. The actual power per time step i is calculated based on the calculated supply volume of air and an assumed pressure head of 0.015bar for the cabins and remaining areas j (areas as listed in table D.2), based on reference data from suppliers. An fan efficiency of 70% is added [93].

$$P_{Fan,i} = \sum_{Cabins} \frac{\dot{V}_{SupplyAir,i,cabin} \, p_{Fan}}{\eta_{Fan}} + \sum_{j} \frac{\dot{V}_{SupplyAir,i,j} \, p_{Fan}}{\eta_{Fan}} \tag{D.21}$$

Cooling power For the cabins and all areas, the cooling demand can be calculated based on the actual mass flow (see volume flow times density) and the enthalpy difference between the intermediate situation before and after the cooler. The local FCUs and AHUs in the public and crew areas are supplied by chiller water from the chilled water plant. Without going into the whole cooling cycle, the electrical demand of the connected valves, compressors and pumps is considered with the applied coefficient of performance (COP). The COP is defined by the received cooling power divided by the net used power within the cooling cycle [36, 93]. Consequently, the cooling demand can be divided by the COP, as shown in the equation D.22. Even if the heat transfer efficiency can vary and be even more efficient by changing from laminar flow to turbulent flow [52] or the sea water temperature would further influence the COP [36], a constant COP over time is implemented of 5 as proposed by other experienced engineers.

$$
\begin{aligned}
P_{Cooler,i,j} &= \frac{\dot{Q}_{TotalCooling,i}}{COP_{Chiller}} = \left(\dot{Q}_{Cooling,i,cabin} + \dot{Q}_{Cooling,i,j}\right) \cdot \frac{1}{COP_{Chiller}} \\
&= \frac{\left(\sum_{Cabins} \dot{V}_{SupplyAir,i,cabin}\, \rho_{Air}\, \Delta h_{cooler,i,cabin} + \sum_j \dot{V}_{SupplyAir,i,j}\, \rho_{Air}\, \Delta h_{cooler,i,j}\right)}{COP_{Chiller}}
\end{aligned} \tag{D.22}
$$

Heating power The cabins are heated individually with the local FCU, which includes an electrical heater. The required sensible heat is directly divided by the heater efficiency of 80% as used by experienced engineers in the early design stage. Similarly for the remaining areas j, the heat can be calculated with the mass flow and enthalpy difference before and after the heater. However, the heat is supplied by heated water as shown in the sketch in figure 7.9. Consequently, an efficiency of 80% of the heat exchanger in the AHU is considered next to an additional COP of 4 for the pumps towards the boiler. In this case, the actual heat is coming more efficiently form the exhaust heat of the engine. All in all, the required electrical power demand of the heaters can be summarized within equation D.23.

$$
\begin{aligned}
P_{Heater,i} &= \sum_{Cabins} \frac{\dot{Q}_{Heat,i,cabin}}{\eta_{Heater}} + \sum_j \frac{\dot{Q}_{Heat,i,j}}{\eta_{HE}\, COP_{Boiler}} \\
&= \sum_{Cabins} \frac{\dot{V}_{SupplyAir,i,cabin}\, \rho_{Air}\, \Delta h_{Heat,i,cabin}}{\eta_{Heater}} + \sum_j \frac{\dot{V}_{SupplyAir,i,j}\, \rho_{Air}\, \Delta h_{Heat,i,j}}{\eta_{HE}\, COP_{Boiler}}
\end{aligned} \tag{D.23}
$$

Power humidifier Not a main contributor, but the small electrical demand of the pumps within the humidification unit is considered as follows. Steam humidifiers are still commonly used, while more efficient ultrasonic humidifiers are mostly still too expensive. The required water steam is defined by the volume flow. Together with the lift of pump (assumed to be 80bar based on supplier data) and an efficiency of around 80%, the electrical power can be obtained.

$$
P_{Hum,i} = \left(\sum_{Cabins} \dot{V}_{Hum,i,cabin} + \sum_j \dot{V}_{Hum,i,j}\right) \frac{\Delta p_h}{\eta_h} \tag{D.24}
$$

D.3.2 Galley and Laundry

In accordance with section 7.3.2, the utilization factor for the galley and laundry is defined as shown in figure D.5.

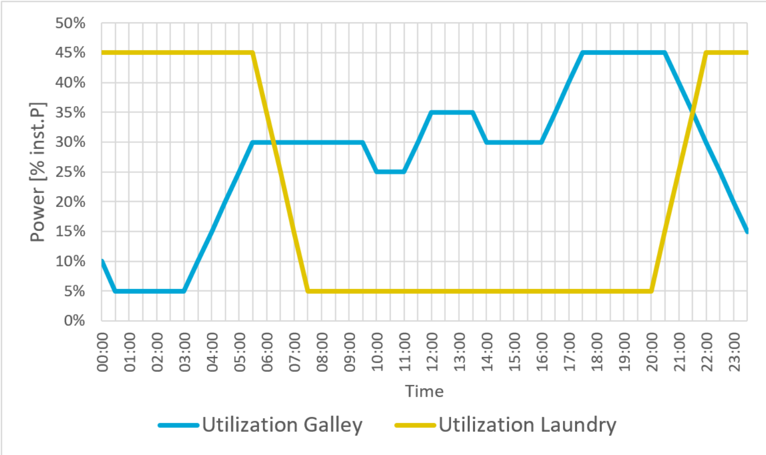


Figure D.5: Defined utilization factor for galley and laundry per time step of 30 min. over one day

For the validation, the study of Styles et al. [78] is used. The demand for the laundry is predicted with the given factor of 4 kg laundry per occupied room per day requiring 3 kWh per kg to process. The demand for the galley is defined by 3kWh per meal, assuming 3 meals per day per person.

As a result, the power demand of galley and laundry can be displayed exemplary for the TDO3 in figure D.6.

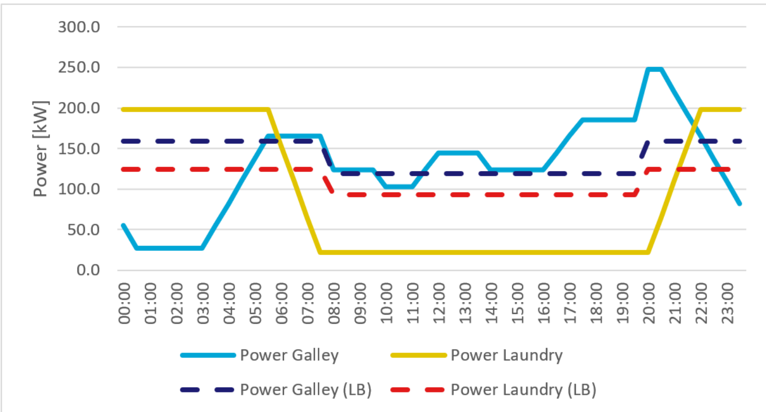


Figure D.6: Power demand of laundry and galley exemplary for TDO3 (moored in port 8:00-20:00), prediction model (solid line) compared to constant values in load balance (LB)

D.3.3 Lighting

Normal passenger cabins are illuminated by normal lighting or atmosphere lighting with less lights per cabin, see table D.3, depending on the defined usage over the day in figure D.7. The remaining areas are either lighted or not lighted. The corresponding parameters in table D.4 are based on common owner specifications and ABS guidelines for passenger and crew comfort [1, 2]. The required lumen can be transferred into Watts per square meter by using the constant of 60 Lumen/Watt [61].

Table D.3: Light intensity $L_{Int,j}$ of cabins considering full lighting and comfort or atmosphere lighting [64]

Area		Light Intensity W/cabin
PAX cabins	*-normal*	105
	-comfort	50

Applied light intensity for defined areas j, based on guidelines of ABS [1, 2].

Table D.4: Light intensity $L_{Int,j}$ of areas following ABS guidelines for passenger and crew comfort [1, 2]

Area	Light Intensity [lm/m^2]	W/m^2
Corridors	200	3.3
Public Spaces	200	3.3
Restaurants (indoor)	300	5
Disco, Gym, Wellness	300	5
Hospital	500	8.3
Outside	30	0.5
Crew cabins	150	2.5
Crew public area, offices, mess	300	5
Laundry	300	5
Galley, Pantries	500	8.3
Garbage rooms, Stores	200	3.3
Technical Rooms, Workshops, ECR, AC rooms	200	3.3
Mooring Decks	200	3.3
Main Engine Room	300	5
Wheelhouse	300	5

Used lighting in occupied passenger cabins. In the night, less lights are used, while a major part of occupied cabins are only lighted with reduced comfort lighting.

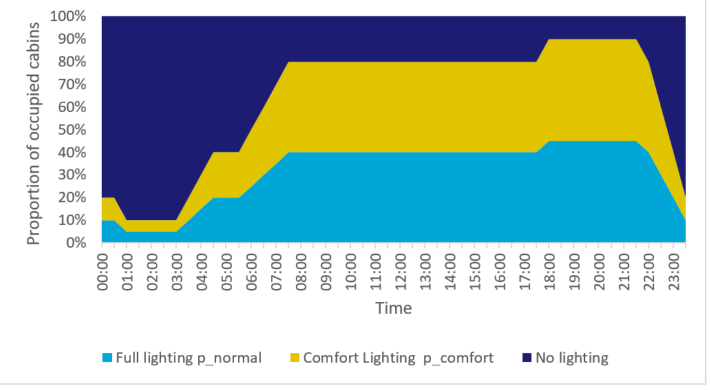


Figure D.7: Proportion of used lights in occupied passenger cabins

Exemplary result for TDO2 in ISO summer condition.

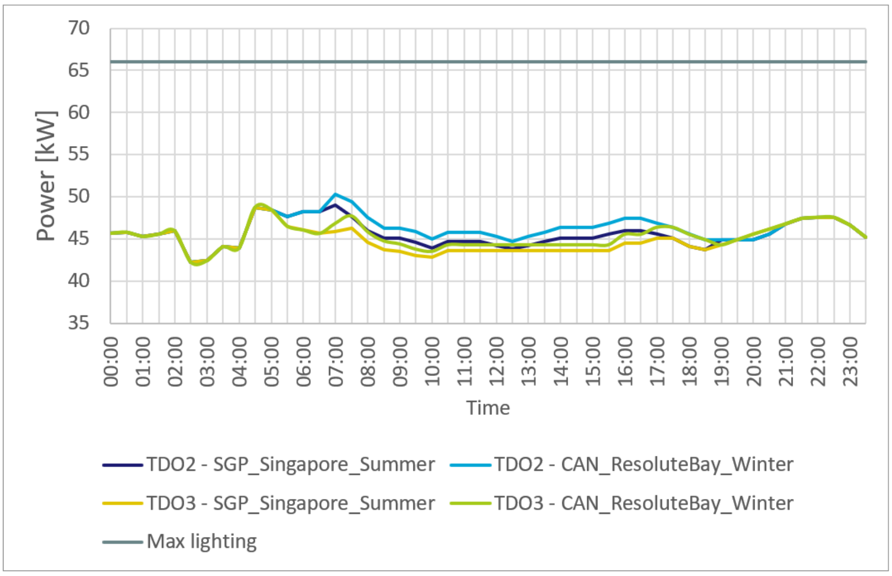


Figure D.8: Power of lighting system over time for sailing day (TDO2) in ISO summer condition, actual demand compared to max. lighting and lighting demand in load balance

D.4 Energy demand

In addition to section 8, the energy demand for the TDO out of the made predictions in chapter 7 can be compared to the commonly used load balance. The energy demand for the defined TDOs is here predicted based on the number of hours in port $h_{Port,TDO}$ and the corresponding power demand for sailing and port condition, as shown in equation D.25.

$$E_{LB} = h_{Port,TDO} \cdot P_{total,Port} + \left(24 - h_{Port,TDO}\right) \cdot P_{total,Sail-Season} \quad \text{(D.25)}$$

With: $h_{Port,TDO1} = 24$h; $h_{Port,TDO2} = 0$h; $h_{Port,TDO3} = 12$h; $h_{Port,TDO4} = 17.5$h and $h_{Port,TDO5} = 6$h

Appendix E

Conference paper

The following paper could be published and presented at the High-Performance Marine Vehicles (HIPER) symposium in Cortona/Italy on the 12-14 October 2020.

Title:

Improved prediction of the energy demand of fuel cell driven expedition cruise ships

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Improved prediction of the energy demand of fuel cell driven expedition cruise ships

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Abstract

Fuel cell systems require a better early-stage prediction of the energy consumption of a ship because they are more expensive, more voluminous and less able to deal with rapid load changes than conventional diesel-powered systems. This paper discusses a model for such an improved prediction of the total energy demand of an expedition cruise vessel. The focus is on identifying the peak loads and load changes under consideration of the passenger behaviour, environmental and operational conditions. The used bottom-up approach builds up a parametric model for the early design stages with limited required input data by using typical operational conditions for this type of vessel.
The paper concludes that the method provides more insights into the dynamic power and substantially lower predicted energy use.

Keywords: Dynamic energy modelling; Electric power demand; Load behavior; Fuel cells; Dynamic operational profile

1. Introduction

The shipping industry contributes significantly to the global greenhouse gas emissions due to the use of cheap fossil fuels. As a response to the Paris Agreement on climate change, the IMO Marine Environment Protection Committee (MEPC) defined the strategy on the reduction of emitted greenhouse gases and emission of carbon dioxide from ships in April 2018. Following this, the carbon dioxide (CO_2) emission per transport work should be reduced across international shipping by at least 40% on average by 2030 with further efforts towards 70% in 2050 in comparison to 2008. The greenhouse gas emissions should peak soon, together with a reduction by at least 50% in 2050 compared to 2018, as stated in the resolution of the MEPC, *IMO (2018)*.

Meanwhile, the cruise ship industry is forced to reduce the carbon footprint to be able to access remote areas with higher restrictions and as part of their marketing strategy towards more sustainability. The majority of ships under construction, including smaller expedition vessels, still use the combination of conventional fuels and scrubbers or SCR systems in order to eliminate harmful exhaust gases. Alternatively, the additional use of batteries can let the engines constantly run at their optimal condition by providing additional electric power in peak loads, as applied in the latest Hurtigruten expedition cruise vessels, *Silk Bidco AS (2017)*.

Research projects by universities, shipyards and other stakeholders address the use of fuel cells with the purpose of eliminating all greenhouse gases, while reducing the high development costs (*Van Biert et al., 2016)*. The storage of pure liquid hydrogen, at a temperature of -253°C is an important challenge to overcome. Other fuels have to be reformed or pressurized. In general, the volumetric and gravimetric energy densities are lower than those of conventional fuels, which results in larger tanks on board when keeping the same operating range and speed. Next to the physical implementation, fuel cells have additional operational limiting factors, which have to be matched with the power demand. Compared to conventional combustion engines, longer start-up times can be expected as well as a lower dynamic response ability. This conflicts with the dynamic power demand of cruise ships in various operational condition (*Baldi, 2018)*. Furthermore, fuel cell systems and the associated fuel storage are significantly more expensive than conventional diesel-based solutions. Therefore, a detailed analysis of the ship's energy use is required, to keep the size and cost of the fuel cell system as low as possible and to prevent undesirable mismatches between the dynamics of energy supply and demand.

Typically, in the conceptual design phase at a shipyard the energy demand is estimated for all electric power consumers with the load balance approach. All systems are designed for the maximum operational power demand. The actual power demand is calculated based on the absorbed power from the net and additional predefined factors for several different operational conditions. The 'number in service' describes the number of running components in the defined operational condition. In addition, the load factor is defined as relative load of the maximum electric power of the component to be absorbed in the actual situation. The third factor, the simultaneity factor, varies between 0 and 1 as well, and describes the mean operational time of the component. Thus, a factor lower than one considers not continuously operating consumers. The last two factors are often combined as utilization factor. The products results in the actual absorbed power per component, which can be summed up to obtain the total power for the given operational condition, as shown in the simplified load balance sheet in table I, *Klein Woud and Stapersma (2015)*.

In general, specific conditions like harbor mode and sailing mode at maximum and design speed are predicted, but without any dynamically changing situations. This method provides a relatively crude overview of the power and energy demand of a ship and lacks details about their dynamics. For the early design stage of classic diesel-powered ships, this is acceptable but as discussed before, it is not for a fuel cell-based solution, especially in hybrid configurations.

Table I: Simplified format of load balance sheet

Consumer name	Absorbed electric power	In port				At Sea				…
	[kW]	Number in service	Load factor	Sim. factor	Average absorbed power	Number in service	Load factor	Sim. factor	Average absorbed power	…
Component 1										…
…										…
Total	∑				∑				∑	

Previous studies distinguish between the different operational modes and the consequences for the propulsion load while keeping the energy demand of the hotel systems constant, e.g. (*Simonsen, 2018)*. For hotel systems for cruise ships, usually part of auxiliary systems, this approach is not defendable due to the high contribution to the total power demand. The focus is mostly on improving the energy efficiency by assessing sea monitoring data in a top-down approach in order to lower the fuel consumption (*Howitt, 2010)*. Even if *Simonsen et al. (2018)* state that the "bottom-up" approach is more complex, such a systematic approach is necessary to study the dynamic energy behavior of every system. Thus, the operational behavior has to be considered more detailed already in the predictions within the first design phase (*Guangrong, 2017)*.

As a consequence, the required power and energy demand of the different systems on board must be further examined under varying operational conditions over time. Considering the starting and transient load response time, the understanding of the load changes is just as important as the total power demand at a certain condition, as normally investigated statically in the load balance approach.

This paper presents a detailed breakdown of the different electrical consumers and subsystems, grouped in propulsion, auxiliary systems and hotel systems. On the basis of predefined typical days of operations (TDO), the operational conditions and passenger behavior are described. The impact of the different environmental conditions is assessed by applying weather profiles for hot, cold and medium conditions. The resulting power prediction for every system focuses on the individual load behavior. The combined energy demand of the typical operational days finally leads to the total energy demand of the entire operational profile. Driving factors of the actual load and additional peak loads can be assessed. The results of the power and energy analysis are finally related to the fuel cell characteristics by identifying more favorable systems to be powered by a reliable fuel cell system.

2. Dynamic Prediction Model

First of all, the varying operational conditions have to be defined. Based on these influencing factors, the dynamic power demand is predicted for the different systems, as identified and grouped in the system breakdown. The varying load is the basis for the following energy prediction of the expedition cruise vessel.

2.1. Operational Conditions

Before predicting the power demand, the operational profile, passenger behavior and environmental conditions over the day have to be defined in the first step. They are also referred to as the three main influencing factors of the load behavior. Although users of the method can define their own settings for these aspects, thus making it suitable for their specific application, the cases as described below are used in a case study to demonstrate the way the approach works.

Cruise ships usually have a very diverse operational profile including a long time spent in part load condition. In contrast to cargo vessels, they do not follow a repetitive daily or weekly schedule. Sailing the whole day might be followed by a harbor day in order to offer land excursions. Alternatively, the ships might also travel at low speeds in scenic areas.
In order to define the operational profile, an activity-based approach is applied to obtain typical speed profiles of expedition cruise vessels. The voyage timeline of several reference vessels could be analyzed, where the actual position and corresponding speed is logged over time by using the Automatic Identification System (AIS). In order to model now the power demand for varying conditions, the obtained speed profile is transferred into five typical days of operations (TDO), similar to the used simplification method in the systematic procedure by *Fazlollahi at al. (2014).* It considers maneuvering, being moored in a harbor or at anchor and sailing at low, medium, design and high speed, as defined in table II. The energy demand over a week or the whole year can be estimated in a later step by adding up different days similar to the planned schedule or typical speed profile as obtained by the available AIS data as shown in the table as well.
The first defined typical day represents a port day. In the second day the ship would constantly sail at design speed. The remaining three days describe the mixed operational conditions, considering the varying speed profile and a port call during the day.

Table II: Proportion of operations in certain speed ranges as obtained out of AIS data and defined five typical days of operation (TDO)

Speed Range	Defined range (% max speed)	Typical profile (based on AIS)	TDO1	TDO2	TDO3	TDO4	TDO5
Port/Anchor & Maneuvering	<1kn	42%	24h	0h	12h	17.5h	0h
Low Speed	1kn-40%	8%	0h	0h	2h	1.5h	12.5h
Medium Speed	40-70%	27%	0h	0h	6.5h	2h	10.5h
Design Speed	70-85%	25%	0h	24h	3.5h	3h	0h
High Speed	85-100%	4%	0h	0h	0h	0h	1h

The occupancy of a certain area influences the power demand in terms of used facilities and electrical components at a certain time. Thus, the passenger and crew behavior are defined in order to consider this in the predictions later on. The definition is in accordance with the TDOs described above. All spaces are grouped into the main types of areas, like passenger cabins, restaurants, outdoor areas, leisure and public spaces. Additional areas for the crew are defined by the laundry, galleys, crew public spaces and cabins. The occupancy rate of these spaces is formulated as the ratio between actual number of people per zone divided by the maximum number of people on board. For example, the rate of 50% in the cabins would mean, that half of the passengers are allocated in the cabins in the actual time. Every type of area is related to an occupancy rate per specific time step. Figure 1 shows the distribution of passengers exemplary for the third TDO including a port call (8am-8pm).

The distribution per time step of passenger and crew is based on logical assumptions for typical passenger movements and crew working hours. For example in the night, most of the passengers are sleeping in the cabins. The main mealtimes are in the morning and in the evening. Lastly, while moored in port, most of the passengers are not on board due to excursions or other individual trips.

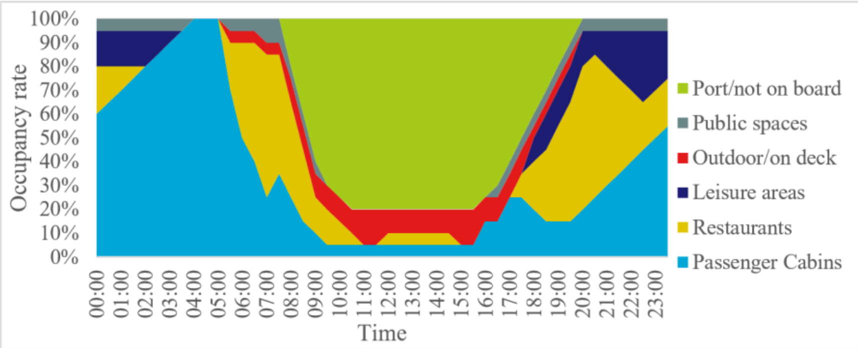

Fig.1: Defined occupancy rate for passengers; TDO3 incl. port call 8am-8pm

Instead of considering only different seasons, varying weather profiles are applied to demonstrate the impact of the environmental conditions on the power demand behavior. The extreme conditions in winter (throughout the day constant at -20°C) and summer (+35°C) are defined by ISO regulations (*ISO 2002)*, as commonly used as design parameter for the HVAC system. For these warm and cold conditions, an example weather profile is considered for Singapore (25-31°C) and Resolute Bay (-16--21°C). The profile of Amsterdam is the third condition as medium weather condition (Amsterdam summer profile used, with varying temperature 17-28°C). In addition, the corresponding hours of sunlight are defined next to a different sea water temperature per location.

2.2. System Breakdown

Before the energy consumption can be predicted, the whole system *cruise ship* has to be subdivided into the main electrical consumers and subsystems. First of all, the three main groups of systems can be defined. The propulsion systems are the systems which are directly related to the generated thrust to propel the ship. The auxiliary systems are all non-propulsion systems which assist and ensure normal operations. This involves for example the survival systems, including any hazard prevention, detection and fighting systems, like bilge or firefighting system.

Finally, the hotel systems are kept separate from the auxiliary systems due to their high power demand on cruise ships. These systems are more related to the passenger comfort and specific hotel facilities on board. In order to model the different operating subsystems, further grouping of the electrical components is applied resulting in the division as shown in figure 2.

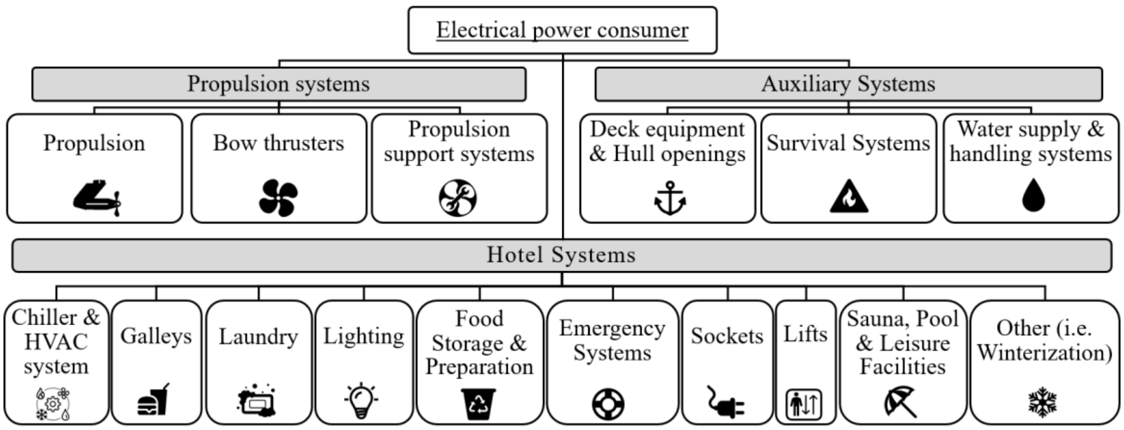

Fig.2: System breakdown of electrical components and systems

The subdivision is made on the basis of the belief that if a specific system or component contributes a higher proportion to the overall power demand, temporarily or constantly over time, then it should be modelled with a higher degree of detail (see figure 3). For example, the bow thrusters need a

significant amount of electric power while maneuvering. Thus, a more detailed investigation can point out the temporarily high loads.
Furthermore, some components or systems can be modelled together if they are highly dependent on each other. For example, the HVAC system is modelled together with the chilled water plant even if both systems consume a significant amount of energy. The cooling demand by the HVAC system is directly supplied by the chilled water plant (compare contrary power contribution of HVAC system and chillers in summer and winter in fig.3). Thus, the systems are directly related and are modelled together under varying conditions.
The third consideration of grouping the components is to take the operating conditions into account. If systems are operating in different conditions, then they should be modelled separately, even if the overall power contribution is low. For example, the emergency systems are only running on stand-by mode in normal operation, while having the higher load in emergency situations.

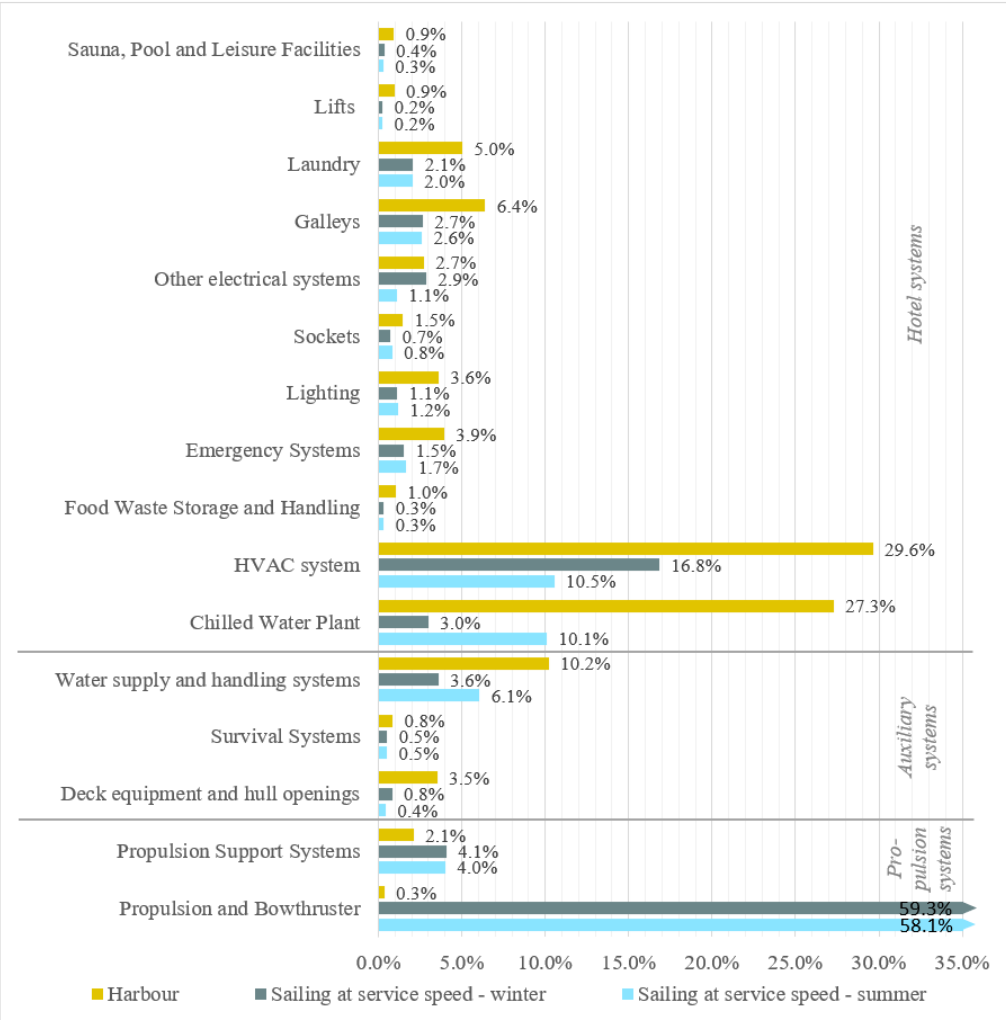

Fig.3: Grouped systems and its proportion of overall power in chosen operational conditions in load balance approach for used reference vessel

2.3. Power prediction

In order to estimate the energy consumption, the power demand has to be understood under the operational conditions. This is done by using separate prediction models for the defined groups of systems and electrical components. The focus is on identifying the maximum power demand to assess the power plant (or fuel cell) size. Additional power fluctuations can be analyzed as well, which are critical for fuel cell systems. If an additional peak load cannot be considered within the used time step size of 30 minutes, then it is listed as immediate peak load manually. The prediction models are briefly described and are included more detailed in the master thesis report *Energy demand of a fuel* *cell driven cruise ship*.

The power that is required by the main propulsion system is predicted based on the empirical method of Holtrop and Mennen (*Holtrop and Mennen, 1982)*. The main dimensions and gross tonnage are used for the vessel as input data, next to defined form factors for a conventional cruise ship hull. The same holds true for using typical efficiencies to obtain the required brake power at design speed. The propeller law can now be used to predict the required propulsion power for speeds unequal to the design speed. The bow thruster is predicted under consideration of the crabbing criteria and the expected side forces. In general, the passenger behavior and weather condition is not considered in the propulsion power predictions.

The power demand of the auxiliary systems is independent of the speed of the ship and only impacted gradually by changing the operational mode (i.e. port to sailing mode). The number of passengers does play a role in predicting the actual load (mainly water supply system), whereas the daily behavior on board is less influencing this group of systems. Lastly, a different sea water temperature per season affects the heating demand within the water supply system, while the varying ambient air temperature does not influence the load behavior of the auxiliary systems.
Except for the water supply system, the auxiliary power demand is widely constant per operational condition. Thus, next to the predicted installed power, constant utilization factors are applied per operational conditions (sailing or port) as well as for the different seasons (summer or winter). The water systems consider the varying demand of potable water and cooling water for the HVAC and propulsion systems.

Lastly, the hotel systems are discussed. The individual configuration of systems and components depends on the owner requirements. However, within the scope of an expedition cruise ship, the limited number of outfitting, leisure and entertainment facilities can be grouped to enable a rough prediction of the electric energy demand in the first design stage.
The HVAC system is one of the most dynamic energy systems on board of a cruise ship. Separate estimations are performed for every area on board. The passenger cabins are supplied by local fan coil units (FCU) and the public and crew areas by centralized air conditioning units (AHU). They include the electrical components of fans, cooler, heater and humidifier. The automated prediction considers the passenger behavior, as defined for the typical operational days, and the different weather profiles for the ambient air in order to get a power demand different for every time step.
The galleys and laundries are related to typical working schedules to consider the varying load. Lighting is reduced in unoccupied areas and cabins and results in varying load depending on the passenger behavior. Minor systems can be linked to a utilization factor for full operation in sailing condition and lower load in port condition due to less people on board.

2.4. Energy prediction

The time-dependent load behavior during the different operational days is the basis for the daily energy demand per typical operational day. It is the basis for sizing the fuel tanks. The required energy per day is calculated directly from a time-domain integration of the power prediction. The demand for a whole operational profile is obtained by adding different typical operational days. For example, the commonly used three-week transit condition is described by using the second operational day, constantly sailing at design speed. Alternatively, a typical coastal profile can be assembled with the different defined days in mixed operational modes considering a varying speed profile of the vessel.

3. Results

The prediction of the power demand is the basis for sizing the fuel cell on board. Using an estimation under dynamic operational conditions provides insight in the demand of the whole cruise vessel after calculating the load of the individual systems. As a potential design point for the different power plant components, it is important to differentiate between the maximum power load and the base load. The base load describes the minimum amount of power needed over the day and is significantly lower than the maximum load, which occurs only temporarily.

Conventional predictions in the design process, like the load balance approach, focus on the maximum loads to size the main engines.
In order to implement fuel cells, most likely within hybrid configurations, the dynamic power prediction identifies the base load and additional power fluctuations up to the temporary maximum load. This provides more well-founded decisions, how to match the operational points of the different power plant components with the individual load more efficiently.

The highest power is required by the main propulsion in sailing mode (see left graph in figure 4). However, expedition cruise ships often operate at lower speeds below the design conditions (see obtained speed profile in table II), which results in a considerably lower demand most of the time (see right graph in figure 4). The highest load changes result from adjusting the speed. In addition, high peak loads are shown in maneuvering condition (see right graph in figure 4, e.g. before mooring). The operating bow and azimuth thrusters need high electric power within a short period of time.

In contrast, the power demand of the auxiliary systems is relatively constant close to its maximum load in sailing condition. Only gradual load changes occur by changing the operational mode for example from sailing to port condition. The maximum load of the hotel systems always appears in the morning, when all passengers are on board and several components ramp up from the lower night mode. In general, the power demand is higher in summer, followed by winter condition. This is due to high heat loads or cooling resulting in a higher electrical load within the HVAC system and chilled water plant. The medium weather condition results in the lowest hotel power demand since no extreme cooling or heating is required. Galleys demand the highest amount of electrical energy in their working hours during the day in mealtimes, while the laundry is often running during the night. The remaining and smaller systems are negligibly impacted by the environmental conditions.

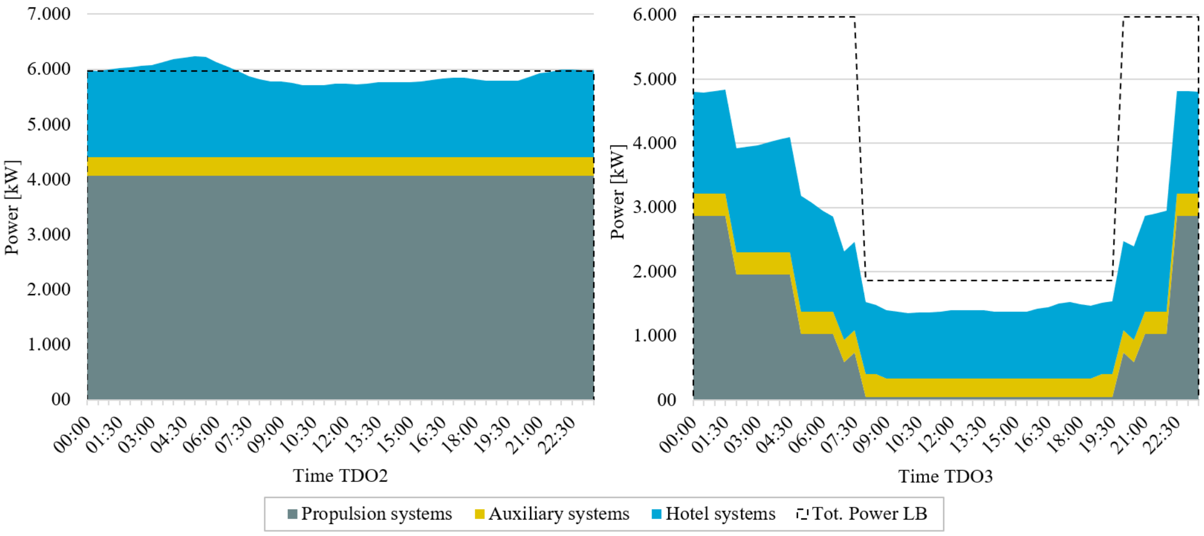

Fig.4: Electric demand of propulsion, auxiliary and hotel systems in winter season, for sailing day constantly at design speed (TDO2) and day including port call, 8am-8pm (TDO3)

Figure 5 shows the power fluctuations for the hotel systems for the used reference vessel. The power fluctuations are mainly influenced by the passenger behavior. Disembarking in port (see right graph in figure 5, e.g. arriving in port in the morning) causes the highest changes due to a lower actual utilization in port condition, of several systems that normally ensure the high passenger comfort. Thus, they can run on lower design conditions. For example, the galley provides fewer meals and the running HVAC system can be reduced in unoccupied areas.
Figure 5 shows also the predicted power for the hotel systems out of the load balance approach. The demand has its constant value for sailing and port condition and differs significantly from the dynamic approach. The maximum demand is reached only temporarily, while most of the time the load is lower. As a consequence, the static approach in the load balance analysis results in an overprediction of the electric power demand of the hotel systems under consideration of the passenger behavior and

environmental conditions.

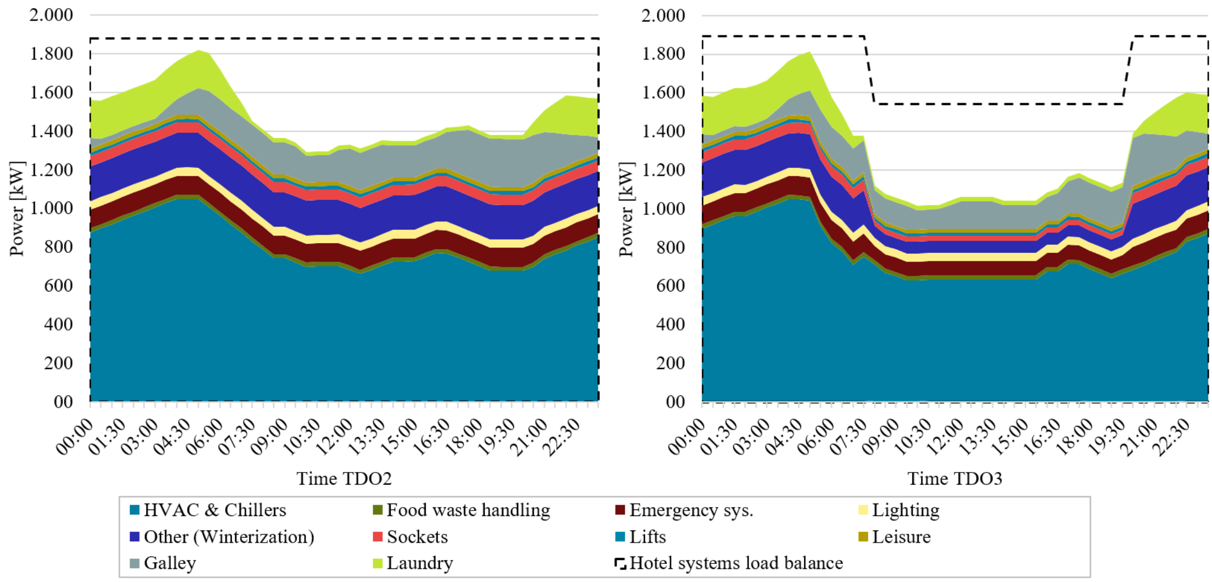

Fig.5: Electric demand of hotel systems in winter season, for sailing day constantly at design speed (TDO2) and day including port call, 8am-8pm (TDO3)

Comparing the total power demand shows that the load changes caused by the hotel systems gets smaller in relation to the changes within the propulsion system as soon as the speed varies (see figure 4, in mixed operational conditions, right side). In port condition, the auxiliary load, including the hotel systems, remains and describes the baseload throughout the day (see right graph in figure 4, during the day). Furthermore, comparing the varying load with the load balance approach, the dynamic prediction clearly shows the usually oversized power plant components. In typical costal operations with a varying speed profile, the average load is mostly lower than 50% of the predicted load at design speed (compare sailing day at design speed, TDO2, with mixed operational condition in coastal profile, TDO3, in figure 4).

The energy demand of the different operational days is predicted for the different considered seasons. Due to the widely constant power demand of the auxiliary systems, the daily energy demand does not vary significantly as well. Different seasons have an impact on the hotel systems due to a different heating or cooling demand of the HVAC system. However, the driving factor for the overall load is the varying speed, which impacts the propulsion system and lowers the energy demand significantly compared to the demand predicted using the load balance approach. The power fluctuations within the hotel and auxiliary systems, as discussed earlier, have a lower impact on the energy demand. They are averaged out due to partly higher and partly lower loads during the day.

The defined operational days are now used to predict the energy demand of a typically used transit profile and an alternative coastal profile of the same endurance of 3 weeks under dynamic operational conditions. An example 21-day cruise is used as case study based on a planned trip by a cruise line. The total energy demand prediction is reduced by around 40% for the reference vessel, mainly driven by the speed reduction and lowering the corresponding propulsion energy by 60%. The energy demand of the auxiliary and hotel systems is only reduced by around 10% in the coastal profile.

Generally, the dynamic prediction clearly shows the potential to better estimate the required power and energy, if varying operational conditions are considered. Optional fuel cells could be designed more efficiently for specific part loads, like the auxiliary and hotel systems. The varying load with its expected gradual load changes can be quantified and covered by fuel cells, rather than the propulsion systems. Conventional combustion engines or balance of plant components, like batteries, can be designed and optimized for the remaining systems with their high loads and temporarily high power fluctuations. A multi-criteria decision analysis on the power supply side can build up on the required energy and power demand of a certain part load to design a hybrid concept. Especially the impact on weight, volume and costs has to be considered. The required fuel cell size can be quantified based on the estimated maximal load and the fuel tanks by considering the predicted energy demand of the specific group of systems or operations.

4. Conclusion

The electrical consumers could be grouped to analyze the individual power demand behavior in varying operational conditions, under consideration of the dependencies and operating time windows. The situations are modelled in five typical days of operations, which present all usual operational modes of an expedition cruise ship.
The following dynamic prediction shows the varying power demand of the individual systems under varying operational conditions, while the total energy demand is still mainly driven by the variation of speed. Looking only into the auxiliary systems including the hotel functions, the fluctuating load is influenced by the passenger behavior and the operating mode, like port or sailing condition. The different weather season impacts the level of the actual electric load, while the daily varying temperature has a lower influence.

The method supports a well-founded decision on the power supply configuration, if it comes to hybrid systems including different power supply components and their operational characteristics. The individual load of systems can be quantified including expectable power fluctuations, which limits the serviceability of fuel cells for certain loads. In addition, the corresponding fuel tanks can be sized for an energy demand of certain systems and operating time windows considering different operational profiles such as ocean-crossing or coastal operations in more sensitive areas.

The commonly used approaches with its static utilization factors for specific operational modes lead to an overprediction of the power plant components. This gets intensified for fuel cells considering lower volumetric and gravimetric energy densities in relation to conventional diesel-based solutions. The maximum condition is only reached temporarily. Especially cruise vessels are mostly running in part load conditions, for which a hybrid system can be optimized by using the proposed dynamic prediction method.

4.1. Recommendations for further research

Simplifications are made within the power prediction, which leads to further room of improvements. Predefined design parameters (e.g. air changes within HVAC system) simplified the load prediction based on common configurations for an expedition cruise ship. However, further investigations into demand-controlled systems (e.g. using sensors) could further lower the energy demand. The dynamic prediction could be also used to assess energy saving strategies (e.g. varying air recirculation rate in HVAC system). The total power demand could be lowered and load changes further reduced.

In addition, the study focused on the electrical demand of a cruise ship as a basis for a sufficient power supply. Fuel cells could replace the commonly used diesel-powered systems. At this point, it is important to consider further thermomechanical consequences as well. The heat in the exhaust, produced by the combustion process, is normally used by the exhaust gas boiler, heating up water directly or any other heat recovery system. The required heat in the other systems has to be balanced by fuel cells or potentially additional electric heaters or boilers.
Lower exhaust temperatures are expected for some fuel cell types, while additional heat could be taken out of the produced water after the chemical process in the stacks. On the other hand, the liquefied chilled fuels in the tanks (e.g. hydrogen and LNG) have to be preheated as well, before bringing them into the fuel cell membrane. This requires additional heat in relation to the commonly used MGO in liquid phase in ambient condition. Meanwhile, the fuel cell modules require less cooling while operating. The reduction of cooling water and additional ventilation can further be optimized. Overall, a thermal load balance under dynamic condition should be performed as well to prove the heat balance on board. Alternatively, additional heat has to be produced, for example electrically impacting the electric power prediction.

After having studied the power demand side, the supply side has to be designed under varying conditions as well. As briefly mentioned earlier, different options are available for a hybrid configuration. Next to the conventional combustion engines, batteries are already in use in the maritime industry to balance immediate peak loads on smaller ferries. A reliable power plant can be optimized in terms of different parameters like volume, weight or costs. The different power sources have to be considered with their different advantages. For example, batteries are comparably heavy and expensive, which limits the application. Next to the initial investment costs, the expected operational costs over its lifetime have to be considered as well. Thus, the right combination has to be analyzed for the specific ship in a multiple-criteria decision analysis supported by the proposed dynamic prediction method of the energy demand.

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