The roadmap towards circular cruise ships

Preventing waste discharge into the environment

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Thank you

0 Abstract

Abstract

Waste streams from cruise ships come back into nature which negatively influences the environment. Research has shown that actions need to be taken to reduce climate change. Not only the government should take their responsibility, but also other businesses, like the cruise industry. The cruise industry is a growing business and cruise ships have an environmental impact. This study aims to contribute to the development of sustainable, circular cruise ships. Specifically, the gas, fluid, and solid waste streams. The final product is a roadmap, based on waste stream analyses, towards a set of targets and goals. This master thesis, examines which steps need to be taken, focusing on the three waste streams to make the transition towards circular cruise ships following the City-zen method to comply with the UN sustainable development goals. Three roadmaps are made, with three different levels of ambition; 1. Fully Circular, 2. Collaboration Ship & Land, and 3. Positive effect on the environment to find the best way to design a sustainable cruise ship.

The research can be subdivided into four main sections, background information, waste stream analysis, master planning, and conclusions. These four main sections are all in relation to the case study, cruise ships from Royal Caribbean Ltd. A literature study is conducted to obtain the needed information. The results show that it is impossible to ensure that no waste enters the environment under the conditions made for the specific roadmaps. On this basis, a combination of the three roadmaps and their technical solutions is made to design the sustainable circular cruise ship. The final design for retrofit cruise ships and newly built cruise ships is not fully circular. The treated black and grey water and bilge water still contain pollutants that come back into the sea. However, the emissions from the gas stream are reduced or fully eliminated, more pollutants are removed from the black, grey and bilge water, pollutant by-products are recycled on land, heat is recovered and reused, clean products as biogas, biodiesel and struvite are produced, seawater as ballast water is not needed, and non-hazardous and hazardous waste is reduced, reused and recycled. These adjustments and additions should be added to prevent waste discharge into the environment. This research also shows that the same design principles and interventions used in cities and building complexes can also be implemented on cruise ships, like the New Stepped Strategy, Cradle to Cradle, material passport, plants, heat pumps, and the energy exchange principle. Further research is needed into technical systems to treat and prevent the waste from entering the environment and into other criteria like cost, energy consumption, needed materials and emissions.

0 Contents

0. Content

1 Introduction

1. Introduction

As a child, I was in the fortunate position to go on vacation with my parents. In 2002 we went for the first time on a cruise vacation with friends. For me, this was an amazing experience that I will always remember. In the following years, we went on some more cruises and in my ignorance, I did not see the unsustainable side of this type of vacation. Years later, when my drive for doing research and design brought me to the Faculty of Architecture and the Built Environment, I learned about the environmental problems and the need for sustainable design.

For me, research and design never stopped at buildings or building on land. Some would raise questions seeing a Building Technology student graduating on a topic that has little to do with ''buildings'' in a traditional sense. However, the built environment and my interest go much further than this. Below a definition of Building vs, a definition from the built environment.

Building

"A relatively permanent enclosed construction over a plot of land, having a roof and usually windows and often more than one level, used for any of a wide variety of activities, as living, entertaining, or manufacturing."
(Dictionary.com, n.d.).

Built Environment

"All the structures people have built when considered as separate from the natural environment."
(Macmillan Dictionary, n.d.)

A cruise ship is a structure that engineers have made to travel over water and facilitates at the same time all the needs of the passengers. It can be seen as a small city with swimming pools, whirlpools, restaurants, theatres, and cabins. Some of the bigger ships even have an ice rink, artificial surf simulator, and indoor skydiving.

Nowadays a lot of research goes into energy strategies to make the transition to energy sustainable cities. These energy strategies should also be made for cruise ships as we can see them as small cities. With this master thesis, I would like to start the movement of making cruising a sustainable vacation, so that people can enjoy and cherish the moments on these ships without damaging the environment.

2 Research Framework

2. Research Framework

2.1 Background

2.1.1 Climate change

Naturally occurring fluctuations in the climate can be found throughout the history of the earth (Wong, 2015). However, these gradual changes took place in a range of tens of thousands or even millions of years (Hardy, 2003). The climate is largely determined by the physics and chemistry of the earth's atmosphere (Lockwood, in Hardy, 2003). Due to human actions as burning coal, oil, and gases and deforestation the composition of the atmosphere is changing. Different types of gases can be found in the atmosphere, a distinction is made between the primary gases and the rare gases. The primary gases, which are 99.9% of the atmospheric volume, are nitrogen, oxygen, and argon. The rare gases, also called greenhouse gases, are carbon dioxide, methane, carbon monoxide, nitrogen oxides, chlorofluorocarbons, and ozone, these gases have the biggest consequences for the climate (Hardy, 2003). Due to the increase of greenhouse gases as carbon dioxide the heat is trapped in the lower atmosphere what will make the temperature rise, also called 'climate change'.

Efforts to reduce greenhouse gases and strengthening the resilience and adaption to climate impacts can be seen as a definition of climate action. Actions, as integrating climate change measures into national policies, creating awareness, and providing the needed education, need to be taken (United Nations Development Programme, n.d.). Cities are trying to make the transition from fossil-based energy to zero-carbon energy to limit climate change by reducing their CO_2 emissions. Greenhouse gases are not the only harmful substances entering our environment. A circular economy tries to prevent waste streams from coming in contact with our environment. In a circular economy, renewable energy sources are used, and products and materials are not seen as waste products but are reused (Het Groene Brein, n.d.). Actions are needed to protect the planet from further harm.

2.1.2 UN Sustainability Goals

The UN defined a set of 17 sustainable development goals (SDGs) as a call for action for all countries to protect the planet (Sustainable Development Goals, n.d.-a). The 2030 Agenda for Sustainable Development, with these 17 goals, where adapted by 193 members in 2015 (Sustainable Development Goals, n.d.-b). The goals have a social, environmental, and economic range focusing on people, planet, prosperity, peace, and partnership. The 17 goals can be seen in figure 1.

The UN emphasizes that it is not only the government that needs to act also businesses, civil society, and citizens. The UN asks businesses to take responsibilities first ''and then

Figure 1: The UN sustainable development goals.
Note. Reprinted from UN. (2015).

pursue opportunities to solve societal challenges through business innovation and collaboration" (United Nations Global Compact, n.d.).

The World Tourism Organization (UNWTO) states that "Tourism has the potential to contribute, directly or indirectly to all of the goals." (UNWTO, n.d.). The cruise industry, part of the tourism industry, should take responsibility. Two big organizations represent the interest of the Cruise lines. This is the international maritime Organization (IMO) and the Cruise Lines International Association (CLIA). Both organizations recognize the importance of UN SDG and work with them.

2.1.3 Cruise industry introduction

Statistics show that the Cruise industry is a growing business. In 2009, 17.8 million cruise passengers were enjoying this type of vacation. The expected amount of cruise passengers in 2019 is 30 million, this is an increase of 12.2 million passengers compared to 2009. The cruise industry has an average growth of 6.9% per year. In 2019 there were 272 cruise ships in operation which fall under the cruise lines international Association (CLIA) (CLIA, 2019). Due to the increase of passengers 18 new ships were scheduled to be launched in that same year, figure 2 shows a cruise ship from the Royal Caribbean Cruises Ltd. This makes a total of 290 cruise ships at the end of 2019. These statistics show that cruising is becoming more popular. Cruise ships, part of the marine industry, must innovate their current systems to comply with the established UNSDGs.
Cruise ships have an environmental, social, and economic impact. Regarding the economic impact, CLIA states the cruise industry provides 1.108.676 jobs globally what is equal to $45.6 billion in wages and salaries. The total output of the world is $134 billion (CLIA, 2019).
Next to the economic impact, cruise ships also have an environmental impact. Cruise ships have several waste streams that should be taken care of. An important and overall know waste stream is the air pollution the ships emits by their exhaust gases such as nitrates, carbon dioxide, and sulfur. These exhaust gases come free for the propulsion of the ship and electricity need, for example, ventilation, appliances, and lightning. However, this is not the only type of waste stream from a cruise ship. Next to the gaseous waste stream, there are also fluid waste streams, for example, black and grey water from the sinks, showers and galleys, bilge water, and ballast water. Besides the gas and water stream, solid waste streams are also found on board, for example, solid waste and hazardous waste.

Figure 2: Allure of the Seas, Royal Caribbean. Note. Reprinted from Marefatschool (2018)

2.1.4 IMO and sustainability goals

IMO is a specialized agency of the United Nations. This agency takes care of the safety, security, and environmental aspects related to shipping. The IMO works with and recognizes the United Sustainability Development Goals (IMO, n.d.-i). Originally IMO was created to prevent and control marine pollution by oil caused by ships. Nowadays IMO is responsible for safe, secure, clean, and efficient maritime transport (IMO, n.d.-d). This means IMO looks after pollution from chemicals and other harmful substances, garbage, sewage, aquatic organisms, ballast water, anti-fouling paints, air pollution and emissions from ships (IMO, n.d.-l). The organization states that all the UN SDG are related to the work of IMO, however they focus on 8 goals which they think are most relevant. These 8 are; #4 Quality Education, #5 Gender Equality, #6 Clean Water and Sanitation, #7 Affordable and Clean Energy, #9 Industry, Innovation and Infrastructure, #13 Climate Action, #14 Life Below Water and #17 Partnerships for the Goals (IMO, n.d.-j).

2.1.5 CLIA and sustainability goals

CLIA is a global organization that represents the interest of the cruise industry community (CLIA, n.d.-a). Like IMO, CLIA recognizes the UN Sustainability Development Goals. There are six sustainability goals that the cruise industry has an impact on according to CLIA (CLIA, 2017). These are: #7 Affordable and Clean Energy, #8 Decent Work and Economic Growth, #9 Industry, Innovation and Infrastructure, #11 Sustainable Cities and Communities, #13 Climate Action, and #14 Life Below Water (CLIA, 2017).

2.1.6 Scope of the paper regarding the UN SDGs

In this master thesis the focus lies on maritime pollution of cruise ships, this includes three main categories. The first category is the gas waste stream. This includes the air pollution from the engines which is needed to produce energy for the propulsion of the ship and for the use 'hotel' load as lights, appliances, air conditioning, galleys etcetera. The second category is the fluid waste streams as grey water, black water, bilge water, and ballast water. The third category is the solid waste stream including solid waste and hazardous waste. Relating this to the UN SDG this will mean the focus is on the following Goals:

#6 Clean water and Sanitation	Category:2
#7 Affordable and Clean Energy	Category:1
#12 Responsible Consumption and production	Category:1,2,3
#13 Climate action	Category:1,2,3
#14 Life Below Water	Category:2,3

The relation between the UN SDGs, the goals of the IMO and CLIA, and the actual goals of this master thesis can be seen in figure 3. #12 is a special case because this goal is not a focus point for IMO and CLIA. However, this goal is included in this master thesis because the responsibility of the passengers and crew could have an impact on waste management and electricity usage. Goals #4, #5, #8, #9 and #17 are excluded from this research because the focus of these goals is more on economic and social level instead of environmental.

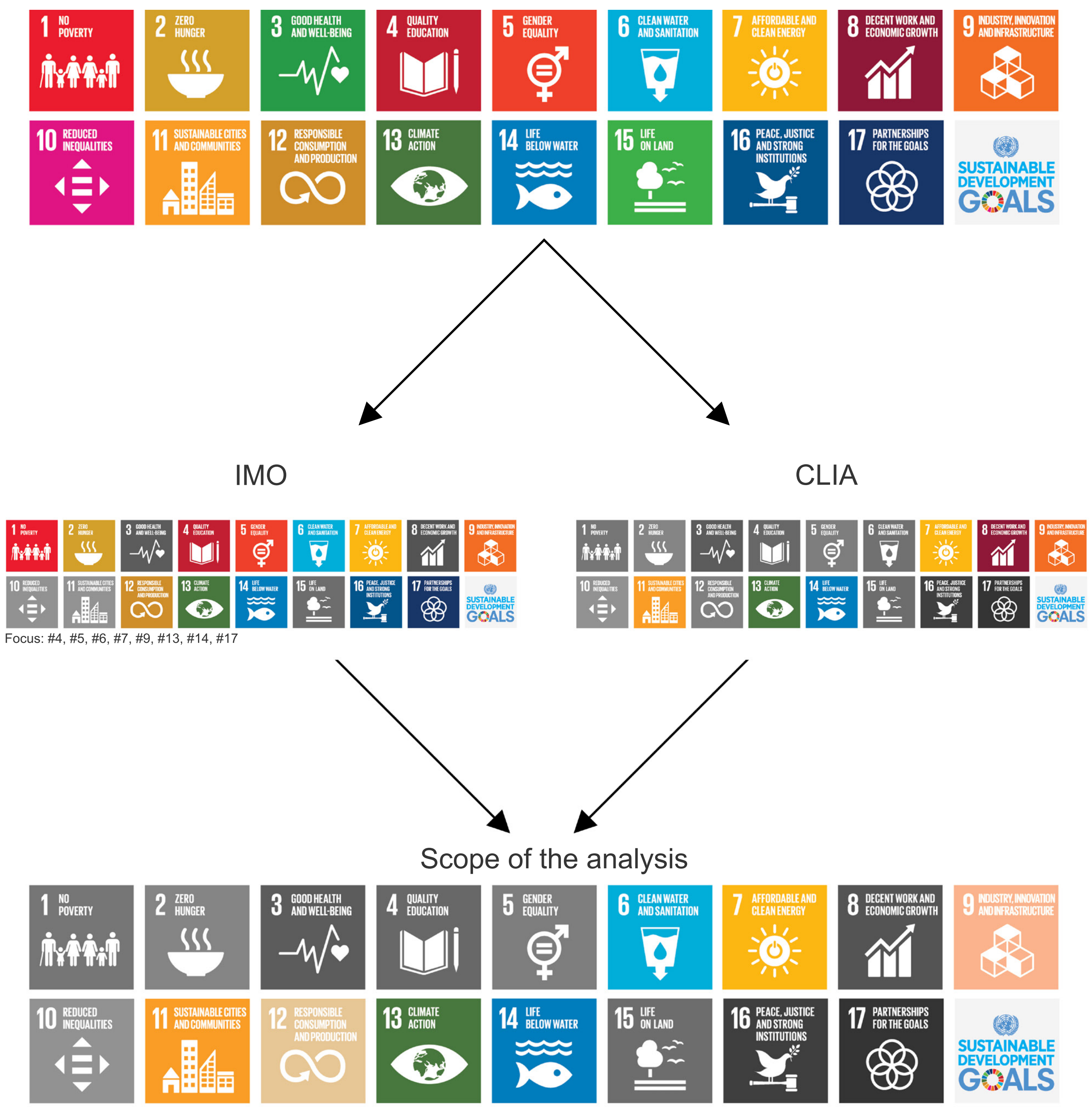

Figure 3: The goals focused on in this master thesis.

2.1.7 The City-Zen method

The City-zen method is a guideline for the built environment to help cities with the transition to a carbon-neutral built environment by 2050 (Van den Dobbelsteen et al., 2019).

> The output of this is an 'Energy Master Plan' for a city or neighborhood, based on an energy analysis of several energy maps (demand and potentials) of the city, with a roadmap that will head for a preliminary set of targets and goals (also beyond 2020) (Van den Dobbelsteen et al., 2019, p.4).

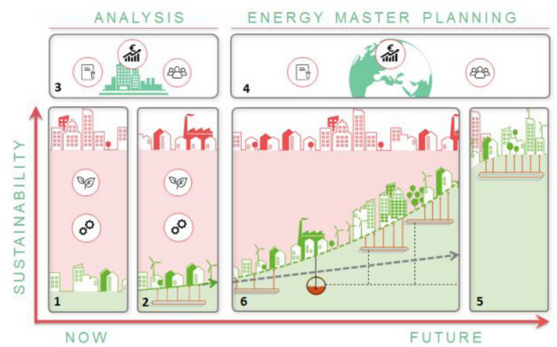

Figure 4: City-zen energy transition methodology. Reprinted from Van den Dobbelsteen et al (2019), p. 4.

The roadmap consists of 6 steps. The first three steps are part of the energy analysis and the last 3 steps are part of the Energy master planning 2050. An example roadmap can be seen in figure 4.

1. Energy analysis (present circumstances, current energy demands, energy potentials of the city, etc.)
2. Current planning and trends (the near future plan already started)
3. Societal and stakeholder analysis (political, legal, social, economic analysis)
4. Scenarios for the future (external variables that will influence the future state of cities)
5. Sustainable city vision with goals and principles (front-runner examples, partly inspired by a so-called Book of Inspiration, produced from the City-zen project)
6. The Roadmap, with energy strategies and actions (partly informed by the City-zen Catalogue of Measures) (Van den Dobbelsteen et al., 2019, p.4)

This existing method helps cities to become climate neutral with the focus on energy flows. This method is used as a guideline to create a roadmap that can be followed to help cruise ships to become circular. This master thesis does not focus on energy streams but on gas, fluid and solid waste streams. This method is used as a guideline and not as a fixed role because the focus of the City-zen method and this master thesis is slightly different due to focus on the three waste streams instead of energy streams.

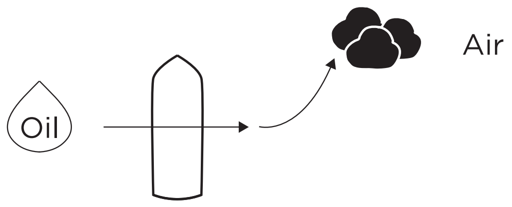

Figure 5: Problem gas stream.

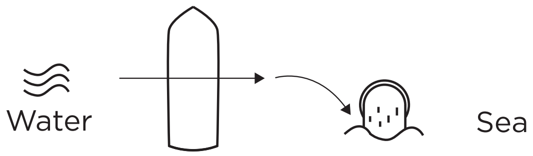

Figure 6: Problem fluid stream.

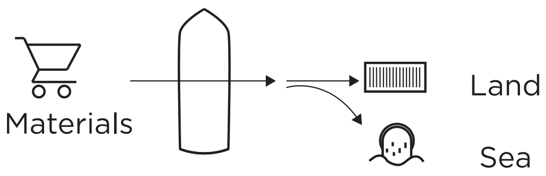

Figure 7: Problem solid stream.

2.2 Problem statement

The problem statement that follows from this background research is:

''Waste streams from cruise ships come back into nature which negatively influences the environment.''

Gas waste streams

Fuel is used as an energy source for the propulsion and electricity needs of the ship. Pollutant emissions come free by the combustion and production of fossil fuel. These emissions go into the atmosphere where it traps the heat and amplify climate change. This has a negative influence on human health. The beginning of this stream, obtaining fossil fuel, negatively influence the environment by land degradation. In short, something dirty, scarce, and bad for the environment goes into the ship, fuel, and something dirty and bad for the environment comes out of the ship, see figure 5.

Fluid waste streams

Water is needed and has several functions on a cruise ship: sewage, cleaning, stabilizing, showering etcetera. Clean water goes into the ship, is used for the specific function and becomes polluted. This polluted water comes out of the ship into the sea where it harms the aquatic environment and indirectly human health, see figure 6.

Solid waste streams

Solid products as plastics, cans, bottles, food, and light bulbs are needed in the daily life of cruise passengers and crew. These products come on board, are used until they reach the end of their lifespan. These products are stored in containers and tanks on the ship and disposed to land when the ship is in port. Some of these materials as food grease and cleaning equipment come in contact with water and end in the sea, see figure 7.

From figure 5, figure 6 and figure 7 can be seen that the waste streams do not stay on board but end up in the sky, the sea, or on land. These three ''incidents'' collide with goals number #6 Clean Water and Sanitation, #7 Affordable and Clean Energy, #11 Sustainable Cities and Communities, #12 Responsible Consumption and production, #13 Climate Action and #14 Life Below Water from the UN. To prevent this from happening in the future action need to be taken.

2.3 Research objectives

The main objective of this master thesis is to contribute to the development of sustainable, circular cruise ships. Specifically, the gas, fluid. and solid waste streams. The final product is a roadmap, based on waste stream analyses, towards a set of targets and goals. The first step for making the transition to sustainable, circular cruise ships, should be made possible by following this roadmap.

The City-zen method is used as the starting point for this master thesis. The following objectives are made following the City-zen method.

- Determine the emissions and waste streams of cruise ships.
- Determine the existing legislation for cruise ships.
- Determine the existing sustainable goals and action cruise ships already take.
- Define the involved stakeholders.
- Determine the external variables that will influence the future state of cruise ships.
- Define the (end) goals and principles cruise ships should comply with to become circular.

Limitations

As stated above the final product of this thesis is a roadmap that can be followed to help cruise ships set a step in the right direction. There are several boundary conditions due to the limited time.

- This research focusses on three waste streams; 1. Gas waste streams 2. Fluid waste streams and 3. Solid waste streams.
- First, a distinction is made between river marketing and cruise lines. The focus of this research is on cruise line corporations because the waste flows of these cruise ships can be compared to small cities. The bigger cruise ships can carry around 8.880 passengers and crew, river cruises, on the other hand, have less capacity, around 250 passengers.
- A second distinction is made between global cruise lines, Australasia cruise lines, and European regional cruise lines. In this research, the focus lies on the bigger cruise line corporations which act globally, specifically the Royal Caribbean Cruises Ltd. This is the second biggest cruise line corporation, see figure 8.

Carnival Corporation
- Aida
- Carnival Cruise Lines
- Costa Cruise Lines
- Cunard Lines
- Holland America Line
- P&O Cruises UK
- P&O Cruises Australia
- Princess Cruises
- Seaborn Cruises

Royal Caribbean Cruises Ltd.
- Azamara
- Celebrity Cruises
- Pullmantur Cruises
- Royal Caribbean International
- Tui Cruises
- Silversea

Norwegian Cruise Lines
- Norwegian Cruise Lines
- Oceania Cruises
- Regen Seven Seas Cruises

Not part of a Holding
- American Cruise Lines
- Crystal Cruises
- MSC Cruises
- Panant Yacht Cruises
- Silversea Cruises
- Windstar Cruises
- Celestryal Cruises
- Disney Cruise Line
- Pearl Seas Cruises
- Seadream Yacht Club
- Virgin Voyages
- Aurora Expeditions
- Coral Expeditions
- Star Cruises
- Dream Cruises
- Fred Olse
- Hapag Lloyed Cruises
- Marella Cruises
- Saga

- Global Cruise Lines
- Australasia Cruise Lines
- European Cruise lines

Figure 8: List of cruise lines.

Assumptions
This research assumes that the information given by the cruise line corporations is based on the truth. It is assumed that the numbers and calculations given of the waste streams are correct and not changed for their own good. Also, the actions and improvements taken, stated in the sustainability report, are assumed to be true. Next to this, the other information taken from papers and sources is assumed to be correct. No extra research is done to double-check the founded literature.

Venn Diagram
In this master thesis, three different disciplines are integrated: Architecture, Urbanism, and Maritime technology. Climate design is part of the Architecture discipline. Within climate design research is done into improving the energy efficiency of buildings. This includes building physics and building service engineering. These developments are also needed on a cruise ship, called maritime technology, to create comfortable and low-energy areas. Also, the more technical side, maritime engineering, and maritime mechanics are included in this research. This is needed to understand the working of the engines, water and electricity distribution on a cruise ship. The energy transition is a known topic in the discipline of Urbanism. Research is conducted to make the step to a zero-carbon city. The knowledge obtained in this discipline on how to approach this transition is used in the maritime sector. Also, the large scale of a city can be compared to the scale of cruise ships. Both facilitate daily needs like housing, restaurants, theatres, swimming pools, bars, gyms, and shops. Aspects, where all three disciplines have to deal with, are; 1. legislation, new goals, and laws to take the step to a sustainable future, 2. Waste streams which are found in single houses, in cities, and on cruise ships, and 3. Circular Design which tries to work to a no-waste economy. Figure 9 shows a Venn diagram of the integration of these three disciplines.

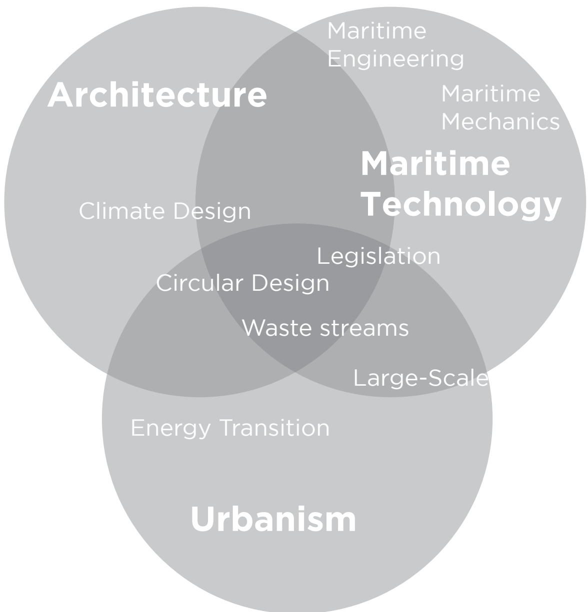

Figure 9: Venn diagram.

2.4 Research question
The research question in this master thesis is: Which steps need to be taken, focusing on gas waste streams, fluid waste streams, and solid waste streams to make the transition towards circular cruise ships following the City-zen method to comply with the UN sustainable development goals?

Several sub-questions need to be asked to answer the main research question:

- SQ 1: What are the emissions and waste streams of a cruise ship? (city-zen step 1.)
- SQ 2: What is the current legislation? (city-zen step 2.)
- SQ 3: What are the existing sustainability goals and actions Royal Caribbean Cruises Ltd. already takes? (city-zen step 2.)
- SQ 4: Who are the involved stakeholders? (city-zen step 3.)
- SQ 5: What are the future scenarios for the cruise industry? (city-zen step 4.)
- SQ 6: How does a sustainable cruise ship look like? (vision goals and principles) (city-zen step 5.)
- SQ 7: How can the sustainability goals be reached? (the roadmap) (city-zen step 6.)

Before these sub-questions can be answered some background questions are asked:

- What is climate change?
- which sustainability goals are set worldwide?
- What is the current state of the cruise industry?
- Which organisations are linked to the cruise industry regarding sustainability?
- What is the City-zen method?

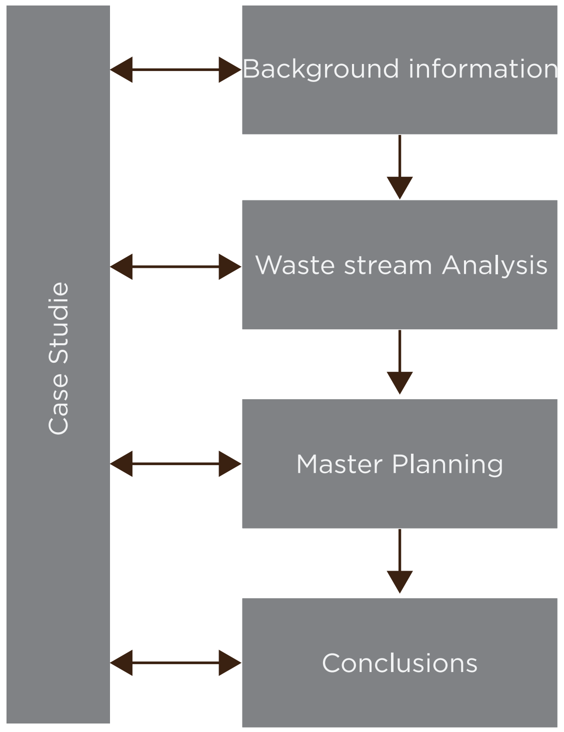

Figure 10: Simplified research approach.

2.5 Methodology

2.5.1 Research approach

The main research question in this master thesis is: "Which steps need to be taken, focusing on gas waste streams, fluid waste streams, and solid waste streams to make the transition towards circular cruise ships following the City-zen method to comply with the UN sustainable development goals?"

This research can be divided into four main sections, background information, waste stream analysis, master planning, and conclusions. These four main sections are all in relation to the case study, cruise ships from Royal Caribbean Ltd., see figure 10.

This study starts with literature research. In the research framework, background information is given to understand the scope of the research. This gives information about climate change and what causes it. Furthermore, general data about the growing cruise industry and how the cruise industry can be linked to the climate changes through the UN Sustainable Development Goals are given. Additionally, it describes the City-zen method that will be used as a guideline for the master thesis.

The next step is the waste stream analysis. A well-documented cruise organization, Royal Caribbean Cruises Ltd., is used as a case study and will be analysed with the focus on gas waste streams, fluid waste streams, and solid waste streams. The findings will be checked with the existing legislation and with the goals and actions taken by the cruise line itself. Next to this, research is conducted into the stakeholders.

From the literature study and case study qualitative and quantitative data is obtained, which is used as input for the master planning. Future scenarios and boundary conditions, which are not developed under the influence of involved actors need to be investigated. This is needed to describe the future visions and goals for cruise ships, which will result in a guideline/design. The last step is visualizing this master plan into a roadmap towards circular cruise ships. This research ends with an additional chapter that shows that the design principles from the building industry can also be applied in the cruise industry.

2.5.2 Research Design

The background information, including climate change, the cruise industry, the UN Sustainability Goals, and the City-Zen method, are obtained through a literature study. The base of this research is the problem; climate change. The UN Sustainability Goals are made to protect the planet, end poverty, and ensure peace. Climate action is one of the goals made, to counter the effects of climate change. These agreements are not only for governments but for everyone including businesses, companies, private sector institutions, organizations, and the cruise industry. These goals influence the cruise industry. Organizations as IMO and CLIA are including the UN sustainability goals into their management systems to protect the planet. The cruise industry itself also influences the sustainability goals because without this sector some goals would be different or not needed. The cruise industry is also connected to climate change due to the pollutants the ship emits. The City-Zen method is only directly connected to climate change and indirectly connected to the cruise industry and sustainability goals.

The information obtained from the background information about the cruise industry, sustainability goals, and climate change is used as input for the waste stream analysis. Throughout a literature study and a case study, more information is obtained about the waste streams on board of the Royal Caribbean fleet, the involved stakeholders, the current legislation, and the goals and actions taken by Royal Caribbean Cruises Ltd. The stakeholders influence the vision and goals of the future cruise ships.

Literature research is conducted in the waste stream analysis and is the master planning. The master planning can start after the literature study of the waste stream analysis is done. The future scenarios are part of the master planning and influence the visions and goals of the future cruise ships and the elaborated waste stream analysis. An elaborated research into the current waste stream treatment techniques and new techniques is needed to design the roadmap. This elaborated research builds upon the waste stream analysis. The information gathered from the waste stream analysis is used as input for the elaborated research and the vision and goals. If the vision and goals are clear and the elaborated waste stream analysis is done, the roadmap can be made to visualize the step by step plan to reach the new vision and goals. Figure 11 shows this research design.

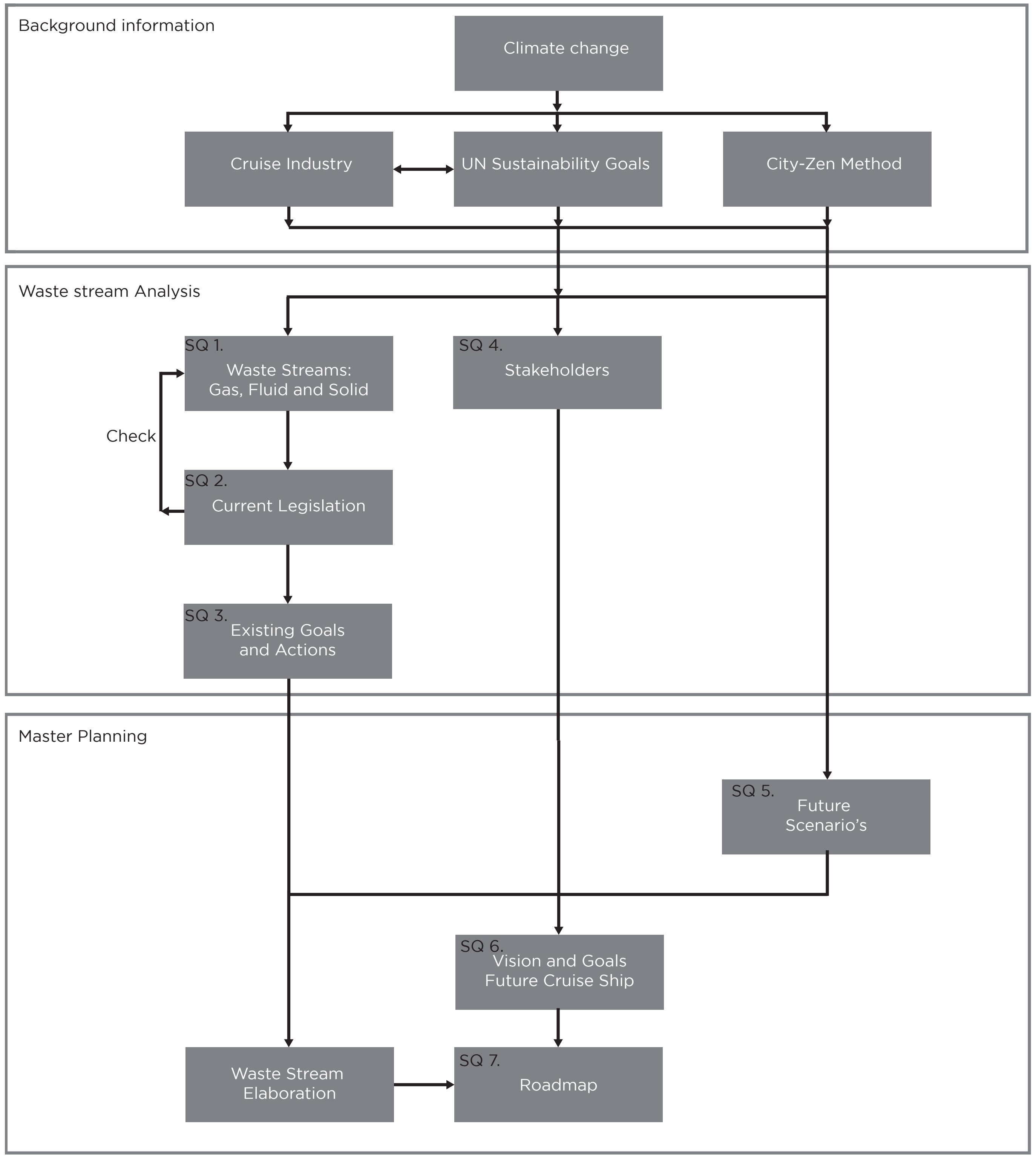

Figure 11: Elaborated research approach.

2.6 Planning and Organization

This research is divided into five main phases, the period between the presentations, see figure 12.

P0-P1: Research framework (literature review)
P1-P2: Waste stream Analysis of cruise ships (literature research & Case study)
P2-P3: Master plan part 1, future scenario's and vision and goals
P3-P4: Master plan part 2, elaborated research and roadmap
P4-P5: Finalizing the report and making the presentation

The research team around the author of this master thesis includes Prof.dr.ir. Andy van den Dobbelsteen and Ir. Nico Tillie.
Van den Dobbelsteen is the main mentor of this master thesis. The City-zen method that is used as a guideline for this research is created by Van den Dobbelsteen and his team. Tillie is the second mentor of this master thesis. He does research into the environmental challenges like climate change and sustainable energy transition in a spatial aspect with the focus on low carbon cities. His knowledge and strategy about mapping streams and the transition to low carbon cities will be used.
More detailed planning is made to get a feeling of what the time is to conduct this research, see figure 13. A weekly schedule is made to see how much time can be used for which sub-question. The waste stream analysis is scheduled to be finished between p2 and p3 to be sure enough time is left for the master plan itself. The waste stream analysis is part of the literature study together with the first part of the master planning. The second part of the master planning, the roadmap, can be seen as the ''Design'' part. This is something that should not be underestimated timewise. A lot of time goes into processing the information, finding connections, and visualize this in a design/roadmap. After every presentation, some time is scheduled to revise the work that was handed in according to the given feedback. The last period is reserved to finalize the report, writing the conclusions, limitations, abstract etcetera, and look back on the research framework to adjust where needed. The orange cells are the set dates for the (interim) presentations. The green cells are excursions that I did. The red cells are excursions that are cancelled due to COVID-19.

Financial framework

Some costs are made for an excursion to Meyer Werft in Germany. During this excursion, the process of how cruise ships are built is shown. This is used as general information to understand the structure of cruise ships better. The cost that is made for this excursion is on own expense.

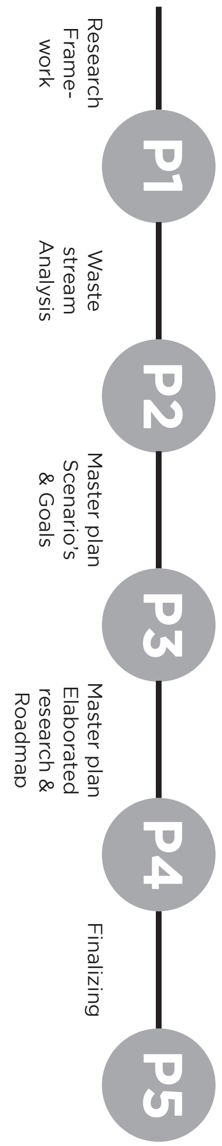

Figure 12: Planning in relation to the interim presentations.

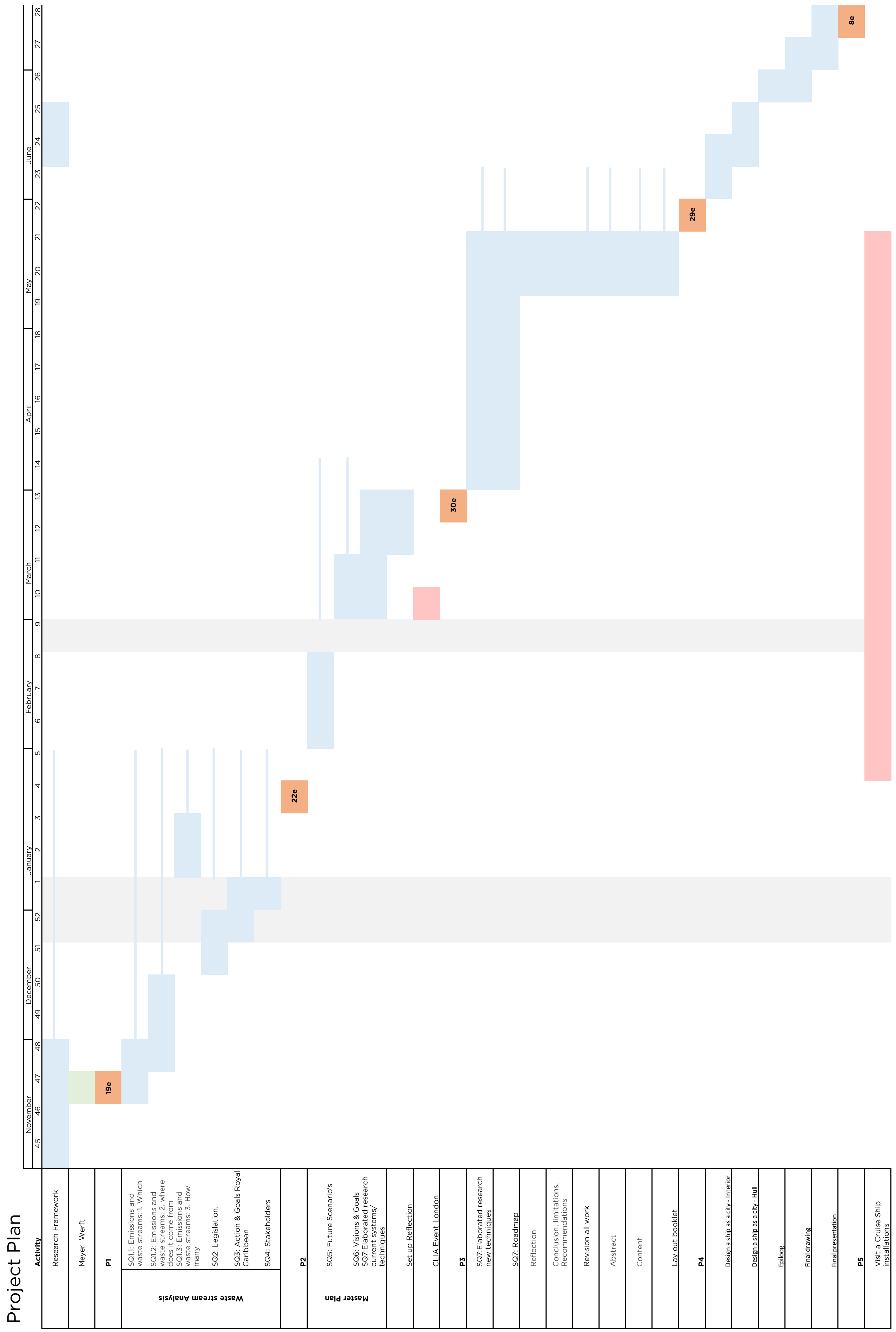

Figure 13: Timeline master thesis.

2.7 Relevance

Times are changing regarding the way we look at our environment and how we deal with it, we are in a transition. Arrangements as the Paris agreement and the UN sustainable development goals are made to get the transition started by making end goals to strive for. At the moment, governments are mainly concerned about the energy transition and make plans and new laws to stimulate this. However, companies and other organizations should also contribute to this energy transition, not because the law says so but because they realize something needs to happen.

The World Tourism Organization UNWTO (2019) states that there is a growth of 6% of international tourist arrivals and they expect it to grow around 3% to 4% in 2019. The cruise industry, part of the tourist industry, has an average growth of 6.9% per year with 290 cruise ships operational in 2019 (CLIA,2019). Cruise ships can be compared with small cities, both systems must deal with; air pollution from cars or the engine, waste streams as grey and black water, food waste, solid waste, hazardous waste, and electricity need for appliances, heating, light etcetera. The law of the European Union says, "Environmental integration in all relevant policy areas is essential in order to reduce pressures on the environment resulting from the policies and activities of other sectors and to meet environmental and climate-related targets" (European Union, 2013, p. 3). There is a need for an integral approach especially in key sectors like transport and buildings (European Union, 2013). This research is a stepping stone to a method that cruise ships can use to minimize their pressure on the environment regarding their gas waste stream, fluid waste stream, and solid waste stream. A lot of scientific research is already done into the transition to sustainable cities, for example in the Climate Design & Sustainability chair at the TU Delft. The City-zen roadshow is a research that is conducted to make this transition happen. In this master thesis, the City-zen method is used as a guideline to create a roadmap that can be followed to help cruise ships become circular. This is possible because cruise ships, sometimes called floating cities, have a lot of similarities with cities. All the daily needs and activities which people find and do in cities can also be found on cruise ships, for example: sleeping places, restaurants, gyms, swimming pools, shops, bars, and theatres, see figure 14-18. Next to this, similar streams can be found as water streams (sewage, drinking water), gas streams (pollutant emissions from engines), and solid streams (food, plastics, etc.) A cruise ship can be seen as a very isolated city. This makes a cruise ship a good case study to find out if cities have the potential to become circular. This research tries to contribute to reducing climate change by using techniques from the architectural sector into relating sectors as the cruise industry. Lee & Brezina (2016) state that there is a lack of academic research focusing on the cruise industry. With this master thesis, some more literature is added to close this gab.

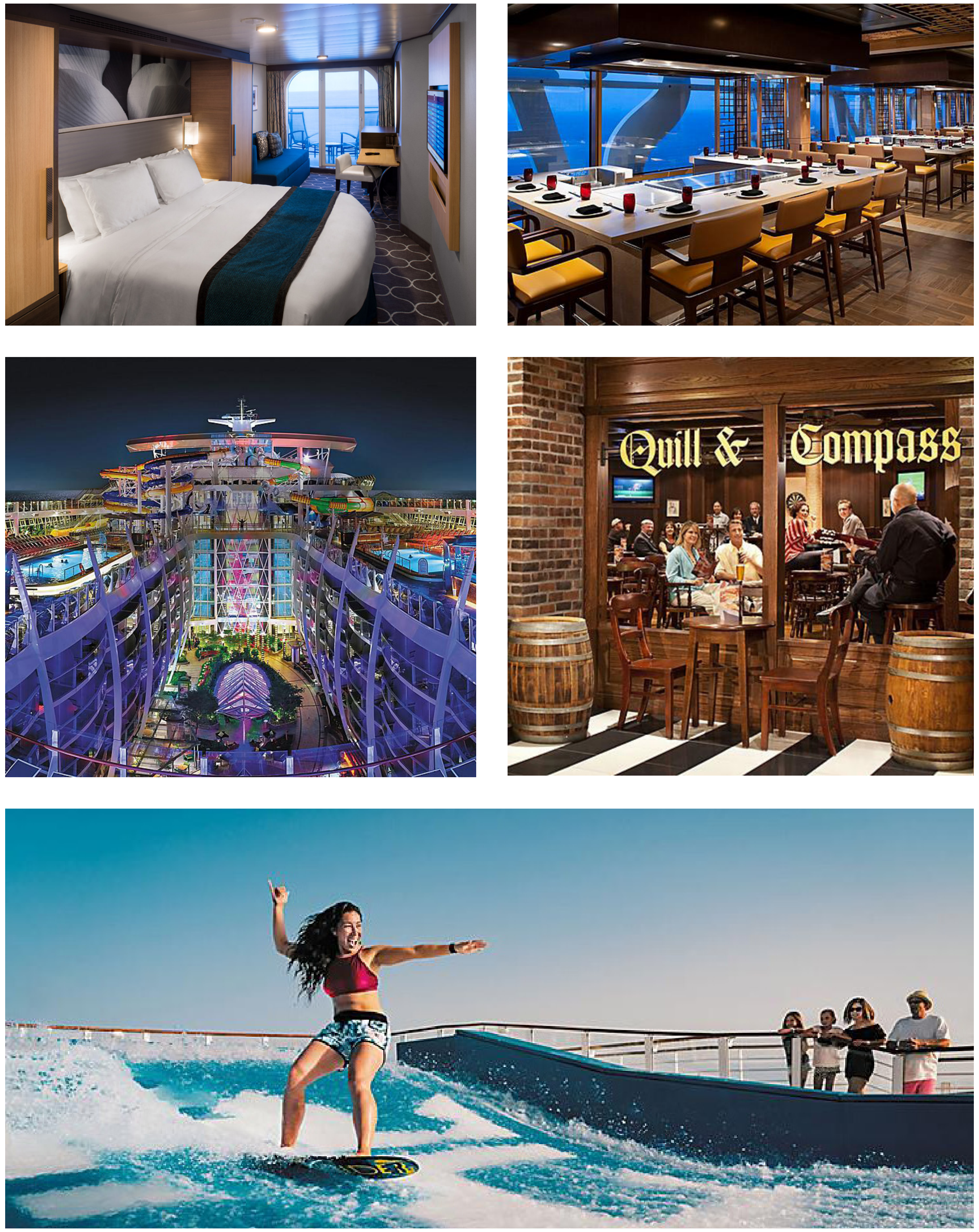

Figure 14- 18: Activities on board of Royal Caribbean
Note. Reprinted from Royal Caribbean International (n.d.-a), Royal Caribbean International (n.d.-b), Royal Caribbean International (n.d.-e), Royal Caribbean International (n.d.-d), Royal Caribbean International (n.d.-c).

3 Waste Stream Analysis

3 Waste Stream Analysis

3.1 Introduction

The methodology described that this research can be divided into four main parts; background information, waste stream analysis, master plan, and conclusion. First, the sub-question: ''What are the waste streams of a cruise ship?'' is investigated. This includes four questions: what are the waste streams, where do they come from, in what quantities, and which measures are already taken. The information comes mainly from the cruise lines itself and where possible crosschecked with papers. After this is clear, research is done into the legislation of cruise ships with the focus on gas, fluid, and solid waste streams. Then the sustainability goals and actions of the Royal Caribbean are discussed, and the involved stakeholders are mapped. These four sub-questions are together the waste stream analysis of this master thesis.

3.2 Waste Streams

3.2.1 Gas Waste stream – Engines

The first question that needs to be answered is: "What are the waste streams of a cruise ship?". This question consists out of three parts, the gas waste streams, the fluid waste streams, and the solid waste streams. Before the gas waste stream can be mapped, background information is needed about which type of engines and fuels are used in the marine industry and specifically on cruise ships of the Royal Caribbean.

The gas emissions of a cruise ship are related to the type of engine onboard and the type of fuel used. Different types of engines are used in the marine industry. The working of the following engines are described in this chapter: diesel engine, gas turbine, steam turbine plant, dual fuel engine and fuel cell.

The following paragraphs are based on Woud & Stapersma (2018), which is also called the blue bible under maritime students. The propulsion system, which ensures that the ship can move, is one of the most important systems on a ship. This system consists out of 3 main parts: prime mover, transmission, and propulsor, see figure 19. The prime mover can be, for example, a diesel engine, gas turbine or steam turbine plant. The main purpose of the prime mover is to transform the chemical energy from the fuel into mechanical energy to make the ship move. The transmission has two functions; it transfers the mechanical energy to the propulsor, and it transfers the thrust generated by the propulsor to the ship's hull. Different types of transmissions can be found in the maritime industry: mechanical drive (direct and indirect) and non-mechanical driven (electric and others). The propulsor transfers the mechanical power

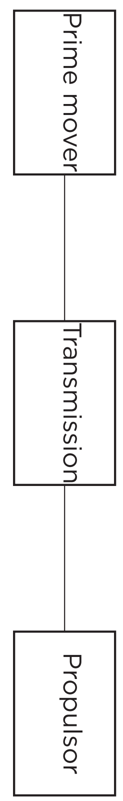

Figure 19: Propulsion system.
Note. Adapted from Woud & Stapersma (2018), p. 42.

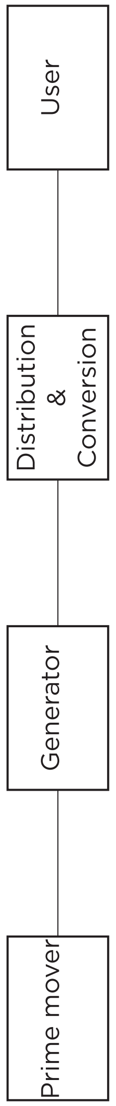

Figure 20: Electric power plant system.
Note. Adapted from Woud & Stapersma (2018), p. 46.

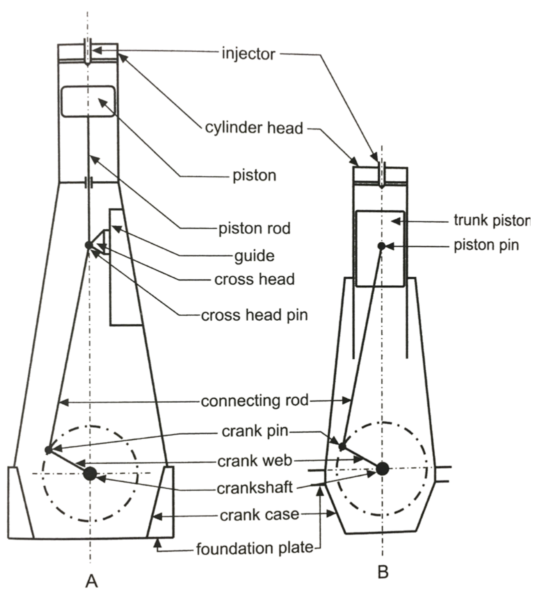

Figure 21: Main parts diesel engine.
Note. Adapted from Woud & Stapersma (2018), p.133.

of the prime mover into mechanical power to make the ship move. The most common propulsor is a propeller that is fixed pitch or controllable (Woud & Stapersma, 2018).

The main components of an electric power plant can be seen in figure 20. An electric power plant is needed to have access to electricity on board. The prime mover can be a diesel engine, gas turbine or steam turbine plant and converts the chemical energy into mechanical energy, as the first system. This mechanical energy is converted into electrical energy by the generator. The electric energy from the generators is distributed to the switchboards. The switchboards receive, control, and distribute the electric energy to secondary energy supplies. When a ship is in port the generator can be connected to the dock to receive electric energy. Every ship has one or more emergency switchboards on board (Woud & Stapersma, 2018).

As stated before, prime movers convert the chemical energy into mechanical energy for the propulsion of the ship or to generated electricity. The diesel engine, gas turbine, steam turbine plant, dual-fuel engine, and fuel cell will be further discussed. The first three prime movers are combustion engines, they convert the chemical energy in thermal energy which is converted to mechanical energy.

Diesel Engine

The diesel engine is the most common engine used in the maritime industry. The advantages of a diesel engine according to Woud & Stapersma (2018) are: the engine is insensitive to the quality of the fuel, the engine is reliable, the engine is made of simple technology what causes high maintainability, the engine is efficient, and the initial and operational costs are low. However, the main disadvantages of the diesel engine are the pollutant emissions as smoke and particles such as NO_x. Next to this it also haves a low power density.

The working of the diesel engine can be divided into four processes: air inlet, compression, expansion, and exhaust. A schematic drawing of a diesel engine can be seen in figure 21. First, the air is pressed into the combustion chamber which makes the piston move down. Then the air is compressed when the piston moves upwards. The temperature of the air rises due to this compression. Fuel is injected and due to the high temperature of the air combustion takes place. Then, due to the gas pressure, the piston moves downwards again, this downwards movement is transformed into a rotational movement of the crankshaft. New air comes into the combustion chamber and the process is repeated. Turbocharged diesel engines are commonly used to increase the amount of fuel that can be combusted. The

air is pre-compressed in a compressor to bring more mass oxygen into the cylinder. With a turbocharger, the engine generates more power with the same volume and less space is needed per kilowatt (Woud & Stapersma, 2018).

Gas turbines

Gas turbines, compared to the diesel engine, are light and compact due to the high-power density, which saves space and weight on a ship. However, gas engines use more fuel which makes them less efficient. It also needs high-quality fuel and it is designed for repair by replacement what makes it difficult to repair the engine in place (Woud & Stapersma, 2018).

The working of the gas engine can be divided into 5 parts: the inlet, the compressor, the combustion, the expansion, and the exhaust, see figure 22. Air is compressed to the combustion pressure, 10 to 30 bar into the compressor. The temperature of the air rises due to compression. Combustion takes place when fuel is injected in the combustion chamber. In the turbine, the hot air expands to atmospheric pressure which gives the power to drive the compressor and load. The gas engine conducts power when the power delivered by the turbine is higher than the needed power for the compressor. A reduction gearbox is needed when the output speed, 3000-7000 rpm, is used to power the propeller. A large amount of excess air is needed compared to diesel engines and steam plants. The intake and exhaust ducts need to have the proper size and large openings are needed in the deck of the ship. Silencers and special air filters are needed when a gas turbine is used. The performance of the gas engine can be improved by recycling the heat of the exhaust gas to heat the compressed air. Due to this less fuel is needed (Woud & Stapersma, 2018).

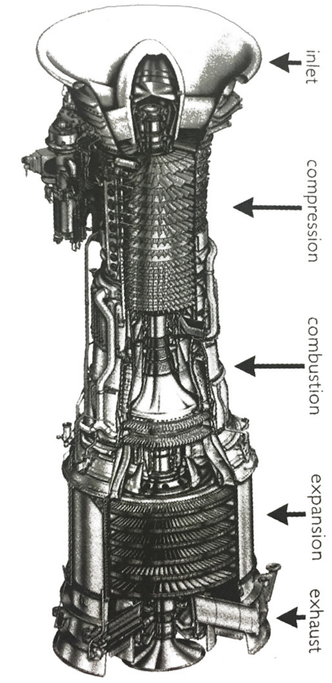

Figure 22: 3D cut-away drawing gas turbine.
Note. Adapted from Woud & Stapersma (2018), p. 138.

Steam turbine plant

A steam turbine which is used as the sole driver for the propulsion of the ship is not common because of the low power density and high initial cost compared to the diesel engine. However, the steam turbine plant can be combined with for example a gas turbine. The exhaust gas of gas engines contains high thermal energy, this energy can be used to generate steam. This will increase the efficiency but also the initial cost. The steam turbine plant consists out of four elements: the boilers, turbines, condensers, and pumps, see figure 23. In the boiler the fuel is burned which generates the steam. This steam delivers power when it expands in the turbines. The power can be transferred to a gearbox for the propulsion of the ship or to a generator for electric power. The pump is needed to move the water into the boiler and the process starts again. The efficiency of marine steam turbines is low, 28 to 32% due to the low temperatures (Woud & Stapersma, 2018).

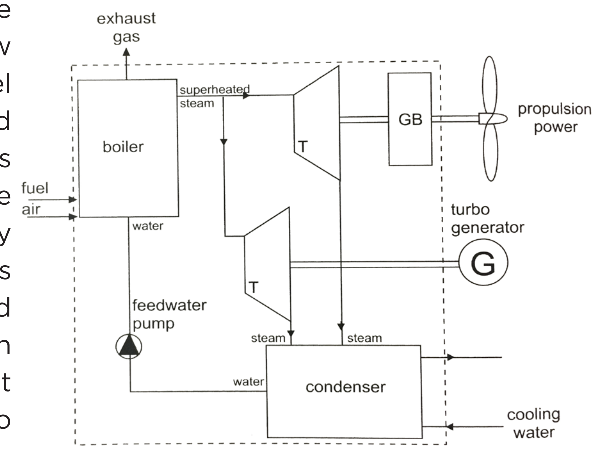

Figure 23: Diagram steam turbine plant.
Note. Adapted from Woud & Stapersma (2018), p. 142.

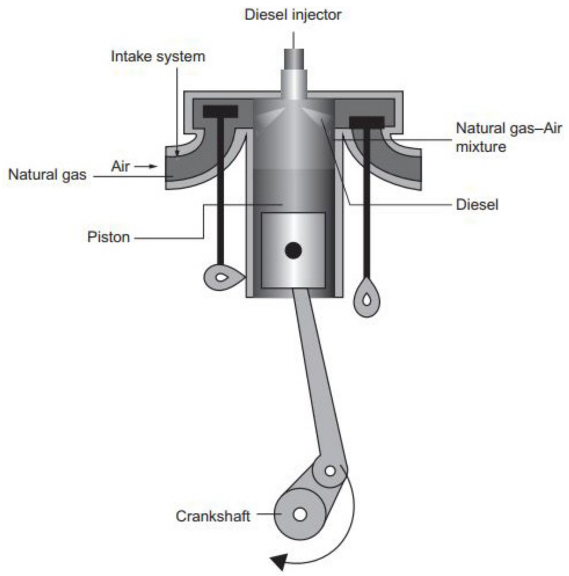

Figure 24: Schematic of a dual fuel engine.
Note. Reprinted from Breeze (2017), p. 44.

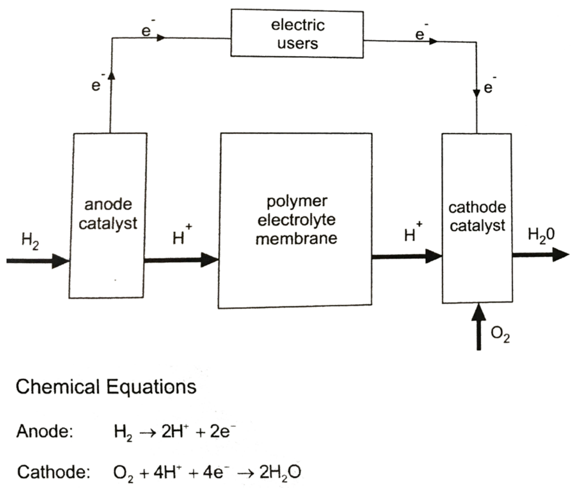

Figure 25: Working principle fuel cell.
Note. Adapted from Woud & Stapersma (2018), p. 147.

Dual fuel engines

A dual-fuel engine uses, as the name suggests, two types of fuel; mostly natural gas and a small amount of diesel. This is to combine the benefits of the two separate engines in one, see figure 24. Diesel engines are more efficient than spark-ignition engines, which use natural gas or petroleum because it can operate with higher compression ratios. The huge benefit of natural gas engines is that it works with lower combustion energy because leaner fuel is used. Fewer nitrogen oxides, excess air, and oxygen are produced what leads to complete combustion. This reduces the number of unburnt hydrocarbons and carbon monoxide what is better for the environment. A gas that could be used in a dual-fuel engine is for example LNG. The diesel is only used as fuel to start the ignition, around 1% to 15% (Breeze, 2017).

Fuel Cell

Fuel cells work in principle different than diesel engines and gas turbines because they do not convert chemical energy in mechanical energy but directly in electric energy. The fuel cell consists out of, two electrodes, the anode, and the cathode and an electrolyte. Hydrogen and oxygen come through separated inlets to the anode (hydrogen) and the cathode (oxygen). The hydrogen is split into a proton and an electron. The electrons create a current that can be used to energize electric users. The protons will go through the electrolyte and cathode where they mix with the oxygen and become water, see figure 25. Fuel cells have a lot of advantages; they are very efficient, produces water as clean emission, and make no noise. There are different types of fuel cells in development: Alkaline Fuel cell, Phosphoric Acid Fuel Cell, Solid Polymer Fuel Cell, Direct Methanol Fuel Cell, Molten Carbonate Fuel Cell, and Solid Oxide Fuel Cell (Woud & Stapersma, 2018).

3.2.1 Gas Waste stream – Fuel

Fossil fuel

Fossil fuels are used for the marine combustion engines described above. Fossil fuels are hydrocarbons, strings of carbon (C) and hydrogen (H) atoms with possibilities of sulfur (S), nitrogen (N), oxygen (O), vanadium (V), sodium (Na) etcetera. The structure of the chemical bonds and the saturation determine the C/H ratio. In the marine industry the following type of fuels are used, from the distillate products; Marine Gas Oil (MGO), Marine Diesel Fuel Oil (MDF or MDO), Blended Marine Diesel Fuel Oil (BMDF), and from the residual products Light Marine Fuel Oil/ Intermediate Fuel Oil (IFO) and Heavy Fuel Oil (HFO)/ Marine Fuel Oil (MFO) (Woud & Stapersma, 2018).

LNG

LNG stands for Liquefied Natural Gas. Nowadays there is a lot of interest from the marine industry in this gas due to the lower emission of NO_x (Brynolf, Fridell, & Andersson, 2014). This is due to the lower combustion energy described in the section of the dual-fuel engine. LNG can be used in different types of engines, spark-ignited gas engines, diesel ignited gas engines with the dual-fuel capability, and direct gas injection diesel gas engine (Environmental Protection Engineering S.A (EPE), 2015).

3.2.1 Gas Waste stream – Emissions per engine

A distinction can be made between the pollutant and non-pollutant emissions. Non-pollutant emissions are for example water (H_2O) which is formed from combustion, leftover oxygen (O_2), and nitrogen (N_2). Pollutant emissions that come free by the combustion of the fuel are carbon dioxide (CO_2), nitrogen oxides (NO_x), soot (C), and particle matters (PM). Hydrocarbons (HC) and carbon monoxide (CO) comes free by incomplete combustion. The emission of sulfur oxides (SO_x) is depended on the type of fuel used (Woud & Stapersma, 2018; Sweeting & Wayne, 2002). In table 1 can be seen when which type of emissions comes free when and what their effect is.

Table 1
Release of pollutant emissions and their negative effects.

Pollutant emissions	Comes free by/ through	Negative effects
CO_2	Combustion of fossil fuel	Greenhouse gas, climate change
SO_x	Type of fuel-related	Acid rain, Ozon depletion
HC	Incomplete combustion, Type of fuel-related, Load and Speed	Greenhouse effect
CO	Incomplete combustion, Type of fuel-related	Greenhouse effect
C	Incomplete combustion, Type of fuel-related	Negative effect human breading system
PM	Incomplete combustion, Type of fuel-related, Load and Speed	Negative effect human breading system
***NO_x (NO, NO_2, N_2O)**	Combustion, type of fuel-related, Load and Speed	Acid rain, Ozon depletion

**N+O= NO happens in the engine, NO+O=NO_2 Happens outside the engine.*

The type of emission is dependent on the type of engine and fuel. A cruise ship that uses diesel fuel, for example, HFO, emits a large range of emissions; CO, CO_2, O_x, and PM which come free by the combustion. Hydrocarbons and carbon monoxide come free as a result of incomplete combustion (Butt, 2007; Copeland, 2005; Diab, Lan, & Ali, 2016; Eyring, Köhler, Aardenne, & Lauer, 2005; Howitt, Revol, Smith, & Rodger, 2010; Poplawski et al., 2011; Sweeting & Wayne, 2002; USEPA, 1996a). The emission of SO_x is directly

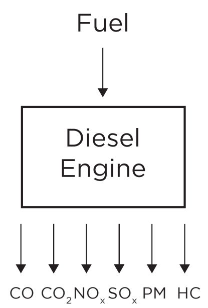

Figure 26: Emissions from a diesel engine.

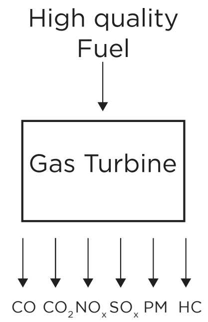

Figure 27: Emissions from a gas turbine.

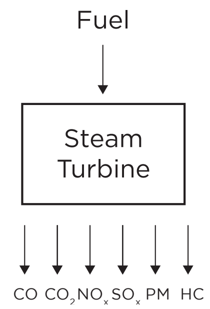

Figure 28: Emissions from a steam turbine

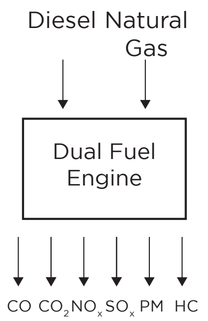

Figure 29: Emissions from a dual fuel engine.

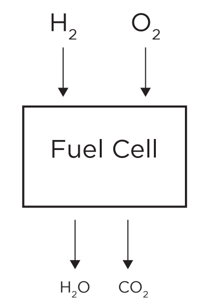

Figure 30: Emissions from a fuel cell.

related to the amount of sulfur in the fuel (USEPA, 1996a). HFO is the most commonly used fuel for diesel engines, which have a high sulfur rate of 4.5% (Koehler, 2000). The type of emissions from a diesel engine can be seen in figure 26.

Instead of using diesel engines, gas turbines can be used. These types of prime movers emit a lower amount of pollutants than diesel engines (Butt, 2007; Johnson, 2002; Woud & Stapersma, 2018). Gas turbines can run on MGO fuel, which is almost Sulfur-free, 0.3%. This means the SO_x emission of a gas turbine is close to zero. The NO_x emission rate is lower than the NO_x rate from diesel engines when measurements against these emissions are taken for both engines (Koehler, 2000). The NO_x, HC, and particles are dependent on the load, speed, and ambient conditions (Woud & Stapersma, 2018). Gas turbines can also run on LNG fuel. When this type of fuel is used as the power source, instead of fossil fuel, the emissions of NO_x, SO_x, PM, and CO_2 will be reduced even more (Banawan, El Gohary, & Sadek, 2009). The type of emissions from a gas turbine can be seen in figure 27 (USEPA, 2000).

A steam turbine plant is most often used in combination with a gas turbine. Both engines have the same type of emissions, see figure 28 (USEPA & CHP, 2015a).

The type of emissions of a dual-fuel engine is similar to a diesel engine. However, in the dual-fuel engine, only 1 – 15% of diesel is used for the ignition. Due to this the number of emissions will be lower than a diesel-only engine, see figure 29 (USEPA, 1996b).

In fuel cells, combustion is not the primary process of generating power. Because of this, the range of emissions is very low. Some hydrogen is combusted at the anode with a temperature of 1800F. Under these circumstances, there is no formation of NO_x but there is the oxidation of carbon monoxide. In most fuel cell systems, the emission of NO_x, SO_x, CO, and HC is negligible. However, some CO_2 comes free together with the formed H_2O, see figure 30 (USEPA & CHP, 2015b).

3.2.1 Gas Waste stream – Existing Solutions

Royal Caribbean ltd. is working on the reduction of the emission of their fleet. They focus on 3 main aspects; Reducing Energy Use, Emission Abatement Technology, and Alternative Fuels and Renewable energy sources.

Reducing energy

Around 60% of the energy Royal Caribbean Cruises Ltd. consumes is for the propulsion of the ship. This makes the propulsion system the main contributor to the carbon footprint (Royal Caribbean Cruises Ltd., 2018e). Royal Caribbean designed a management software system that seeks the ship's optimal balance, speed, and route. Next to this, the system suggests how many engines are needed, at what time, and in which setting to improve the efficiency of the ship (Royal Caribbean Cruises Ltd., 2018e). Another system regulates the thermostats and makes sure that the lights, appliances, and balcony doors are closed when people are not inside (Royal Caribbean Cruises Ltd., n.d.-d). Around 95% of the emissions come from fuel consumption. It is important to make the propulsion system and the ship more energy efficient to reduce the needed fuel. A hydrodynamic design is made for a podded propulsion system and propulsion plants on the existing Vision class are upgraded. Other ships of the fleet have been upgraded with a more efficient integrated rudder-propeller system which improved the efficiency of these ships with 5-10%. Next to this, the needed energy for the propulsion system is reduced by the air lubrication system. This system reduced the frictional resistance of the ship by blowing out microscopic bubbles. Royal Caribbean ltd. saved around 50.000 metric tons in emission by improving the hydrodynamics and speed management on 29 ships and upgrade the HVAC and mechanical systems on 21 ships (Royal Caribbean Cruises Ltd., 2018a). Cold seawater is used to cool water on board and reduce the load on the AC system. Next to this, the heat from the engine is used to heat the water from the showers and galleys (Royal Caribbean Cruises Ltd., n.d.-d). Other actions to reduce the energy use of the ships are by placing energy-efficient equipment and using LED or fluorescent lights instead of incandescent bulbs (Royal Caribbean Cruises Ltd., 2018e).

Emission Abatement Technology

As discussed in the previous section cruise ships emits a large range of emissions in their exhaust gases. The Royal Caribbean works with the Advanced Emissions Purification (AEP) system also known as an exhaust gas cleaning system or scrubbers. Water jets are placed in the funnels/stacks where they spray water mist over the engine exhaust gases. A chemical reaction takes place when the water reacts with the sulfur from the exhaust gas. The sulfur is removed, and a white plume comes out of the chimney. Since 2005, 5 new ships have AEP system and 19 existing ships installed one (Royal Caribbean Cruises Ltd., 2018b). This EAP system takes out 98% of the sulfur dioxides, 40-60% of particulate matter, and 12% of the nitrogen oxides (Royal Caribbean Cruises Ltd., 2018e). Royal Caribbean decided to focus on emission abatement technology instead of lower sulfur content fuel because this could be limited (Royal Caribbean Cruises Ltd., 2018a).

Alternative Fuels and Renewable Energy Sources

Royal Caribbean ltd. is looking into new renewable energy sources for the future as: biomass, biofuels, solar power, wind power, natural gas, and fuel cells. The diesel engine is the most pollutant engine as can be seen from the previous research. However, this is the most commonly used engine onboard cruise ships. The gas turbine engine emits a lower amount of pollution than a diesel engine. Royal Caribbean implemented these gas turbine engines on eight ships of their fleet since 2000. The new Icon-class, which comes out in 2022 will use LNG as the power source and fuel cells (Royal Caribbean Cruises Ltd., 2018a). This is the next step to reduce pollutant emissions. To generate renewable energy onboard energy-efficient glass, solar panels and solar window films are used (Royal Caribbean Cruises Ltd., n.d.-d).

Next to these measures, Royal Caribbean is developing a wind farm in Kansas to reduce its carbon emission. The energy produced by this wind turbine farm will be sold and used as an offset for their direct emissions (Royal Caribbean Cruises Ltd., 2018e). Something the Royal Caribbean ltd. is not implementing is Cold Ironing. This means the cruise ship connects to the electrical grid of the port and does not need to burn fuel. CLIA supports this way of reducing emissions by port infrastructure development. However, the cost of retrofitting existing cruise ships so that they can connect to shore power is very high and the availability of these connections is rare. That is why Royal Caribbean ltd. is not investing in this (CLIA, 2016; World Cruise Industry Review, 2015).

"Our company generates a significant amount of emissions from our operations. Naturally, reducing our greenhouse gas emissions, and other air pollutants, becomes a critical part of our approach to addressing climate change" (Royal Caribbean Cruises Ltd., 2018e, p. 39)

3.2.1 Gas Waste stream – Number

Now that it is clear what kind of gaseous waste streams can be found on a ship, where the waste streams come from, and which measures Royal Caribbean is taking to prevent pollution coming into the air, the question arises: How many gaseous pollutions does come free?

Royal Caribbean Cruises Ltd. (2018) states in their sustainability report the following numbers for their entire fleet, including diesel engines and gas turbine engines, see table 2.

Table 2

Amount of gaseous waste streams

CO_2			
GHG – metric tonnes CO_2e	4,397,039	4,234,770	4,465,268
*1 Scope 1	4,369,021	4,225,453	4,465,268
*1 Scope 2	13,859	9.317	10.270
*2 CO_2e in kilograms per ALB-km	0.228	0.232	0.235
SO_x			
SO_x – per metric tonnes	55,315	54,027	57,130
NO_x			
NO_x – per metric tonnes	61,601	60,059	63,277
PM			
PM – per metric tonnes	6,807	6,650	7,035

Note. Data retrieved from: Royal Caribbean Cruises Ltd. (2018)

**1 Scope 1: Emissions that come free from the fuels that are used to operate the ships.*

Scope 2: Emissions that come free from the leased offices onshore.

**2 ALB stands for Available Lower Berth; the available guest beds on a cruise ship, assuming two people are in each cabin.*

It can be seen from the table that the greenhouse gas emission in 2018 was 0.228 kg/ALB-km. This is equal to 0.114 kg/p.-km. However, the occupancy rate is not yet included in this number. Cruise ships sail often with an occupancy rate higher than 100%. This is because the occupancy rate is calculated as follows: (Number of guests)/ (Number of cabins x 2). However, there is the possibility for families to add a drop-down bed or a sleeper couch to have the children in the same cabin. Due to this, the occupancy rate can be higher than 100%. The average occupancy rate of Royal Caribbean Cruises Ltd. is 1.09 (Lee & Brezina, 2016). The final greenhouse gas emission, including the occupancy rate, is then; 0.104 kg/p.-km. This is quite low compared to other CO_2 e emissions from the transport sector. Planes for example have a CO_2 e of 0.297 kg/p.km for regional flights, 0.200 kg/p.km for continental flights and 0.147 kg/p.km for intercontinental flights (Otten, 't Hoen, & den Boer, 2015). The cruise ships from Royal Caribbean emit less CO_2e per kg/p.km than intercontinental flights calculated with the given emission and occupancy rate.

The factor from CO_2e metric tonnes to CO_2e kg/ALB-km can be calculated from the given information. This factor is used to calculate the amount of SO_x, NO_x, and PM in kg/ALB-km. First, the number of metric tonnes is changed into kg by multiplying it by 1000. Then the factor for ALB-km is calculated by dividing the CO_2e kg/ALB-km by CO_2e kg. The obtained factor is used to calculate the amount of SO_x and NO_x, in kg/ ALB-km, see table 3. The calculations can be seen in appendix A.

Table 3
Emissions per kg/ALB-km and per kg/p.km

Gas Waste Streams	2018	2017	2016
SO_x			
SO_x – per metric tonnes	55,315	54,027	57,130
SO_x in kilograms per ALB-km	0.0029	0.0028	0.0030
SO_x in kilograms per p.-km	0.0013	0.0013	0.0014
NO_x			
NO_x – per metric tonnes	61,601	60,059	63,277
NO_x in kilograms per ALB-km	0.0032	0.0031	0.0033
NO_x in kilograms per p.-km	0.0015	0.0014	0.0015
PM			
PM – per metric tonnes	6,807	6,650	7,035
PM in kilograms per ALB-km	3.55×10^{-4}	3.47×10^{-4}	3.67×10^{-4}
PM in kilograms per p.-km	1.63×10^{-4}	1.59×10^{-4}	1.68×10^{-4}

The legislation which is covered in chapter 3.3 shows the limit of NO_x in g/kWh, see table 4 (Entec UK Limited, 2010). These emission values in g/kWh from the cruise industry are not made public. Research from Entec includes the emissions from bulk carriers, container ships, tankers, passenger ships etcetera (Entec UK Limited, 2010). In the absence of specific values from the cruise industry, these numbers are used to cross-check the emission with the legislation. The emission is dependent on the type of engine and fuel used, see table 5. HFO stands for heavy fuel oil and MGO stands for marine gas oil which is the same as MDO, marine diesel oil. High-speed engines are engines with an RPM>1000, medium-speed engines have an RPM≤ 1000 and RPM ≥300, and slow speed engines have an RPM≤ 300 (Entec UK Limited, 2010). It can be seen that the high-speed diesel engine does not comply with the Tier regulations. The medium-speed diesel engine does not comply with TierIII, only to TierI and TierII if the rotation speed is higher than 130, see appendix A for the calculations. The slow speed diesel engines comply with TierI and TierII but cannot sail in special emission control areas. It can be seen that the gas turbine engines perform much better than the diesel engines and do comply with TierI and TierII. However, because these values are from a range of different types of vessels it can not be concluded that all cruise ships do not comply with the legislation.

Table 4
Tier regulations.

Regulation	NOx Limit	Engine speed	
Tier I **Constructed after 2000**	*17 g/kWh *45 n-0.2 g/kWh (130= 17.0 and 2000=9.8) *9,8 g/kWh	n < 130 130 ≤ n < 2000 n ≥ 2000	Slow speed Medium speed High speed
Tier II **Constructed after 2011**	*14.4 g/kWh *44 n-0.23 g/kWh (130= 14.36 and 2000= 7.6) *7.7 g/kWh	n < 130 130 ≤ n < 2000 n ≥ 2000	Slow speed Medium speed High speed
Tier III **Constructed after 2016 and sail in special emission control areas**	*3.4 g/kWh *9 n-0.2 g/kWh 130= 3.4 and 2000=2.0) *2 g/kWh	n < 130 130 ≤ n < 2000 n ≥ 2000	Slow speed Medium speed High speed

Note. Data retrieved from: Entec UK Limited (2010).

Table 5
Allowed NO_x emission according the type of engine

Type of Engine	Type of fuel	NOx pre-2000 engine	NOx post-2000 engine
Gas Turbine	MGO/ MDO	5.7	4.7
	HFO	6.1	5.1
High-speed diesel	MGO/ MDO	12.0	10.0
	HFO	12.7	10.5
Medium-speed diesel	MGO/ MDO	13.2	11.0
	HFO	14.0	11.6
Slow-speed diesel	MGO/ MDO	17.0	14.0
	HFO	18.1	15.0

Note. Data retrieved from: Entec UK Limited (2010).

There is no legislation about the number of SO_x in the exhaust gases from ships, only about the amount of sulfur in the fuel, see chapter 3.3, legislation. HFO contains a higher percentage of sulfur then MGO and MDO. However, the price of MGO and MDO is higher than the price of MFO. The cruise industry is looking for other solutions as scrubbers to reduce the amount of SO_x coming into the air and keep the cheaper fuel. These scrubbers are discussed in chapter 4.3.2.1.

3.2.2 Fluid Waste stream

Cruise ships produce huge amounts of fluid waste including: black water, greywater, ballast water, and bilge water (Butt, 2007; Copeland, 2005; Herz & Davis, 2002; Sweeting & Wayne, 2002).

Blackwater, also sewage, is wastewater from toilets and medical facilities. Blackwater on cruise ships is more concentrated then on land because less water is used to flush the toilet (Herz & Davis, 2002). Bacteria, pathogens, diseases, viruses, internal parasites, and harmful nutrients can be found in blackwater. When this untreated blackwater is discharged into the sea, marine organisms absorb these nutrients which cause a risk for the public health (Copeland, 2005; Herz & Davis, 2002).

Greywater, also non-sewage wastewater, comes from sinks, showers, galleys, laundry, and washbasins. They contain pollutants as: faecal coliform, detergents, shampoo, oil and grease, metals, nutrients, food waste, and medical and dental waste. The nutrients and phosphorous substances are oxygen demanding. They will use the oxygen in the sea which is necessary to support life. This will harm the marine environment (Copeland, 2005; Herz & Davis, 2002; Sweeting & Wayne, 2002).

Cruise ships use ballast water to make sure the ship is stabilized. When for example wastewater and cargo are unloaded in the port of call the ships will become lighter. Ballast water, from that area, is taken on board to make sure the weight of the ship stays the same. In the next port of call new cargo is loaded, which means the ships gets heavier. Some of the ballast water is released back into the sea, in a new area. Ballast water contains plants, animals, viruses, and bacteria from the area where it is taken on board. When this water is discharged it will mix with the water in the new port, with its own plants, animals, viruses, and bacteria. These non-native, exotic species can cause harm to the aquatic ecosystem. This will lead to environmental risks and economic costs (Copeland, 2005; Herz & Davis, 2002; Sweeting & Wayne, 2002).

The lowest part of the ship is called the bilge. The oil that leaks from the engine, machinery spaces, and during maintenance activities will mix with the water in the bilge, this is called bilge water. This water contains oil, gasoline, and by-products of petroleum. If this bilge water comes into the sea it will harm and kill the fish and wildlife, which is indirectly a threat to human life. Occasionally, the bilge needs to be pumped dry to maintain the stability of the ship and prevent oil vapours in the bilge. The oil from the bilge water needs to be extracted before it is pumped dry, the oil can be reused, incinerated, or offloaded. When the extractor does not work properly, the oily bilge water comes into the sea where it will harm the wildlife. This happened to several cruise lines (Copeland, 2005; Herz & Davis, 2002; Sweeting & Wayne, 2002).

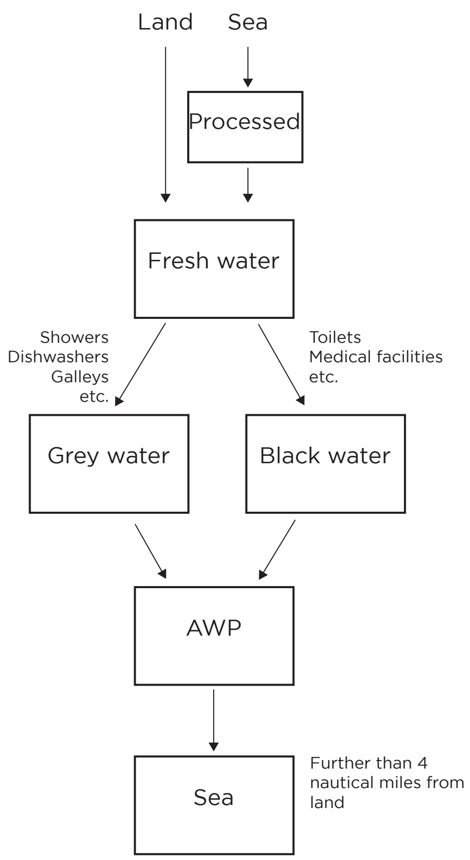

Figure 31: Black and grey water process.

3.2.2 Fluid Waste stream – Existing Solutions

The fleet of royal Caribbean uses a lot of (fresh) water on board. There are two ways of obtaining water on board. The first way is through steam desalination or reverse osmosis of seawater into potable water. Water can also be produced onboard through waste heat recovery and using condensation from air-conditioning. The second option to obtain water is by bunkering it from local sources at the port of call. The used water comes into the grey and black water waste stream. The ballast water waste stream uses seawater (Royal Caribbean Cruises Ltd., n.d.-g; Royal Caribbean Cruises Ltd., 2018b).

Black and greywater

The fresh bunkered water from land or the processed seawater is used for showering, flushing the toilets, and in the galleys. This black and grey water is treated with the Advanced Wastewater Purification (AWP) system. These systems are installed on 37 ships of the Royal Caribbean Fleet. Three ships of the fleet do not comply with the above and beyond compliance policy due to operational and design issues (Royal Caribbean Cruises Ltd., 2018b). The AWP systems the Royal Caribbean uses on her ships work twice as good for in port wastewater discharge as the U.S. federal standards require. The Quantum of the Seas

has an AWP system that can comply with the special area legislation for nutrient reduction, which is needed in, for example, the Baltic sea. All newly built ships will contain an AWP system (Royal Caribbean Cruises Ltd., n.d.-f). This process can be seen in figure 31.

Bilgewater

Bilge water is fresh, and saltwater mixed with oil, oily chemicals, and cleansers from the mechanical system of the ship. According to the IMO, bilge water may only be discharged when it contains less than 15 ppm. However, Royal Caribbean strives with its above and beyond compliance to 5 ppm. The bilge water is treated by the Oily Water Separator (OWS). The water is cleaned in several steps. The bilge water is stored in a treatment holding tank. The oily water rises to the top of the tank, is skimmed off, and stored in the sludge tank. When the ship docks in a port with a certified contractor the sludge is discharged to land. The sludge can be recycled in the pavement or as fuel in energy generators. The water in the holding tank, without the sludge, is passed through three filters. The last filter is a special carbon activated filter that removes more pollutants. The water is stored in storages thanks when the cruise ship is less than 12 nautical miles from land. This is a self-imposed minimum discharge point the Royal Caribbean set for herself. The white box checks if the water contains less than 5 ppm if that is the case and the ship is further than 12 nautical miles from land the water will be discharged into the sea. This process can be seen in figure 32. Royal Caribbean states that the average ppm value of their fleet is less than 1.5 ppm (Royal Caribbean Cruises Ltd., 2016c).

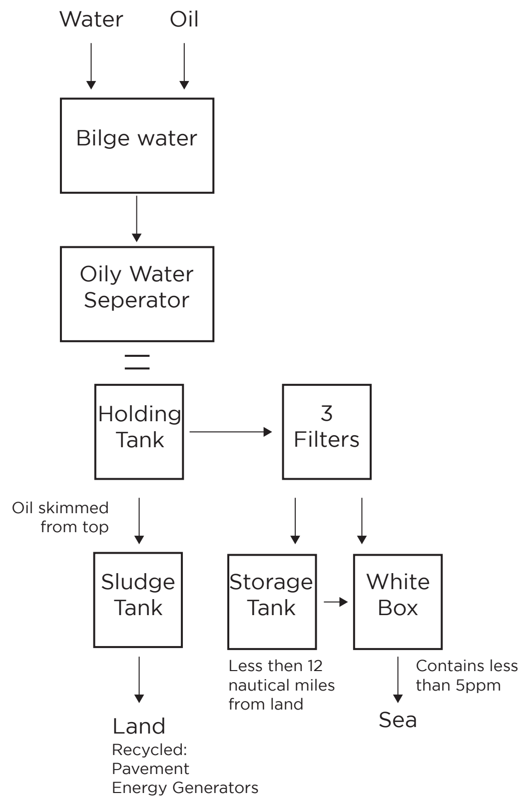

Figure 32: Bilge water process.

Ballast water

All the ships of the Royal Caribbean have a ballast water management plan onboard and discharge their ballast water according to the international rules; ballast water exchange. This means that the ballast water can only be discharged into the sea when the ship is 200 nautical miles from land and the sea has a minimum depth of 200 meters (IMO, n.d.-e; Royal Caribbean Cruises Ltd., 2016a). It is impossible for organisms picked up at the coast to survive at the open sea as well for the other way around. Royal Caribbean implements it's above and beyond principle also into a treatment system for ballast water. The older ships are retrofitted with this new system, and it is automatically installed on their newest ships. The ballast water taken onboard goes immediately through multiple layers of filter disks. Everything that is filtered out is discharged back into the sea. Due to this, no transfer of organisms is possible. After this, the ballast water goes through a UV system that kills all organisms that got through the filter system. Then

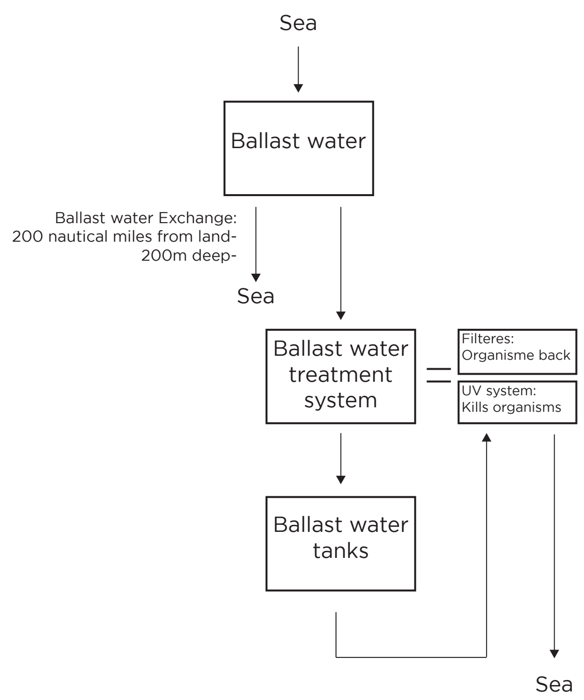

Figure 33: Ballast water process.

the water is stored, as long as needed, in the ballast water tanks. When the ballast water is not needed anymore the water goes through the UV system and finally discharged back into the sea (Royal Caribbean Cruises Ltd., 2016a). This process can be seen in figure 33.

Reducing water usages

Royal Caribbean does not only focus on cleaning its wastewater streams but also on reducing the water usage itself. They state that the average person on land uses around 380 litres of water per day. A passenger on a cruise ship uses around 200 litres of water per day. This is a reduction of almost 48%. The company installed water-saving technologies as, new ice makers which use less water, sink aerators, low-flow showerheads, water-reduction technology in kitchens and laundries, and reuses clean condensation from air conditioning units in laundry areas (Royal Caribbean Cruises Ltd., 2018e). Next to this royal Caribbean works together with the WWF and have their own Save the Waves Program, a commitment to environmental stewardship. The Save the Waves Program has four main principles: 1. Reduce, Reuse, Recycle, 2. Practice Pollution Prevention, 3. Above and Beyond Compliance, 4. Continuous improvement (Royal Caribbean Cruises Ltd., 2018e).

3.2.2 Fluid Waste stream – Numbers

There are three groups of fluid waste streams as can be seen from the previous chapter, black and grey water, bilge water, and ballast water. Royal Caribbean tries to reduce the pollutant discharge of this waste stream into the sea. The amount of discharged black water, greywater, and bilge water can be seen in Table 6.

Table 6
Amount of fluid waste streams

Fluid Waste Streams	2018	2017	2016
Black and Grey Water			
*Black water sea Discharge Rate – Liters/ Person-day	65.0	65.9	69.1
*Grey Water sea Discharge Rate – Liters/ Person-day	146.6	144.6	155.9
Bilge Water			
*Bilge Water – Liters per NM	17.1	18.5	21.9
Ballast water			
Ballast water	-	-	-

*These numbers come from the sustainability report of Carnival Corporation & PLC because this information could not be found in the Royal Caribbean Cruises Ltd. Seastainability 2018 report (Carnival Corporation & PLC, 2018).

From the table above can be seen that the amount of discharged black water per litres per person-day is decreased between 2016-2018. The amount of greywater discharged into the sea per litres per person-day in 2018 is significantly lower than in 2016, but slightly higher than in 2017. A stronger trend can be seen in the amount of produced

bilge water per nautical mile. In the period between 2016-2018, this amount of produced bilge water reduced from 21.9 litres per NM to 17.1 litres per NM. The amount of used ballast water is not recorded in the sustainability reports of the biggest cruise line organizations. However, when the ballast water treatment system is used, there will be no exchange of organisms. The amount of used ballast water does not matter.

3.2.3 Solid Waste stream

The third waste stream are the solid waste streams. These solid waste streams are divided into regular (non-hazardous) solid waste and hazardous solid waste.
There is a lot of non-hazardous, solid waste, generated on cruise ships as: aluminium and steel cans, glass, paper, kitchen grease, cardboard, and plastic. Depended on the type of solid waste, it is incinerated onboard and later discharged at sea or disposed on land in the port of call. Paper, cardboard, combustibles, and food waste are for example incinerated onboard and discharged at sea. Plastics, cans, and glass are recycled and disposed to land. When solid waste is directly discharged at sea, birds, mammals, and fish can die from entanglement with plastics and other solid waste (Copeland, 2005; Herz & Davis, 2002; Sweeting & Wayne, 2002).
Some activities on board, as photo processing, dry-cleaning, and cleaning of equipment will lead to hazardous waste. When materials contain, hydrocarbons, chlorinated hydrocarbons, heavy metals, paint, solvents or fluorescent, and mercury vapour, they will fall under hazardous waste. Some daily life examples are light bulbs, batteries, and outdated pharmaceuticals. Special waste management is needed to prevent the mixing of hazardous waste with greywater, bilge water of solid waste. It will be fatal for marine organisms when they come in contact with hazardous waste (Copeland, 2005; Herz & Davis, 2002).

3.2.3 Solid Waste stream - Existing Solutions

As mentioned before, Royal Caribbean ltd. works with their Save the Waves policy. This does not only include fluid waste streams but also solid waste streams. Together with the Waste Management Working Group and the Environmental officers, the company tries to reduce, reuse, and recycle the solid waste. Nothing may be disposed into the sea (Royal Caribbean Cruises Ltd., 2018f).

Solid waste

Waste from all the trash cans around the ship is hand sorted by the crew. The waste that can be recycled is separated from the rest and leaves the ship when it docks in the ports of Miami, Ft. Lauderdale (Port Everglades), Tampa or Port Canaveral, Florida. Books and clothes are donated, and dry

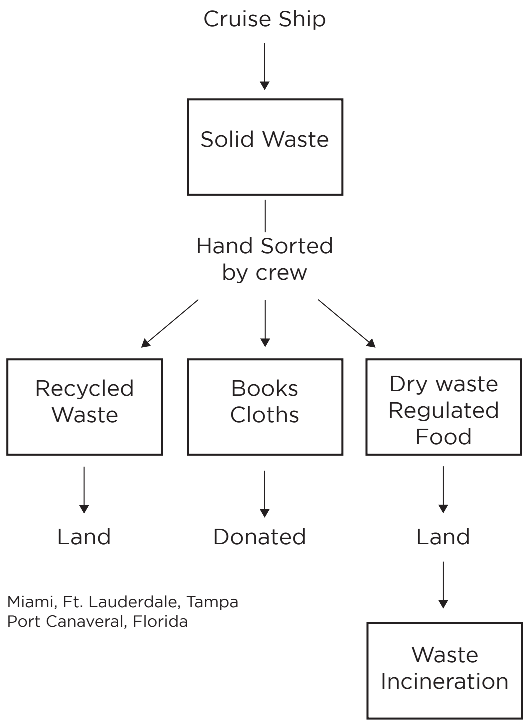

Figure 34: Solid waste process.

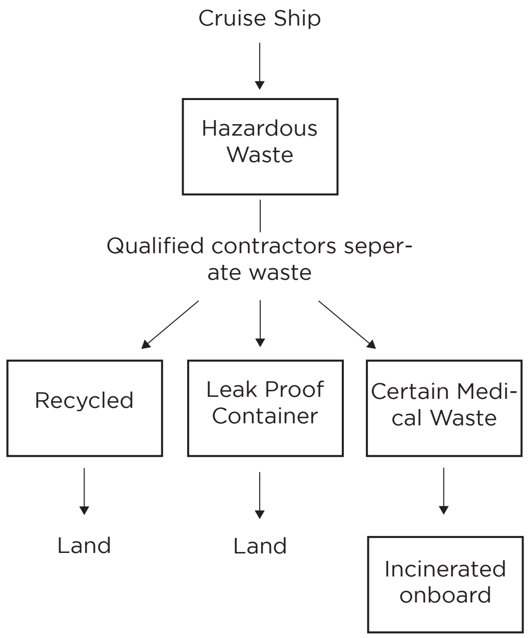

Figure 35: Hazardous waste process.

waste and regulated food-contacted waste is brought to a waste incinerator (Royal Caribbean Cruises Ltd., 2018f). This process can be seen in figure 34. In 2013 the Oasis of the Seas and the Allure of the Seas implemented a waste to energy conversion of 100% of their operational waste (Royal Caribbean Cruises Ltd., n.d.-f).

Hazardous waste

Cruise ship produces a small amount of hazardous waste. However, due to the big consequences, this is one of their highest priorities. This waste stream cannot get in contact with other waste streams as trash cans (solid waste) or into sinks and sewage (fluid waste streams) because of the big consequences. Specially qualified handlers onboard store the hazardous waste into leak-proof containers. When the ship docks into the port the hazardous waste goes to an approved disposal facility. Certain types of this hazardous waste are recycled on land, for example, fluorescent bulbs and batteries. Only some medical waste is incinerated onboard (Royal Caribbean Cruises Ltd., n.d.-f). This process can be seen in figure 35.

The Royal Caribbean uses a special Chemical Purchasing List (CPL) database which refers to the SDS Forum database. The handling uses, manufacturers' rating of health, flammability, and requirements for personal protective equipment (PPE) can be found here. Next to this, a Green Rating System is used to see which ingredients are in the chemical products. With this system, the cruise line can foresee the effects when the product comes in contact with the environment and they can control their purchasing (Royal Caribbean Cruises Ltd., 2018f).

Reducing waste

Next to these procedures to handle waste Royal Caribbean also works on reducing their waste. Royal Caribbean states that the waste to landfill ratio of an average person on land is around 1.27 kilo per day, which they reduce to 0.23 kilo per passenger per day (Royal Caribbean Cruises Ltd., 2018e). Together with their suppliers, they work on reducing packing materials and using sustainable resources. They try to work towards a circular economy. An example of these sustainable resources can be found in their food supply. Royal Caribbean Ltd. tries to buy MSC seafood and cage-free eggs. Next to this, they are banning the use of plastic straws, stirrers, and food picks. These plastic stirrers and food picks are replaced by FSC-certified Bamboo products (Royal Caribbean Cruises Ltd., 2018e). The chapter goals and actions will further elaborate on this.

"Today, 8 million metric tons of plastic enter the ocean each year because of inadequate waste management systems, causing irreversible harm to our ocean habitats." (Royal Caribbean Cruises Ltd., 2018e, p. 17)

3.2.3 Solid Waste stream - Numbers

There are two groups in the solid waste stream, the general solid waste, and the hazardous solid waste. A part of this waste is recycled, and the other part goes to landfills, this can be seen in Table 7. This table also shows the total amount of non-hazardous waste and hazardous waste generated on the ships of Carnival Corporation & PLC.

Table 7

Amount of solid waste streams

Solid Waste Streams	2018	2017	2016
Waste			
Solid waste to landfill - pounds per available cruise passenger day	0.34	0.37	0.40
Total waste recycled (pounds in millions)	43.7	40.3	37.42
Regular Solid waste			
*Solid waste (non-Hazardous waste) in metric tonnes	233,906 (104 ships)	219,810 (103 ships)	227,051 (102 ships)
*Solid waste (non-Hazardous waste) in metric tonnes per ship	2249.1	2134.1	2226.0
Hazardous Waste			
*Hazardous waste in metric tonnes	144,236 (104 ships)	137,957 (103 ships)	127,105 (102 ships)
*Hazardous waste in metric tonnes per ship	1386.9	1339.4	1246.1

*These numbers come from the sustainability report of Carnival Corporation & PLC because this information could not be found in the Royal Caribbean Cruises Ltd. Seastainability 2018 report (Carnival Corporation & PLC, 2018).

From the first row in the table can be seen that less solid waste per available cruise passenger day goes to the landfill every year. Row two shows that over the years more waste is recycled. This could imply that a bigger part of the generated waste per available cruise passenger day is recycled. However, there could also be no connection at all. For example, when more waste is recycled due to the fact that more passengers went on a cruise vacation and produced more waste.

From the numbers of Carnival Corporation & PLC (2018) can be seen that more solid waste is produced in the period between 2016-2018. However, their fleet also expended. When the solid waste is divided by the number of ships it can be seen that in 2017 less solid waste was generated compared to 2016 but this increased again slightly in 2018. Also, the amount of hazardous waste is increased over the years per ship. According to the similar goals set by both cruise line organizations, the expectation would be that the amount of solid and hazardous waste would decrease.

However, this expectation cannot be found in these three recorded years.

Conclusion
In this chapter, a literature study was done to answer the first sub-question: ''What are the emissions and waste streams of a cruise ship?''. This includes their place of origin, the quantity in which they are found on board, and which actions Royal Caribbean already takes to minimize this.

Three types of waste streams can be found on a cruise ship; gas waste streams, fluid waste streams, and solid waste streams. It can be concluded that that the gaseous waste, fluid waste, and solid waste does not stay on board but finds its way to land or into the sea or air.

The emissions that come free by the combustion of fuel are released into the air. Steps that are taken to minimize these emissions are: replacing diesel engines by gas turbine engines, reducing the energy need on the ship, and installing emissions abatement technology. The newest step is to use LNG fuel with fuel cells as a power source. However, even with this technology emissions are still coming into the air. The CO_2e emission from cruise ships is quite low compared to planes. A cruise ship emits 0.104 kg/p.-km CO_2e, compared to 0.147 kg/p.km CO_2e for intercontinental flights. Most high-speed diesel engines ships do not comply with the Tier regulations. The medium-speed diesel engine does not comply with TierIII and only to TierI and TierII if the rotation speed is higher than 130. The low-speed diesel engines do comply with TierI and TierII because the value of g/kWh is allowed to be higher. The gas turbine engines emit the lowest amount of NO_x. The gas turbine engines do comply with TierI and TierII but are also not allowed to sail in special emissions areas as the diesel engines. There is no special legislation for the emission of SO_x into the air. The law only states that there is a maximum amount of sulfur allowed in the fuel.

Also, in the case of the fluid waste streams, the pollutant chemicals are not staying on board. Sludge from the bilge water is brought to land and the filtered water, with less than 5 ppm pollution is discharged into the sea. Also, black and grey water finds its way back into the sea. It can be directly discharged into the high sea without filtering. Or it is filtered through the advanced wastewater purification system and then discharged into the sea. Ballast water is released into the high sea because organisms picked up at the coast cannot survive in the open sea. Some ships have a ballast water treatment system that filters and kill the organisms in the picked-up water. As a result, organisms cannot settle in new places. In this case, no pollution comes

into the sea. The negative effect of this is that organisms get killed. The amount of discharged grey and black water in 2018 is less than the amount of discharged water in 2016. The amount of discharged bilge water is also reduced from 21.9 litres per NM to 17.1 litres per NM. This could be a result of the actions taken by Royal Caribbean Cruises Ltd. to reduce their water use.

Regular waste and hazardous waste are both hand-sorted. Most of the waste is sent to land or incinerated on land or onboard. Through incineration, pollutant gases come free into the air. Onboard of the ships from Carnival Corporation & PLC can be seen that more non-hazardous and hazardous waste is generated. The expectation would be that the amount of waste decreases due to the actions taken by the cruise company as banning plastic and other packing material. This trend cannot be seen from the given numbers.

An overview of the waste streams flows can be seen in figure 36. It is a linear process, not a circular process.

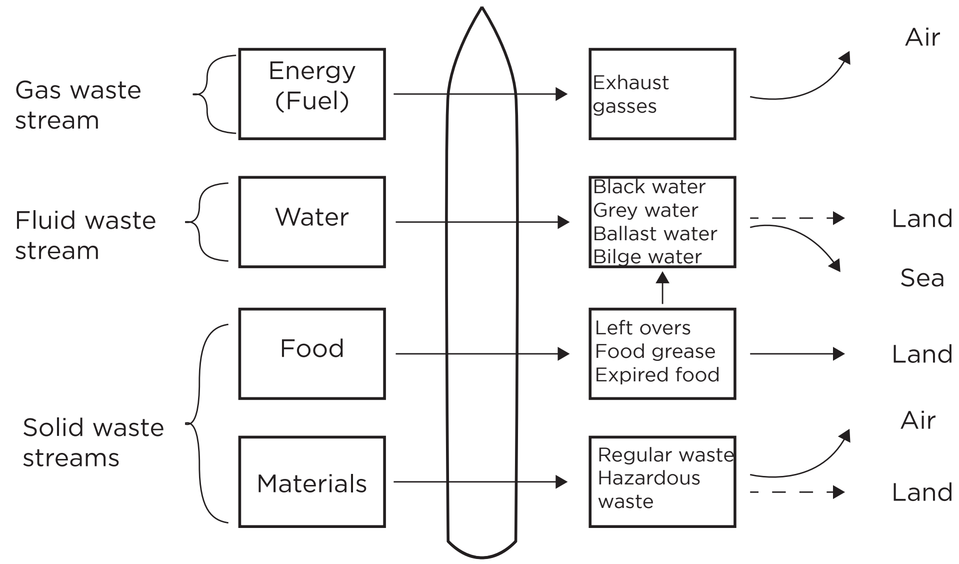

Figure 36: Linear process of waste streams on board of a cruise ship.

3.3 Legislation
3.3.1 Introduction
As mentioned in the background information, CLIA and IMO are the two main organizations related to the cruise industry that take responsibility for the marine environment. Cruise ships move between multiple continents and countries which all have their own legislation. Therefore, IMO strives for universal standards that are internationally agreed upon. CLIA supports this umbrella organization and implements the measures set by IMO (CLIA, 2016). The role of IMO is to develop new conventions when needed and maintain the existing ones. IMO is established in 1958, before this establishment, there were already two conventions: the international convention for Safety of life at Sea 1948 and

the International Convention for the prevention of Pollution of the Sea by Oil (OILPOL) 1954. Nowadays there are more than 50 conventions for the maritime industry and a special Marine Environmental Protection Committee (MEPC) who meet three times biannually (IMO, n.d.-c; IMO, 2011). Next to these international conventions made by the IMO, there are also conventions made by national and local authorities. The working of these conventions and the most important conventions regarding the waste streams of cruise ships are mentioned in this chapter.

3.3.2 Flag state and conventions

Ships sail under a flag, most of the time this is not the flag of where the company is established, the United States, but a foreign flag. This is done due to several advantages; reduce tax, mild safety standards, fewer inspections, and the possibility of having a non-domiciled crew. Some examples of often-used flag states are: Aruba, Bahamas, Bermuda, Gibraltar, Malta, etcetera (Herz & Davis, 2002). When the country of the flag state has signed for example the MARPOL convention the ship is subjected to these rules, it does not matter where it sails. This flag state is also responsible for the certificates of the ships which are needed to comply with the standards of MARPOL (Copeland, 2005; Herz & Davis, 2002). The country where the ship docks, the port of state, can examine the ship to make sure they follow the international standards (Herz & Davis, 2002). This works the same for all the other conventions signed by the flag state.

The date found behind the convention is the date when the convention is adopted by the IMO. This does not mean the convention went on that day into force and became binding for the governments who signed the contract. The convention must be accepted by the individual governments, which is a long process. When the convention went into force new governments cannot sign the contract unless they ask for accession. Amendments are needed due to innovations. The implementation of these new conventions happens automatically when no objections are made by several parties, this is called ''tacit acceptance''. Before this, a minimum of two-thirds of the parties had to accept the amendment before it could be applied, this made it difficult to alter the conventions (IMO, n.d.-c).

3.3.3 International conventions

The IMO regulates international conventions. The International Convention for the prevention of Pollution from Ships (MARPOL) is the key convention regarding the prevention of maritime pollution (IMO, n.d.-k). IMO adopted MARPOL on 2 November 1973. Due to a tanker accident, the MARPOL protocol 1978 was made which entered into

effect on 2 October 1983. A new Annex VI was added on 18 May 2005 (IMO, n.d.-f). Throughout the years MARPOL has been updated with amendments and now consist out of the following 6 Annexes; Annex I: Regulation for prevention of pollution by oil (Oct 1983), Annex II: Regulations for control of pollution by Noxious Liquid Substance in bulk (Oct 1983), Annex III: Regulation for prevention of pollution by harmful substance carried at sea in packaged form (July 1992), Annex IV: Regulation for prevention of pollution by sewage from ships (Sep 2003), Annex V: Regulation for prevention of pollution by Garbage from ships (Dec 1998) and Annex VI: Regulation for prevention of Air pollution from ships (May 2005) including the emission limits of Tier I, Tier II and Tier III (IMO, n.d.-f; IMO, 2011). The OILPOL convention is subsumed in MARPOL.
The three waste streams can be linked to these regulations, see table 8.

Table 8
The relation between MARPOL Annexes and waste streams.

Annex I: Oil	Bilge water
Annex II: Substance bulk	n.a.
Annex III: Harmful substances	Hazardous waste
Annex IV: Sewage	Blackwater, Greywater
Annex V: Garbage	Solid waste
Annex VI: Air pollution	Gaseous waste

Another key convention of the IMO is the convention of Safety of Life at Sea (SOLAS) (IMO, n.d.-k). This convention is about the safety of merchants' ships. Most chapters are not applicable for this research excluding part A of Chapter VII. This chapter is as MARPOL Annex III about the carriage of dangerous goods and includes rules about classification, packing, marking, labelling and documentation of dangerous goods (IMO, n.d.-a).

Next to these two key conventions IMO points out to 5 other conventions concerning the marine pollution which fall into the scope of this thesis (IMO, n.d.-k). The International Convention Relating to Intervention on the High Seas in Cases of Oil Pollution Casualties (INTERVENTION) made in 1969. The Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (LC) 1972, also called the London convention. The London convention is one of the first conventions protecting the sea from human activities (IMO, n.d.-b; IMO, 2011). The International Convention on Oil Pollution Preparedness, Response and Co-operation (OPRC), 1990, which is made after the industrial nations in Paris asked for extra measurements against pollution from ships (IMO, n.d.-g; IMO, 2011). The Protocol on Preparedness, Response, and Co-operation to pollution Incidents by Hazardous and Noxious Substances (OPRC-HNS Protocol), 2000, builds upon the previous convention (IMO, n.d.-o). Lastly, the International Convention for the

Control and Management of Ships' Ballast Water and Sediments, 2004. Which is made because there were no measures against Ballast water included in the MARPOL (IMO, n.d.-e).

3.3.4 National Conventions

Next to these international conventions made by the IMO, there are also national and local conventions. In the U.S, the Coast Guard, the Environmental Protection Agency (EPA), and the Departments of Justice have their own set of national rules to protect the U.S. waters (Herz & Davis, 2002). They have for example the oil pollution act of 1990, the clean water act, the clean air act, the Resource Conservation and the Recovery Act (rcra), and the act to prevent pollution from ships (Herz & Davis, 2002; IMO, 2011). Other port states as the Caribbean, Mediterranean, Baltic, Australia, and Asia have their own port state control where the international and national measures are registered (CLIA, 2016). Some states have their own legislation to reduce the environmental impact, for example, Alaska, California, and Hawaii. Alaska is the first country that forbids the discharges of untreated greywater. Next to this, cruise ships must register to the state, maintain records of discharges, pay ''head tax'' and they have stricter rules about discharging sewage and greywater along the coast (Herz & Davis, 2002). Cruise ships must comply with those stricter national rules when they visit such a state (CLIA, 2016).

3.3.5 Safety Management system

Cruise ships have a special Safety Management System (SMS) onboard where the waste management policies of international, national, and local standards are incorporated (CLIA, n.d.-b). This system is checked by a third-party, classification society or a non-governmental organization, throughout the lifecycle of the ship. Special awards are given when ships exceed the standard set of rules (CLIA, 2016). The members of CLIA share their waste management strategies as they all have common goals to prevent pollution and waste coming into nature. Next to this, special training sessions are given to crew whose work is connected to for example waste management systems. This is to create awareness and give responsibility to the people close to it.

3.3.6 Legislation per waste stream

Table 9 shows the most important conventions in relation to their waste streams.

Table 9
Conventions in relation with their waste streams.

Waste Stream	Convention	Legislation
Gas Waste stream		
	MARPOL Annex VI	-Limits pollutants as Sulfur Oxides (SO_x), Nitrous Oxides (NO_x) (IMO, 2011) -Deliberate emissions of ozone-depleting substances are prohibited (IMO, 2011) -Regulates shipboard incineration (IMO, 2011) -Regulates emission of volatile organic compounds (IMO, 2011) -Sulfur cap for fuel, 5.5%m/m 2012 (IMO, 2011) -Sulfur cap for fuel, 0.5% from 2020 or 2025 (IMO, 2011; CLIA, 2016). -Sulfur cap in an Emissions Control Area of 0.10% from 2015 (IMO, 2011; CLIA, 2016). -A maximum of 3.5% sulfur is allowed in the fuel (CLIA, 2016). -Mandatory measures to reduce GHG emissions focused on the propulsion (IMO, 2011). -Ships must comply to minimum mandatory energy efficiency performance levels which can be found back in the Energy Efficiency Design Index (EEDI). -The Ships Energy Efficiency Plan (SEEMP) helps with improving their energy efficiency by measuring weather routing, trim, and draught, speed and arrival in port. -Tier I (ships constructed on or after 2000) are allowed to emit 17.0 g/kWh NO_x if the rotation speed (n) is under 130 rpm, 45 X n-2 g/kWh NO_x if the rotation speed is between 130-1999 rpm and 9.8 g/kWh NO_x if the rotation speed is above 2000 rpm (IMO, n.d.-m). -Tier II (ships constructed on or after 2011) are allowed to emit 14.4 g/kWh NO_x if the rotation speed (n) is under 130 rpm, 44 X n-0.23 g/kWh NO_x if the rotation speed is between 130-1999 rpm and 7.7 g/kWh NO_x if the rotation speed is above 2000 rpm (IMO, n.d.-m). -Tier III (ships constructed on or after 2016 and in special emission control areas) are allowed to emit 3.4 g/kWh NO_x if the rotation speed (n) is under 130 rpm, 9 X n-0.2 g/kWh NO_x if the rotation speed is between 130-1999 rpm and 2 g/kWh NO_x if the rotation speed is above 2000 rpm (IMO, n.d.-m).
Fluid Waste Stream		
	MARPOL Annex I	-Record books with the amount of discharge and disposal of oily water, bilge water, is required (Butt, 2007) -Bilge water which went through the separator can have 15ppm max (IMO, 2011). -The maximal sulfur content of fuel oil can have 3.5% Sulfur otherwise an exhaust gas cleaning system is needed (CLIA, 2016). -The maximum sulfur content in Emissions Control Areas (ECAs) is 0.1% (CLIA, 2016).
	MARPOL Annex IV	-Discharge of not treated sewage is allowed in the 'high seas' (more than 12 nautical miles from land and with a speed equal or higher than 4 knots) because natural bacteria in the oceans can assimilate and deal with raw sewage (Butt, 2007; IMO, n.d.-n). -Treated sewage may be discharged within 12 miles from land (Butt, 2007).

		-Discharging within 4 miles from land is forbidden (Butt, 2007). -Governments need to provide reception facilities for sewage at ports (IMO, n.d.-n). -Ships must have an approved sewage treatment plant or a disinfecting system or a holding tank (IMO, n.d.-n). -Sewage may be discharged into the sea when a sewage treatment plant or a disinfecting system is used at a distance of more than three nautical miles from land (IMO, n.d.-n). -In special areas, the discharged sewage must meet the nitrogen and phosphorus removal standards (IMO, n.d.-n). -There are no discharge rules for grey-water (Butt, 2007).
	INTERVENTION	-It allows coastal states to take measures on high seas to prevent pollution by oil in consultation with the flag state of the ship (IMO, n.d.-h).
	OPRC	-A shipboard oil pollution emergency plan which is connected to a national system is mandatory on board to make a quick and effective response possible (IMO, n.d.-f; IMO, 2011). -Incidents of oil pollution need to be reported by the ship (IMO, n.d-f). -Calls for oil spill equipment, oil spill exercises and detailed acting plans in case of pollution (IMO, n.d-f). -All the parties who signed the convention need to help each other in case of a pollution emergency (IMO, n.d-f).
	OPRC-HNS	-Emergency plans on ships are needed when they carry hazardous and noxious substances that cause harm to human health when it comes into the ocean (IMO, n.d.-O).
	BWM	-Ships need to have a ballast water management plan (IMO, n.d.-e). -Ships need a ballast water record book (IMO, n.d.-e). -Ships need to have ballast water management (IMO, n.d.-e). -Ships need to have a ballast water treatment system (IMO, n.d.-e). -Other methods that ensure the same level of protection from ballast water are also allowed (IMO, n.d.-e). -Ballast water exchange should preferably happen at least 200 nautical miles from land and in a sea that is at least 200m deep (IMO, n.d.-e). -If the rule above is not possible ballast water exchange should happen at least 50 nautical miles from land and in a sea, which is at least 200m deep (IMO, n.d.-e). -If both options are not possible special areas may be pointed out as ballast exchange areas (IMO, n.d.-e). -A 95% volumetric exchange of ballast water is needed when ships exchange ballast water or pumping three times the volume of the tank (IMO, n.d.-e). -Ballast water that is discharged should contain less than 10 viable organisms per cubic meter which are bigger than 50 micrometres in minimum dimension and less than 10 viable organize per millimetre which is smaller than 50 micrometres in minimum dimension and bigger than 10 micrometres (IMO, n.d.-e). -New ballast water treatment systems are allowed to be tested on ships when they are approved by the administrator (IMO, n.d.-e). *These measures are implemented step by step, the final goal is that all ships have an on-board ballast water treatment system (IMO, n.d.-e).

	CLIA Waste management system	-All sewage, black water, need to be threatened before discharge, to meet the standards of Type II marine sanitation device or use an advanced wastewater purification System (AWPS) (CLIA,2016). -It is not allowed to discharge wastewater within 4 nautical miles from land and with a speed below 6 knots without using AWPS (CLIA,2016). -greywater can be discharged when the ship has a speed higher than 6 knots and is further than 4 miles away from land unless treated by AWPS (CLIA,2016). -Hazardous waste cannot come in contact with other waste streams (CLIA,2016). -Hazardous waste is stored in leak-proof tanks and transferred to shoreside disposal facilities (CLIA,2016).
Solid Waste stream		
	MARPOL Annex V	-A complete ban on dumping plastics (Butt, 2007; IMO, 2011). -Obligates ports to have facilities to take the garbage from the ships (IMO, 2011). -Stricter requirements for Emissions Control Areas (ECAs).
	London Convention	-Dumping any kind of waste into the sea is forbidden unless it is on the reverse list (IMO, n.d.-b; IMO, 2011).
	OPRC-HNS	-Emergency plans on ships are needed when they carry hazardous and noxious substances that cause harm to human health when it comes into the ocean (IMO, n.d.-o).
	Act to prevent pollution from ships	-Discharge of all garbage within 3 miles from shore is prohibited, certain types of garbage from 3-25 miles offshore. (United States Environmental Protection Agency, 2008). -A complete ban on plastics. (United States Environmental Protection Agency, 2008). -Need to record the discharge of incineration and garbage in the Garbage Record book (United States Environmental Protection Agency, 2008).
	Clean water act (CWA)	-No person is allowed to discharge any pollutant into the water from a point source (cruise ship) (United States Environmental Protection Agency, 2008). -The rule above mentioned above does not count when it complies with National Pollutant Discharge Elimination System or legal according to the Act (United States Environmental Protection Agency, 2008). -It is prohibited to discharge oil or any other hazardous substance into navigable water (United States Environmental Protection Agency, 2008).
	RCRA	-Ships need to have management requirements on any persons who comes in contact with hazardous waste.

Conclusion

Throughout a literature study, the sub-question ''what is the current legislation?'' can be answered. From this chapter can be seen that there is a difference between international, national, and local legislation. IMO tries to establish one set of international regulations but does not succeed in this due to the stricter legislation made on a national level by countries like Alaska. Cruise ships need to comply with these stricter laws if they want to dock into these ports. The most important regulations according to their waste stream can be found in table 9.

3.4 Goals and actions

3.4.1 Introduction

Besides the international, national, and local legislation, the cruise industry has its own set of goals that they want to achieve. These goals go beyond the overall legislation. The Royal Caribbean works with the Sustainable Development Goals from the UN. Figure 37 shows the goals Royal Caribbean focusses on and the goals which fall into the scope of this research. Next to the general goals, Royal Caribbean also set 8 types of ambitious and measurable environmental targets for 2020. With these targets, the company wants to reduce its environmental footprint and raise awareness. The eight goals are; 1. Emission Reduction, 2. Sustainable Tours, 3. Sustainable Seafood, 4. Sustainable Destinations (public) 5. Sustainable Destinations (private), 6. Sustainable Sourcing, 7. Plastic Reduction and 8. Waste (Royal Caribbean Cruises Ltd., 2018e). Goals numbers 1, 3, 6, 7, and 8 will be further discussed in their waste stream. Next to this Royal Caribbean established the Save the Waves Program in 1992. All three waste streams fall into the scope of this program. As already mentioned, the save the waves program has four main principles; 1. Reduce, Reuse, Recycle, 2. Practice Pollution Prevention, 3. Above and Beyond Compliance and 4. Continuous improvement (Royal Caribbean Cruises Ltd., 2018e).

''We have a responsibility to the guest who sail with us, the people wo work for us and the communities we visit, but most critically we have a responsibility to the oceans – they are not only the heart of our business, but connect each and every one of us.'' (Royal Caribbean Cruises Ltd., 2018e, p. 9)

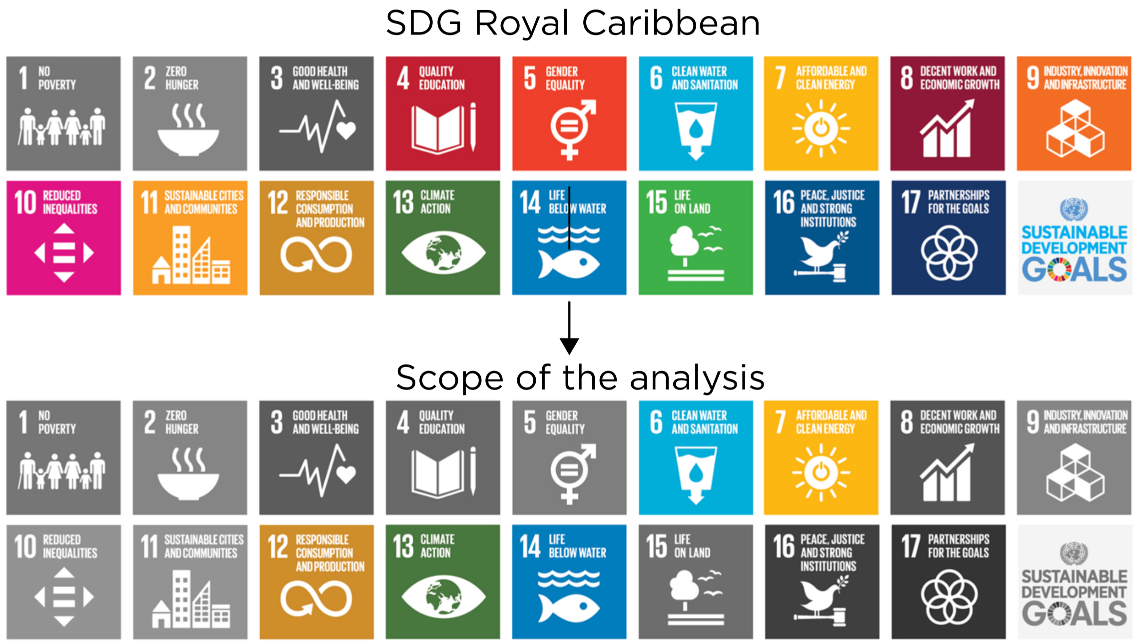

Figure 37: Selection of the UN SDG's discussed in this master thesis.

3.4.2 Goals of Royal Caribbean Cruises ltd. – Gas

Royal Caribbean strives to reduce its greenhouse gases emissions, which is also one of the 2020 goals. The intention is to reduce greenhouse gas emissions by 37% compared to the 2005 levels. This goal is already achieved before the 2020 target (Royal Caribbean Cruises Ltd., 2018c). The main contributor to their carbon footprint is the propulsion of the ship, 60% (Royal Caribbean Cruises Ltd., 2018e). Advanced Emission Purification systems are installed across 60% of the fleet which reduces the sulfur dioxide for 98% in their emissions (Royal Caribbean Cruises Ltd., 2018d; Royal Caribbean Cruises Ltd., 2018e). Next to this, also some small changes are implemented to reduce the emissions, for example, using LED light instead of incandescent bulbs to save electricity need. The UN SDG number 7; Affordable and Clean Energy is part of the gas waste stream. The Royal Caribbean states that they want to increase their percentage of renewable energy and that they want to double the improvement of their energy efficiencies (Royal Caribbean Cruises Ltd., 2018d). To increase the percentage of renewable energy Royal Caribbean is developing a wind farm in Kansas to offset their carbon emission. This wind farm will consist of 62 wind turbines which will generate around 760,000- megawatt-hour per year over a 12-year agreement. This is around 10-12% of Royal's direct emission (Royal Caribbean Cruises Ltd., 2018e). Royal Caribbean is taking the next step in using renewable energy by implementing fuel cells and LNG as prime power for their ship's hotel load (Royal Caribbean Cruises Ltd., 2018e). Next to this the newly built ships are more energy-efficient than the previous ones. The techniques from the new ships are implemented on the existing fleet. A Fleet Optimization group watches the outcome of a trillion measure points on the ship to find out the most efficient fuel operation possible. It does not only look at the weather forecast to optimize the propulsion system, but it also looks at how the galleys and staterooms can be more energy efficient. The UN SDG number 13; Climate action falls also under the gas waste streams. With this goal, the royal Caribbean wants to improve her education and awareness on climate change, promote mechanisms for climate change-related planning, and strengthen resilience to natural disasters. They educate around 5 million guests about ocean conversation and climate change through their partnership with the WWF. The company also joined the we are still in movement, which is a coalition of companies, cities, states, and universities who pledge to commit to the Paris Agreements (Royal Caribbean Cruises Ltd., 2018e).

''We often say that what gets measured, gets better.'' (Royal Caribbean Cruises Ltd., 2018e, p. 4)

3.4.2 Goals of Royal Caribbean ltd. – fluid

Goal number 6; Clean Water and Sanitation falls under the fluid waste stream. The goals Royal Caribbean set are; safe and affordable drinking water, improve water quality and wastewater treatment, provide access to sanitation and hygiene, improve water-use efficiency, and ensure freshwater supplies (Royal Caribbean Cruises Ltd., 2018d). To improve the quality of wastewater, they use water treatment plants. These plants on the fleet of the Royal Caribbean are twice as strict as the U.S. standards. Next to this, the guests use less water onboard a cruise ship than in their daily life (Royal Caribbean Cruises Ltd., 2018d). Royal Caribbean implements water-saving technology as sink aerators, new ice makers which uses 65% less water, low-flow showerheads, water-reducing technologies in kitchens and laundry facilities, and reusing clean condensation water from air conditioning units to improve their water efficiency. The freshwater that is used onboard is made through reverse osmosis on the ship itself. This is to reduce the usage of bunkered water from local sources. Next to taking care of the water on their ships Royal Caribbean also take care of the water from the Haitian village Labadee, which is one of their private destinations. The corporation installed clothes washing stations, toilets, and showers and work together with the Pan American Development Fund to build water filling stations (Royal Caribbean Cruises Ltd., 2018d; Royal Caribbean Cruises Ltd., 2018e). Oceanographic and metrological instruments are placed on 5 ships of the Royal Caribbean fleet to measure atmospheric and ocean conditions which is important to climate change research (Royal Caribbean Cruises Ltd., 2018e).

3.4.2 Goals of Royal Caribbean ltd. – Solid

A big part of the solid waste stream can be reduced by creating awareness. That is why goal 12; Responsible Consumption and Production is part of the solid waste streams. Royal Caribbean set several sub-goals which fall under this. An important aspect is to know and manage the supply chain from the beginning till the end which is one of the eight 2020 goals; sustainable sourcing. Royal Caribbean wants to use sustainable and natural sources and promote public procurement practices (Royal Caribbean Cruises Ltd., 2018d). Next to this, they want to reduce their waste and implement responsible management for chemicals and other waste. Finally, they want to monitor sustainable tourism, promote the sustainable lifestyle under their guest, and report this sustainable practice. Royal Caribbean is taking several actions to implement these goals into its management. The supply chain can be divided into 4 stages; sourcing, transport, use, and end-of-life. In all these stages steps need to be taken to reach a circular economy. To improve the first stage of the supply chain royal Caribbean

wants to work with sustainable products. One of the 2020 goals is working with sustainable seafood (Royal Caribbean Cruises Ltd., 2018c). The ambition is that 90% of the wild-caught seafood is from MSC certified fisheries and 75% of the farmed seafood is from ASC-certified farms by 2020. Together with WWF Royal Caribbean supports fishery improvement projects (Royal Caribbean Cruises Ltd., 2018e). Next to using sustainable seafood, Royal Caribbean uses cage-free eggs (2022 goal), GAP-certified sources for their whole broiler chicken (2024 goal), and pork from gestation crate-free producers (2022 goal) (Royal Caribbean Cruises Ltd., 2018e; Royal Caribbean Cruises Ltd., 2018g). They analysed the key food commodity categories to find out which commodity has the highest environmental impact. Coffee, tea, and sugar are the three chosen commodities that Royal Caribbean wants to improve the sustainable sourcing from, by 2020 (Royal Caribbean Cruises Ltd., 2018c; Royal Caribbean Cruises Ltd., 2018e). As can be seen from the previous examples Royal Caribbean tries to work to a circular economy (Royal Caribbean Cruises Ltd., 2018e). By using local products their carbon footprint is reduced, the quality of the products is higher and fresher, and they support the local economy of their destinations (Royal Caribbean Cruises Ltd., 2018e). The second stage is transport. Next to using local materials, Royal Caribbean tries to reduce its fuel consumption and emissions by maximizing the capacity and routing of the trucks. Before a product comes on board the environmental impact of the product is identified to minimize the impact. This is part of the third stage of the lifecycle; use. To optimize the end of life stage, Royal Caribbean tries to use products that can be recycled or reused (Royal Caribbean Cruises Ltd., 2018g).

''We have an opportunity to make choices that can extend the life cycles of products and support sustainable sourced products to achieve a circular economy.'' (Royal Caribbean Cruises Ltd., 2018e, p. 15)

Next to optimizing their supply chain Royal Caribbean also works on reducing their waste; they strive to a zero-waste journey (Royal Caribbean Cruises Ltd., 2018e). Royal Caribbean state that 80% of the waste from the ships does not see any landfill. The goal set for 2020 is that the waste to landfills is reduced by 85% compared to 2007. They are on track to achieve this goal (Royal Caribbean Cruises Ltd., 2018c). The final goal is to have a fleet that is equipped to be landfill-free. To achieve this, they use the Reduce, Reuse, Recycle model. They reduced the waste to landfill per passenger from 1.27 kilo per day to 0.23 kilo per passenger per day (Royal Caribbean Cruises Ltd., 2018e). Also, goal number 14; Life Below Water, falls within the scope of the solid waste streams. This includes sub-goals as sustainable

fishing, increasing scientific knowledge of ocean health, reducing marine pollution, conserving coastal areas, and protect and restore ecosystems. Actions that are taken to protect the life below the sea are banning plastic straws, stirrers, and picks and replacing them with sustainable alternatives. The plastic reduction is one of the 2020 goals set by the Royal Caribbean (Royal Caribbean Cruises Ltd., 2018c). They started with a straw on-request program and now they are plastic-free. Royal Caribbean Ltd. removed 77 million plastic straws from their supply chain and the focus for 2020 lies in searching alternatives for packaging. The number of plastic bags and water bottles needs to be reduced (Royal Caribbean Cruises Ltd., 2018e). Next to this, special rating systems are implemented to reduce the threat of hazards of chemicals by improving the tracking and storage of these products. All the sustainability practices are reported since 2008 and go to the GRI since 2013. GRI is the first standard that is globally used to report standards for sustainability.
As last step to prevent solid waste from entering the environment, Royal Caribbean wants to educate its guest. They have a 5-year partnership with the WWF and together they made educational materials to educate and stimulate their guest in protecting the ocean (Royal Caribbean Cruises Ltd., 2018e).

Conclusion
This chapter answers sub-question 3: ''What are the existing sustainability goals and actions Royal Caribbean Cruises Ltd. takes?''. These actions and goals are subdivided into their waste stream, gas, fluid, or solid.

Royal Caribbean strives for reducing its greenhouse gases by 37% compared to the 2005 levels. This is something they already achieved before the 2020 target. Due to the advanced emission purification system, sulfur dioxide emission is reduced by 98%. Also, UN SDG goal number 7: Affordable and Clean Energy is a goal Royal Caribbean strives for. They want to increase their use of renewable energy and double their energy efficiency. The fleet optimization group finds the most efficient fuel operation to reduce their energy use. Next to this they create awareness and educate their guest about climate change which falls under the UN SDG goal 13: Climate actions.

Next to improving its gas waste stream Royal Caribbean also want to improve its fluid waste streams. UN SDG goal 6; Clean Water and Sanitation is part of the fluid waste streams. The goals they have set are: providing safe and affordable drinking water, improve their water quality and wastewater treatment systems, provide access to sanitation and hygiene, improve water-use efficiency, and

ensure freshwater supplies. Examples of actions taken are the wastewater treatment system that produces water that is twice as clean as the U.S. standards, installing water-reducing technologies, and use fresh water that is made through reverse osmosis from the ship itself. Next to this, special oceanographic and metrological instruments are placed on 5 ships to contribute to the research of climate change.

Goal 12; Responsible Consumption and Production contribute to the improvement of the solid waste stream. Improving their supply chain is a big goal royal Caribbean strives for. They subdivide their supply chain in four stages: sourcing, transport, use, and end of life. In all these stages steps are taken to reach a circular economy. Next to this Royal Caribbean uses the Reduce, Reuse, Recycle model to reduce their waste. The goals as; sustainable fishing, increasing scientific knowledge of the ocean's health, reducing marine pollution, conserving coastal areas, and protect and restore ecosystems are part of UN SDG goal 14: Life below water. Actions, as banning plastic straws, implementing a special rating system to reduce the threat of hazards, and creating and spreading educate material to their guest, are taken to reach these goals.

It can be concluded that Royal Caribbean is working on the improvement of its waste streams. In some cases, they make already good developments. However, waste streams still end up in the environment. Figure 38 shows an overview of the taken measures by Royal Caribbean according to their waste stream.

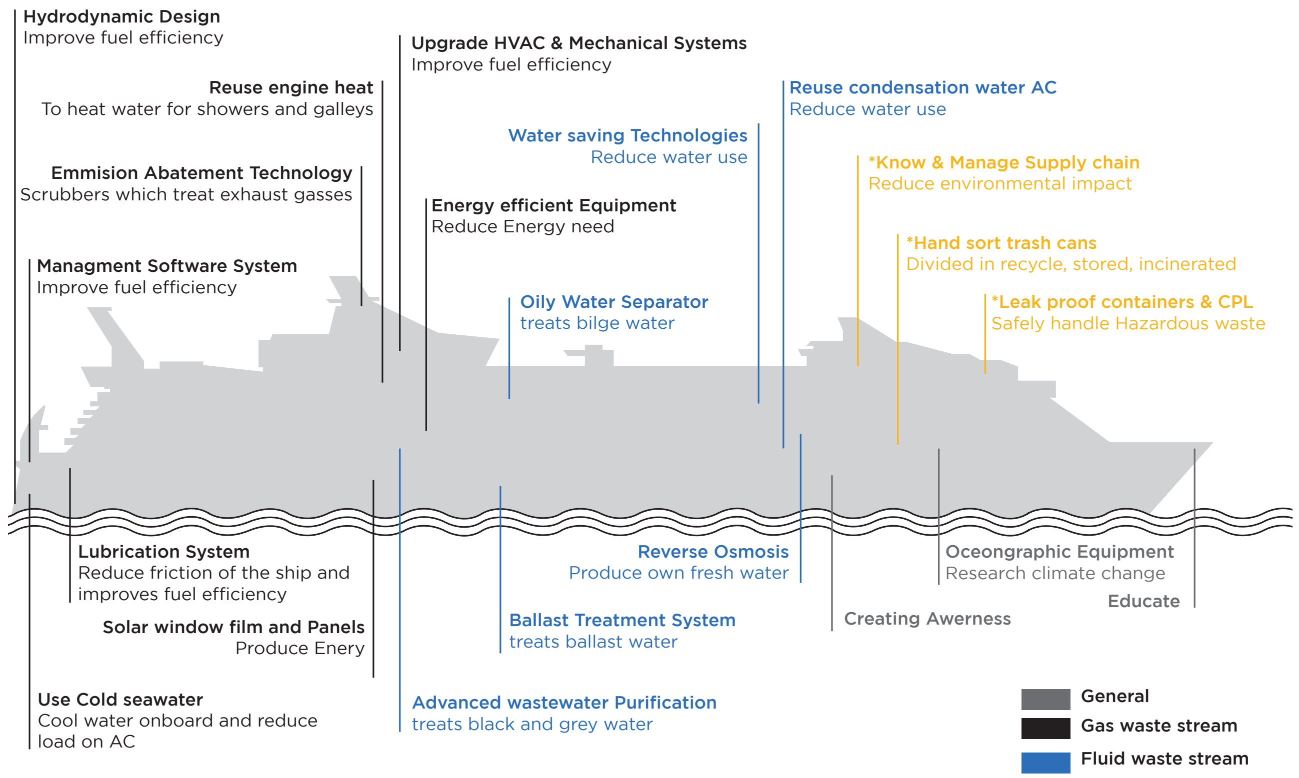

Figure 38: Measures taken by the Royal Caribbean according to their waste stream.

Figure 39: Stakeholders from Royal Caribbean Cruises Ltd.
Note. Adapted from Royal Caribbean Cruises Ltd (2018e), p. 47.

3.5 Stakeholders

3.5.1 Introduction

Almost every listed company comes in contact with stakeholders. Stakeholders have an interest in the company which can affect or be affected by the business. This also applies to the cruise industry. Royal Caribbean (2018e) works together with several stakeholders who have a direct and indirect effect on the business, see figure 39. This chapter describes the different types of stakeholders and their roles.

3.5.2 Stakeholders Royal Caribbean Cruises ltd.

As can be seen in figure 39, there are 11 parties Royal Caribbean is working with: Travel Agents, Research Institutions, Shareholders, Guests, Employees, Destinations, Communities, Suppliers, Non-Governmental Organisations, Policy Makers and Industry Associations.

Working close together with travel agents is one of the reasons the cruise industry started to grow. Travel agents are responsible for 98% of the bookings. Between 1972 and 1991 the affiliated travel agencies grow from 7,900 to 19,952 (Perry Hobson, 1993). The collaboration between cruise lines and travel agencies is beneficial for both parties. The benefit for the cruise industry is that more cabins are booked through travel agencies. Travel agencies on the other side generate a higher profit when selling a cruise vacation. When someone books a cruise through a travel agency 85-90% of the vacation is immediately paid, compared to 40-45% for a land-based trip. This leads to higher commissions for travel agencies (Perry Hobson, 1993).

The second stakeholder group is the research institutions. Royal Caribbean is working together with the University of Miami because they believe research is the base of making improvements (Royal Caribbean Cruises Ltd., 2018e). With grants from Royal Caribbean and labs on boards of several cruise ships research is conducted to oceanographic and atmospheric data which is part of climate change research. They developed OceanScope which tracks and maps unique intersections of currents and simultaneously gathers data that is needed to predict El Niño and La Niña. There is also a collaboration with the Regional Maritime University (RMU) in Accra, Ghana where cadets are trained (Royal Caribbean Cruises Ltd., 2018e). A dockyard is next to the university a place with a lot of knowledge and research. Dockyards work closely together with cruise lines to design new ships and continue their research to make innovation possible. These research institutions are needed to help Royal Caribbean and set the next step to sustainable cruising.

The third group of stakeholders is the shareholders also

known as a stockholder. This can be a person, company, or institution that owns a share of the company's stock. This means that they have bought a percentage of ownership in the company. Arne Alexander Wilhelmsen owns the largest part of 12.0% and is part of the board and independent director of Royal Caribbean Cruises Ltd. Other shareholders are The Vanguard Group, Inc. an investment company with 8.67%, Capital Research & Management Co. a financial service company with 5.51%, and Osiris Holdings, Inc, an investment company with 5.38% (MarketScreener, n.d.). Royal Caribbean Ltd. needs these shareholders to make investments that are needed to maintain the company and ensure growth. The shareholders invest in Royal Caribbean for their own financial purposes.

The fourth group of stakeholders is the guests where the company works with every day. Without the guests, the cruise industry would not be growing as it is today. Royal Caribbean Ltd. wants their guest to be happy and enjoy their cruise to make sure that they come back. With electronic on-board surveys, they gather the opinion of their guest to make sure everything was as desired and if not where they should improve (Royal Caribbean Cruises Ltd., 2018e). They inform the guests through their website, social media, and customer hotlines. With onboard marketing and guest loyalty programs, they try to lure them back into another cruise (Royal Caribbean Cruises Ltd., 2018e). The guest needs the cruise company to go on this type of vacation and the cruise company needs the guest to deliver the vacation. Both parties influence each other. The guest has the power to show their wishes and if the cruise company does not comply with these wishes they will leave to another cruise line. Due to this, the company needs to improve every day otherwise they lose their guests.

Next to the guests, the second group of stakeholders on board is the employee which forms the fifth stakeholder group. Royal Caribbean (2018e) states that the employees are for a big part responsible for the memories of their guests and form the front line of their company. Without their employees and the effort, they put into their work everyday cruise vacations would not exist. A big range of employees works on cruise ships: housekeepers, cooks, entertainment staff, captain, officers, engineers, doctors, nurses, mechanics etcetera. To make sure this group is content with their work employee engagement surveys and performance and career development reviews are held (Royal Caribbean Cruises Ltd., 2018e).

The sixth stakeholder is the destinations. The port of the destination is the connection between the cruise ship and the in-land cruise attractions (Esteve-Perez & Garcia-

Sanchez, 2014). If a destination is chosen as a port depends on five factors. The first factor is if the port is a homeport or just a port of call. Homeport is a port where passengers embark and disembark from the ship and where supplies are loaded. A port of call is just a destination port where the ship will be around 5-24 hours. Depending on the itinerary one of the two types of ports is chosen. The second aspect is that every port of call has a different type of tourist hinterland. There are 5 categories: the black hole, where the port city has so many attractions that the passengers do not leave the city. The semi-black hole, where most passengers stay in the city and a niche of passengers goes to attractions further away. The third category is balanced, where there is an equal share of attractions in the city and in the hinterland. The fourth category is the semi-gateway, where most activities are outside the city but the city itself has a few attractions worth seeing, and the last category is the gateway where the city is just a transport link for shore excursion into the hinterland (Esteve-Perez & Garcia-Sanchez, 2014). The amount of activities and their place relative to the port is something to consider when a cruise line is making their itinerary. Next to the different types of hinterlands, there can also be a difference in the management of the port. There are four types of ports, the public service port, the tool port, the landlord port, and the privatized port. The public interest is mostly represented in the public and tool port. The landlord port tries to combine the public and private interest and the private port focus mostly on private shareholders. The issue for the ports is to create a good partnership with the cruise lines without subsidizing their private interest with public money. Cruise lines are collaborating and making their own terminals. These public and private partnerships work as a tool to generate money for the infrastructure and share the risk between the public and private sectors (Esteve-Perez & Garcia-Sanchez, 2014). Another aspect is the passenger fee a ship must pay, which differs in every port. When a ship can dock a few miles further with a lower passenger fee and both cities have the same hinterland the ship will dock at the port with the lowest fee. This is something to take into consideration as a destination. Also, the capacity of berthing is a factor that is considered to decide if the specific destination is chosen or not. Is the quay long enough, how many cruise ships can dock simultaneous and are there possibilities to tender? (Esteve-Perez & Garcia-Sanchez, 2014). When a destination decides to work together with cruise ships, they take a big responsibility. Before a cruise ship can dock the port has to meet several safety criteria. It will also limit the ports' cargo activities. These are all factors the destination and the cruise lines must think and agree on before they establish a partnership.

The seventh stakeholder group is the communities. Royal Caribbean Cruises Ltd. (2018e) states in its sustainability report that they are responsible for the communities they visit. Since 2014, they work with local communities in the Galapagos to support for example local farmers through organic agriculture activities and create clean and safe processing plants to store, prepare, and sell their daily catch fish. Next to this, the Royal Caribbean support their employees to help their communities by Volunteer Time Off and employee volunteer days and campaigns. They also organize the G.I.V.E day where the employees, families, friends, and business partners help communities where they live and work. An example of this is the beach cleanup. They also help with disaster relief, from carrying relief suppliers to evacuating people (Royal Caribbean Cruises Ltd., 2018e). Helping their communities is in the first place a social act of the Royal Caribbean as well as an investment in their destinations.

The eighth group of stakeholders is the suppliers. Royal Caribbean strives to work with suppliers that are committed to quality, safety, innovation, sustainability, and customer satisfaction (Royal Caribbean Cruises Ltd., 2018e). Royal Caribbean has a special Supplier Registration Portal where suppliers can learn about their business. All the suppliers that are interested to work with Royal Caribbean must comply with the RCL's Supplier Guiding Principles which states their loyalty to fair labour, ethical business conduct, and environmental protection (Royal Caribbean Cruises Ltd., 2018e). A cruise ship cannot sail without their suppliers, think about the needed food and beverage, fuel, technical products, and hotel supplies as towels and toilet paper. In short, everything that is needed in a city. A supplier must be willing to meet these standards to work with Royal Caribbean. If so, then they have a costumer that is frequently in need of their supplies.

The Royal Caribbean also works together with Non-Governmental Organisations which is the ninth group. They work together with the WWF, United way, and Toys for the Poor (Royal Caribbean Cruises Ltd., 2018e). Part of the profit they generate is put into these non-governmental organizations as a social deed. In the first place, Royal Caribbean does this to help the chosen organization. The beneficial side effect is that by doing this they link their name to something ''good'' what helps with marketing. Non-Governmental Organisations are very happy with this collaboration because they get the needed money.

The tenth stakeholder group is the policymakers. This group of stakeholders is responsible for the legislation. This includes all local, national, and international organizations regarding policy. Tours on boards of the ship are given to qualified members who check for example the technical installations and give recommendations where needed (Royal Caribbean Cruises Ltd., 2018e). The industry associations are indirectly connected to this because, as mentioned before, the IMO takes responsibility for international legislation. The Royal Caribbean needs to work closely together with this group of stakeholders because if they do not cooperate, they can be banned from certain destinations if they do not comply with the legislation. Good collaboration is needed to ensure that the cruise runs smoothly.

The eleventh and last stakeholder group are the industry associations (Royal Caribbean Cruises Ltd., 2018e). This includes CLIA which is directly connected to the Royal Caribbean by representing their interest. Royal Caribbean has similar interests as other cruise lines. Close cooperation is needed with CLIA and these other cruise lines to make sure that CLIA can represent all their interests. Next to this, IMO is an important stakeholder, cruise ships fall under the passenger ships and must work closely together with the IMO. Without this collaboration, Royal Caribbean will not be aware of the latest legislation which means that they cannot dock in certain ports. IMO needs to work with cruise lines to know their standards and possibilities to innovate. Another industry association is the dockyards. Without this group of stakeholders, it is not possible to expand the fleet. Close collaboration is needed to know each other's wishes and possibilities.

Conclusion

This chapter answers sub-question 4: ''Who are the involved stakeholders?''. Royal Caribbean Cruises Ltd. works with 11 stakeholders; Travel Agents, Research Institutions, Shareholders, Guests, Employees, Destinations, Communities, Suppliers, Non-Governmental Organisations, Policy Makers, and Industry Associations. These stakeholders have a direct and indirect effect on the development of the cruise industry. The relation between Royal Caribbean and the stakeholder are all different. However, they have one thing in common; they need each other to co-exist. For example, guest needs to Cruise Industry to go on their holiday and the cruise industry need the guest to deliver their product. If the wishes and needs of the guest change, the cruise line needs to change with it otherwise they will lose their guests.

4 Master Planning

4 Master Planning

The master planning starts with the fifth sub-question: “what are the future scenarios for the cruise industry?”. After this is clear, research is done into the vision and goals of sustainable future cruise ship. Before the final sub-question can be answered, an elaborated literature research is done into the current treatment techniques and new techniques. These three sub-questions form together the master planning, with the roadmaps as final product.

4.1 Future Scenario’s

4.1.1 Introduction

The definition of scenarios, according to Van den Dobbelsteen et al. (2019): ‘’Scenarios are developments outside the influence of the actors involved, which define the boundary conditions within which the city can develop itself.’’ (p.29). These scenarios need to be defined and analyzed before a future vision for the cruise industry can be described.

4.1.2 Scenario methods and tourism

Scenarios are made as a tool to talk about alternative future environments when there is a lack of empirical data (Schwartz, in Formica & Kothari, 2008). In the literature, several methods can be found, for example, the Special Report on Emission Scenarios, also called SRES scenarios. These scenarios are divided by Global vs local and Environment vs Economic aspect which leads to scenario A1, A2, B1, and B2, see Figure 40 (Arnell et al., 2004).

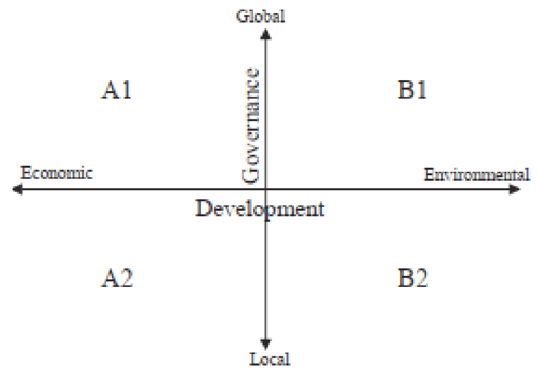

Figure 40: SRES scenarios.
Note. Reprinted from Arnell et al. (2004) p. 5.

4.1.3 STEEP

Several methods can be used to describe the future scenarios of the tourism industry. However, all these scenarios are influenced by certain aspects. For example, the environment, and in particular, climate change is connected to the tourism industry and influences the future developments of this sector. The quality of the natural environment as weather conditions (snowfall, sun, rain), wildlife, and biodiversity influence the flow of tourism (Gössling, Hall, Peeters, & Scott, 2010). The environment is not the only aspect that influences the future of tourism. The STEEP model can be used to categorize trends and forces of change. STEEP is an acronym that stands for social, technological, economic, environmental, and political. These aspects can be found back in the discussed scenario method. Nordin (2005) wrote a book called Tourism of Tomorrow where she used the STEEP model to find out which factors may influence the tourism industry in the future. She asked a group of Swedish experts to select the factors that they believe would most likely impact the tourism industry (Nordin, 2005). A selection of these aspects is made and can be found in table 10.

Table 10
STEEP Factors

Social	-Increased global average life length/ older population
	-Crimes and terrorism (social unrest)
	-Global social networks
	-Travelling as self-fulfilment
	-The economic situation, that is the amount of money available that allows us to prioritize travelling
	-Epidemics
	-Values and desires
	-Trendy and popular destinations will be increasingly crowded
Technological	-Low-price transportation
	-Energy supply/ access to oil & gasoline
	-Alternative fuels, means of transportation managing the pollution levels of the future
	-More effective aeroplanes/ better performance
	-High-speed trains
	-Sun-driven vehicles
	-The combination of authentic & virtual experiences
	-Congestion in general & capacity limitations in the air
Environmental	-Climate change/ global environmental changes
	-Environmental and nature catastrophes
	-Global warming and the decreasing ozone (affecting skin cancer and people's willingness to be in the sun, in the long term affecting choice of destination & activities undertaken)
	-An increasing customer awareness/ the importance of ecological consideration
	-Increased environmental demands on the airlines
	-Transports are affected by the Kyoto agreement & rising oil prices resulting in more expensive trips
	-Weather extreme may increase (for instance storms and heat waves)
	-The risk of pandemics like SARS (and COVID19)
Economic	-Value for money
	-Economic prosperity in the home country/ economic situation
	-Increased global prosperity
	-Inexpensive and effective infrastructure such as low-cost carriers
	-Number of days off
	-Oil prices
	-Increased knowledge about the economic situation in the industry
Political	-Global terrorism/ threats
	-Environmental politics (the Kyoto agreement, tax on air-fuel)
	-Demographic changes related to economic possibilities affected by for instance the retirement system (can we afford to travel)
	-Increased equality
	-The increasing liberalization in many countries affecting in- and outbound travel flows
	-A recognition by political actors of the tourism industry as an important economic driver in regions and destinations.
	-Global democratization

Note. Data retrieved from: Nordin, (2005).

4.1.4 Future Scenario's – General

In this research, the SRES scenarios, A1, A2, B1, and B2 are used as the base for the alternative future scenarios.

Scenario A1 is a world that has high economic growth, new efficient technologies that are fossil intensive are introduced, and there is a growing global population until mid-century which declines thereafter. In this scenario, there is convergence among regions and growing interaction between cultures (IPCC Working Group III, 2000).

Scenario A2 is a world that strives for the conservation of local identities and self-reliance. The population is growing continuously, economic developments are regional, and technological growth is slower than in the other scenarios (IPCC Working Group III, 2000).

Scenario B1 has the same growing population as A1. The economy changes into an information economy. This world strives to reduce the material intensity and introduce clean and efficient technologies. The focus lies on finding a solution for the economic, social, and environmental sustainability (IPCC Working Group III, 2000).

Scenario B2 has a growing population which is slightly less than A2 and an intermediate level of economic growth. This world focusses on a local solution for economic, social, and environmental sustainability. There is a diverse technology range due to this local focus (IPCC Working Group III, 2000).

4.1.4 Future scenarios - The Cruise industry

Scenario A2 can be seen as the ''Autarky'' scenario, see figure 41. In this world, countries do not work together but focus on local identities. The economic developments differ per location. Factors from the STEEP model that can be connected to this scenario are for example; values and desires (Social), energy supply/ access to oil & gasoline (Technological), environmental and nature catastrophes (Environmental), global warming and decreasing ozone (Environmental), increasing weather extreme (Environmental), value for money (Economic), and oil prices (Economic).

Figure 41: Autarky Scenario.
Note. Adapted from Davi & Shellgren (2019).

In this scenario, cruise ships do not cross continents due to the local focus. Continents do not work together and mainly focus on their economy. Due to this the oil price differ per country. Some countries pay the ultimate price because they must import oil and gasoline. This makes it difficult for the cruise industry to operate because it has to deal with a lot of different local circumstances. This could lead to special cruise line hubs all over the world that have the same circumstances. Due to the focus on the economy instead of the environment, there is no research done on environmental sustainability. This leads to environmental and natural catastrophes like tsunamis and hurricanes which results in circumstances ships cannot sail in. Next to this, people are avoiding the sun due to climate change and ozone depletion. This will affect the choice of destination and activities. The private islands and beaches of the cruise lines in the Caribbean will become less popular or avoided because these destinations are focussed on enjoying the sun. Indoor activities are becoming more popular. The cruise industry has a hard time to exist in this scenario due to the local focus, rising oil price, bad weather conditions, and the changed values and desires of the people. There is no wish for a vacation type that crosses borders. The cruise industry should drastically change to a local, indoor vacations resort with its hub in each country. But what is then the difference between an all-inclusive resort and a cruise ship when the travelling part is taken away?

Figure 42: Technical Reality Scenario. Note Adapted from i.redd.it (2018).

Scenario A1 can be seen as the ''Technical Reality'' scenario, see figure 42. Countries work together in this world but focus on economic prosperity. Factors from the STEEP model that can be connected to this scenario are for example; global social networks (Social), the economic situation (Social), energy supply/ access to oil & gasoline (Technical), more effective aeroplanes (Technical), high-speed trains (Technical), environmental and nature catastrophes (Environmental), global warming and the decreasing ozone (Environmental), increasing weather extreme (Environmental), value for money (Economic), economic prosperity in the home country (Economic), increased global prosperity (Economic), and oil prices (Economic).

In this scenario, cruise ships sail around the world without the need for their hubs due to the global focus. Continents work together and mainly focus on economic growth. There is almost no focus on improving environmental sustainability. The natural resources are exhausted due to the maintaining focus on the economy. These resources are used to create the newest technological innovations. Due to this, the oil price increased together with the price of all other raw materials. Cruise ships have more advanced technologies onboard as robots and VR rooms but struggle with expanding their fleet due to the limited amount of resources. Cleaning the cabins, doing the laundry, and shaking cocktails are all activities done by robots onboard due to the increased global prosperity and technological improvement. In this world, the focus lies on the economy instead of the environment. There is no research done on environmental sustainability because of this. As in scenario A2, this has led to circumstances ships have trouble sailing in. The private island and beaches from the cruise lines are becoming less popular due to climate change and ozone depletion. Indoor activities are becoming more popular

and the cruise industry can offer this due to the new technologies. Hard to reach places can be seen by using VR without the need of being outside. There are the wish and the opportunity to travel to and with friends from across the globe due to the big social network and economic prosperity.

Figure 43: Ecological Synergy Scenario. Note. Adapted from GIZMODO (2015).

Scenario B1 can be seen as the ''Ecological Synergy'' scenario, see figure 43. Countries work together to reduce climate change and create efficient technologies that are not less bad, but good for the environment. Factors from the STEEP model that can be connected to this scenario are for example; increased global average life length/ older population (Social), alternative fuels (Technological), the combination of authentic & virtual experiences (Technological), increasing customer awareness/ the importance of ecological consideration (Environmental), rising oil prices (Environmental), increased knowledge about the economic situation in the industry (Economic), increased global prosperity (Economic), global democratization (Political), environmental politics (Political), and increased equality (Political).

In this scenario, cruise ships do not strive to be less bad or better than aeroplanes, trains, or cars. The cruise industry strives to contribute to the environment their cruise ships sail in. Instead of not contributing to the pollution of the sea and air by using alternative fuels ships take the next step and clean the seas they sail in by capturing plastics and CO_2. Ships could become fully circular. Besides contributing to the environment when the ship is in operation the construction of the ship is biobased due to new techniques. Governments are willing to invest in technological innovations that contribute to a sustainable vacation, due to environmental politics. Customers are also willing to spend more on a sustainable vacation due to increasing customer awareness. The global approach in this scenario leads to a convergent world. Cruise ships are allowed to sail over the world and connect continents and people.

Figure 44: Sustainable Communities Scenario. Note. Adapted from Wallace (2016).

Scenario B2 can be seen as the ''Sustainable communities'' scenario, see figure 44. In this world, countries do not work together but focus on improving their environmental sustainability. Factors from the STEEP model that can be connected to this scenario are for example; values and desires (Social), energy supply/ access to oil & gasoline (Technological), alternative fuels (Technological), the combination of authentic & virtual experiences (Technological), increasing customer awareness/ the importance of ecological consideration (Environmental), increased knowledge about the economic situation in the industry (Economic), oil price (Economic), and environmental politics (Political).

In this scenario, cruise ships do not cross continents due to the local focus. Continents do not work together and mainly focus on improving their environmental sustainability. The cruise industry strives as in scenario B1 to contribute to the environment their ships sail in. Actions, as cleaning the sea and air and construct ships from sustainable materials, can also be found in this scenario. The oil price is very high due to the local focus. However, this has less influence on the cruise industry than in scenario A2 because new sustainable energy sources are used on cruise ships. Multiple cruise line hubs can be found across the world, to solve the problem of the different local circumstances due to the local focus. The cruise industry focuses on a combination of authentic and virtual experiences to find a balance between local and global wishes, and sustainability.

4.1.4 Future scenarios – Anticipation

It can be seen that in most scenarios the oil price is rising. In scenario A2 and B2 due to the local focus and in scenario A1 due to scarcity. The cruise industry could anticipate by doing research into alternative fuels today and limiting their need for oil. Scenario B1 is the most optimal scenario that can happen for the cruise industry. In this scenario, there are no limitations by the environment as natural catastrophes, and due to the global focus, there is no need to set up special hubs all around the world. The cruise industry must protect the environment because this is a key aspect of selling their product. A healthy environment is needed to sail across the sea and to attract people to new beautiful, healthy places. This would not be possible when people avoid the sun due to ozone depletion and seas cannot be sailed due to tsunamis and storms. There is a local focus around the world in scenarios A2 and B2, because of this, the cruise industry created local hubs. They can anticipate by talking to the local governments they visit. They could make agreements about some standard circumstances cruise ships need and start a collaboration. This collaboration between the cruise industry - local government (or harbour) could also contribute to making cruising more sustainable. Scenario A1 focusses on new technical innovations which leads to the scarcity of natural resources. Due to this the cruise industry has a hard time expanding its fleet. Cruise lines should already think about if there is the need to expand their fleet and if there is perhaps another way which not includes the use of scarce natural materials. It is smart for the cruise industry to invest in sustainable fuel, a sustainable environment, and in a collaboration with the local governments and harbours regardless of the scenario.

Conclusion

This chapter answers sub-question 5: ''What are the future scenarios for the cruise industry?''. To answer this question the SRES scenarios and the STEEP factors are combined to describe four alternative future scenarios. The distinction between the scenarios is made through the different focus on Global vs Local and Economic vs Environment. The four scenarios are called: Autarky (A2), Technical Reality (A1), Ecological Synergy (B1), and Sustainable communities (B2), see figure 45. The cruise industry has a hard time in the Autarky scenario. Due to the local focus cruise ships must deal with a lot of different circumstances and high oil prices. Also, the economic focus instead of the environmental focus makes it difficult for cruise ships to sail because of the change in environmental circumstances. In the scenario called Technical Reality, the cruise industry is also challenged by the bad environmental circumstances due to the economic focus. Technological progress is at the expense of natural materials. Cruise ships have more advanced technologies onboard but struggle with expanding their fleet due to the limited amount of resources. There is a big wish to travel due to the growing social networks and the economic prosperity of people. In the scenario called Ecological Synergy, the cruise industry contributes to the environment their ships sail in. Governments are willing to invest in technological innovations that contribute to a sustainable vacation and customers are also willing to spend more for a sustainable vacation. Cruise ships can easily sail around the world due to the global focus and connect continents and people. In the fourth scenario, called Sustainable Communities cruise ships do not cross continents and cruise line organizations have created special hubs around the world due to the local focus. Cruise ships are not less bad but good for the environment in this scenario by leaving the places they visit cleaner than they found it.

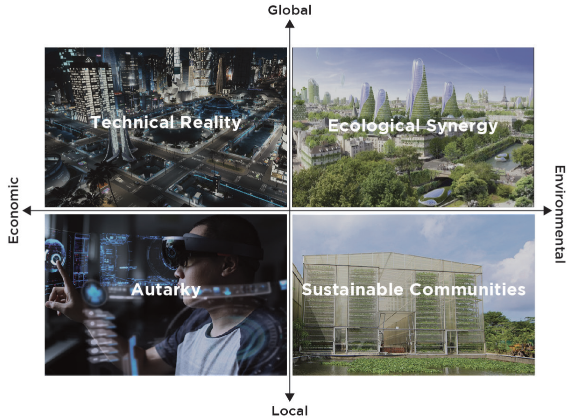

Figure 45: Future scenarios in SRES model. Adapted from i.redd.it (2018), GIZMODO (2015), Wallace (2016), and Davi & Shellgren (2019).

Scenario B1, Ecological Synergy, is the most optimal scenario for cruise ships. However, they can already anticipate on the scenarios by investing in sustainable fuel, a sustainable environment, and in a collaboration with the local governments and harbours regardless of the scenario. When possible, cruise ships could also think about new ways of building their ships without the need for using natural materials. By doing this today they can make sure they still exist in the future.

4.2 Sustainable Cruise Ship

4.2.1 Introduction

It is important to set and describe the vision of the quality of cruise ships in the future. This includes climate goals and additional sustainability objectives according to Van den Dobbelsteen et al. (2019). Next to this, the quality of life on board should also be considered. This chapter starts with a brief explanation of the history of cruise ships and the change of the facilities offered onboard. Then the three levels of sustainability are explained. The chapter ends with the vision of a sustainable cruise ship.

4.2.2 History of Cruising

The first-ever cruise ship was called; Prinzessin Victoria Luise. The ship was launched on June 29, 1900. It was made for wealthy travellers and looked more like a private yacht than a commercial vessel. Albert Ballin can be seen as the founder of cruising. He saw that it is impossible to go on ''excursions'' -the early name of cruising- with the existing ships and gave the order to build the Prinzessin Victoria Luise. She consisted of 120 first-class cabins which were very luxurious. Besides the cabins, there was a library, a gymnasium, a darkroom for photo development, and multiple dining venues to choose from (Grace, 2010; Wilde, 2018). During world war I and world war II the cruise liners were transformed into troopships. After the war, the cruise industry had a hard time because of the passenger jet service which was quicker to travel from A to B. The tv show called The Love Boat made cruising popular again. Viewers could see the lounges, dining rooms, swimming pool area, etcetera. In the nighties cruising was a vacation for elderly people and honeymooners. Today, cruise line organisations as Royal Caribbean and Carnival added more facilities to entertain their guest, including the younger ones (Resolve Maritime Academy, 2018).

4.2.3 Principle of Cruising

The main principle of cruising is to bring people from destination A to destination B of their holiday. In contrast to flying this does not have to be as quick as possible. People should be able to entertain themselves on the ship and enjoy their holiday. Basic facilities as a cabin to rest and clean yourself, a restaurant to eat and drink and entertainment should be provided. These facilities were already on board of the first cruise ship. However, the number of entertainment facilities and dining venues increased over time. See appendix B for a complete list of facilities on board of the Empress of the Seas which is built in 1990 and the facilities on board of the Symphony of the Seas, the largest cruise ship in the world, which is built in 2018 (Royal Caribbean Cruises Ltd., n.d.-c, n.d.-e). The 'basic' facilities on the Empress of the seas are also found on the Symphony of the Seas. Where the Empress just has the main dining room, the buffet (windjammer) and 1 themed dining venue the Symphony has the main dining room, the buffet, and 15 other themed dining venues. The same applies to the entertainment facilities. The entertainment facilities on board of the Empress are the pool, casino and theatre.

The Symphony on the other hand, has 3 pools, casino, theatre, indoor surf simulator (Flowrider), zipline, an ice rink and several other entertainment areas. The expansion of facilities is needed because of the increasing number of passengers. The Symphony of the Seas has a maximum capacity of 6,680 passengers and the Empress of the seas 1,853 passengers (Royal Caribbean Cruises Ltd., n.d.-c, n.d.-e). This means that more people should be fed and entertained. The cruise industry did this by implementing a varied range of restaurants and entertainment farcicalities instead of only expanding the existing facilities. More entertainment activities are added to entertain and attract families with younger children. Some activities are perhaps unnecessary, but it is most likely difficult to get rid of. Cruise organisations are placing these facilities onboard to attract people to their organisation. A distinction is made between entertainment ships and luxury ships. Luxury ships do not have over the top entertainment facilities onboard because they focus on another target group.

4.2.4 Level of Sustainable cruise ships

There are multiple levels of ambition cruise ships can strive to. In this thesis, research is done into three scenarios; 1. Fully Circular, 2. Collaboration Ship & Land, and 3. Positive effect on the environment.

Fully Circular (A) means that all the waste streams generated on board of the cruise ship stay onboard. It is not allowed to send waste to land or discharge it into the sea or air. Ships need to handle their own waste. The reduce, reuse, recycle principle is used in this scenario. To make a ship fully circular an assessment of all the outcoming waste streams and their exact composition is needed.
In the second scenario (B) there is a collaboration between the cruise ships and land. This means that the cruise ship itself does not have to be fully circular, it can send parts of some waste streams to shore. This is only allowed when the harbour has special facilities to handle the waste in such a way that it is beneficial for the environment. This scenario also uses the private islands of cruise lines to make cruising more sustainable.
The third and last scenario (C) goes one step further, the cruise industry contributes to the environment their cruise ships sail in. Instead of not contributing to the pollution of the sea and air, cruise ships take the next step and help the environment.

Figure 46 shows the three sustainability levels in a graph. The horizontal line on the bottom represents the scenario when the cruise industry does not take any action at all. Number 1 represents the end goal where the cruise industry aims to be sustainable. Scenario A is trying to become fully

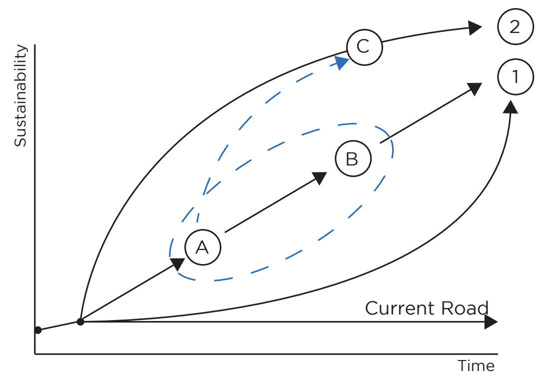

Figure 46: Relationship sustainability levels and scenarios.

circular. When this is not possible because some waste streams cannot be reused or recycled on the ship itself a collaboration with the harbour can be established (B). This will lead to a combination of scenario A and B. Number two represents a cruise ship that takes the next step and contributes to a sustainable environment. This scenario makes up for the mistakes made in the past (today).

A day on a circular cruise ship

The future cruise ships will be circular, meaning that the ship is in control over all its waste streams. The ships use multiple renewable energy sources as fuel, for example, solar energy, wind energy, and tidal energy. Cruise ships contribute to the environment they sail in by cleaning the sea and air. Plastics and other pollutants are removed from the sea as well as the pollution in the air. Next to cleaning the sea the ships also monitor the health of the sea and seabed. When needed the ship can stimulate the growth of plants and animals by discharging the needed minerals or seeds. The ships also work as a research institute and weather station, see figure 47. Nesting places for birds are not incorporated because this has a negative effect on their migration. Where possible the construction and material of the ship are changed to become fully circular. Some jobs have been taken over by robots. This includes basic work in the hold of the ship where there is no contact with people and poor working conditions, for example placing towels in a folding machine. Onboard special techniques are included in the windows to manipulate the view of the weather outside. By doing this, people will see the actual view but with good weather, if desired. Next to the current stabilizers, extra stabilizers are included in the individual decks to prevent people from getting seasick. Ships have special rooms under sea-level where people can look outside into the marine life. These rooms are also used for scientific research into the marine environment. The cruise ship is able to adjust its draft, it can go underwater or hoover above the sea when needed or wished for. There are multiple gardens onboard to unwind and greenery is used to ensure a healthy environment together with birds and animal sounds. Food that is served onboard is cultured meat and vegetables that come from the ship itself or sustainable farms. Cruise ships do not have to pay the dock in the harbour. Countries and cities want cruise ships to dock at their harbour because of three reasons. The ships generate more energy than needed and gives this to cities in need. It can take cargo on board what needs to go to another country. By doing this it can reduce the pressure on cargo ships and help the countries they visit. Finally, the ship can take waste streams from land onboard and sustainably treat this. By doing this the cruise ship changed from paying guest to collaborating friend.

Conclusion

This chapter answers sub-question 6: ''How does a sustainable cruise ship look like?''. The history of cruise ships and their facilities were first investigated. After this was clear the three scenarios a cruise ship can strive to where made: 1. Fully Circular, 2. Collaboration Ship & Land, and 3. Positive effect on the environment. These scenario's influence the way a sustainable cruise ship will look like. This chapter also describes the future vision of a circular cruise ship. In this scenario cruise ships contribute the environment they sail in and meet all requirements to give the passengers the sustainable vacation wished for.

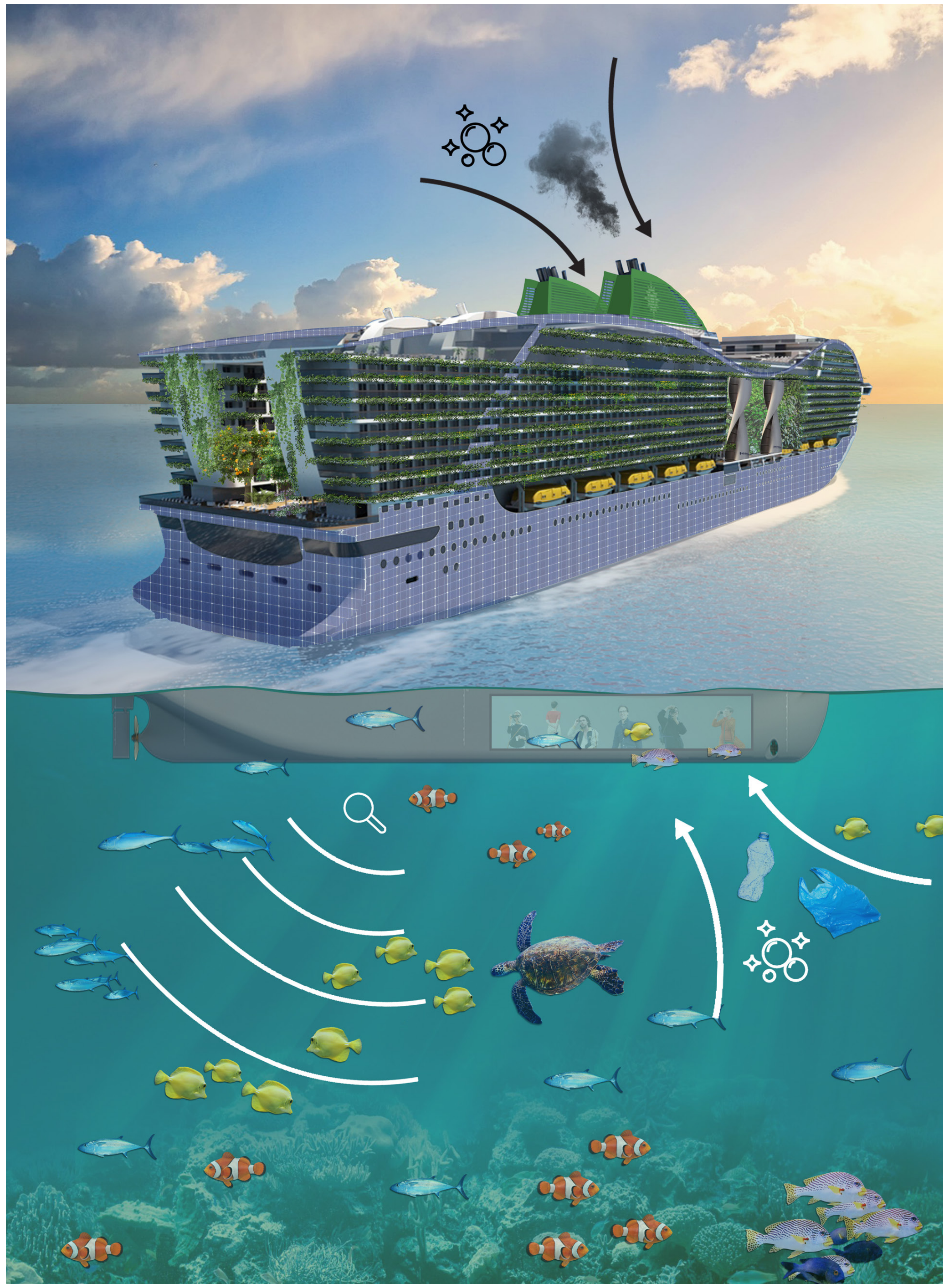

Figure 47: Impression future cruise ship.

4.3 Elaborated Research

4.3.1 introduction

More detailed information is needed about the treatment systems and new sustainable techniques before the roadmap to a circular cruise ship can be designed. It is necessary to exactly know which materials and substances enter the ship and which materials and substances leave the ship before advice can be given. After this is clear, research is done into options to improve the current waste streams. This technical chapter is made to provide this information.

4.3.2 Detailed research treatment systems

4.3.2.1 Gas waste stream

The gas waste stream is related to the type of engine and fuel used onboard the ship. There are three options to comply with the limits regarding sulfur emission; using MGO fuel, HFO fuel + scrubbers, or LNG (den Boer & 't Hoen, 2015). The diesel engine is the most common used engine in the marine industry including the fleet from the Royal Caribbean. Next to the diesel engine, Royal Caribbean has 8 ships with a gas turbine and the new Icon-Class will use LNG as the power source and fuel cells as discussed in chapter 3.2.1 Gas Waste stream – Existing Solutions. They do not focus on lower sulfur content fuel (MGO) which means they use the cheaper HFO fuel in combination with a scrubber. In this chapter further research is done into the working of the scrubber.

There are two main types of fuel, distillate fuel, and residual fuel. Residual comes from the word residue. This means that the residual fuel is the fraction of crude oil that is leftover from the refining process. High levels of sulfur, heavy metals as vanadium and nickel, ash, and high molecular weight aromatic hydrocarbons are found in residual fuel. When this HFO is combusted significant amount of carbon dioxide (CO_2), sulfur oxides (SO_x), nitrogen oxides (NO_x) and aerosols, which includes particle matter (PM) that contains organic carbon (OC), black carbon (BC), polycyclic hydrocarbons (PAHs), and heavy metals come free, see table 11 (Endres et al., 2018, p. 1; Eyring et al., 2005, p. 1). This leads to a slower and delayed combustion which could cause the emission of black carbon (American-Bureau-of-Shipping, as cited in Lack & Corbett, 2012, p. 3986). Distillate fuel is a liquid fuel that is distilled from crude oil. This type of fuel leads to a lower amount of emission per unit fuel and better combustion (Lack & Corbett, 2012, p. 3986). This is because distillate fuel does not contain residual components as nickel and vanadium (den Boer & 't Hoen, 2015).

Table 11
Composition and Emissions from HFO.

Substances in HFO	Emission HFO
Heavy metals (vanadium, nickel)	Heavy metals
Sulfur S	SO_x
Ash	CO_2
Hydrocarbons	NO_x
	polycyclic hydrocarbons
	Organic Carbon
	Black carbon
	PM

Note. Data retrieved from: Endres et al., (2018).

Around 80% of all commercial vessels sailing in the period between 2007 and 2011 used high-sulfur content fuel as HFO according to Smith et al. (2015). Most ships choose to install scrubbers instead of using lower sulfur content fuel (e.g. MGO) due to the price difference between HFO and MGO (Jiang, Kronbak, & Christensen, 2014, p. 19). The IMO allows scrubbers if the emission of sulfur is equivalent to or lower than the emission of sulfur when low-sulfur fuel is used (Endres et al., 2018, p. 5).

Scrubbers

There are three types of wet scrubbers; 1. Open-loop scrubber, 2. Closed-loop scrubber, and 3. Hybrid loop scrubber. Royal Caribbean uses hybrid scrubbers.
The open-loop scrubber uses seawater as media to react with the sulfur dioxide (SO_x). The acid ions are neutralized by the buffer capacity of seawater and sodium hydroxide, see reaction below. The scrubber mainly removes SO_2, some NO_x (NO_2) but no CO_2 (den Boer & 't Hoen, 2015; Endres et al., 2018).

$SO_2(gas) + H_2O + {}^{1/2}O_2 \rightarrow SO^{2-}_4 + 2H^+$
$HCO^-_3 + H^+ \rightarrow CO_2 + H_2O$

The wash water that comes out of the scrubber has a pH of 3, which is very low and has a high temperature. It also contains PAHs, heavy metals, and nitrate. The speed of the water flow depends on the alkalinity of seawater. This is the capacity of the seawater to resist changes in pH. If the alkalinity of the seawater is low, as in the Baltic sea, higher water flow is needed. When the alkalinity is to low, sodium hydroxide can be added. The average flow of the wash water is $45m^3\ MWh^{-1}$. It is possible to clean the sludge from the wash water which contains the PM, heavy metals, and oily residues before it is discharged into the sea. Extra seawater is added to the wash water (without the sludge) until the wash water has approximately the same amount of pH, turbidity, PAH, and nitrate as seawater. The sludge must be stored onboard and is not allowed to be discharged. However, a survey done in the EU shows that most of the time the sludge in an open-loop system is not collected and discharged into the sea (Endres et al., 2018, p. 5).

In a closed-loop system, freshwater with extra sodium hydroxide is used instead of seawater. The average flow is slower than in the open-loop system, namely 20m³ MWh⁻¹. The wash water is treated and used again. Some small fraction of the wash water (~0.1 m³ MWh⁻¹) is discharged into the sea, this is called the bleed off. This system can store the fraction in a holding tank when it is not allowed to discharge. As in the open-loop system, the scrubber sludge can be removed from the wash water. The concentrations of harmful substances in the discharge of the closed-loop system are higher than in an open-loop system. The mass flow determines how harmful it is for the environment (Endres et al., 2018, p. 5).

A hybrid system is a combination of an open and a closed-loop scrubber. The wash water can be stored and disposed to land when it works as a closed-loop system or it is discharged into the open sea when it works as an open-loop system. Half of all the ships with a scrubber uses a hybrid system, 40% use an open-loop system. This indicates that a large share of the wash water is disposed into the sea (Endres et al., 2018, p. 5).

Table 12 shows the performance of the scrubber. The table shows that the scrubber works effectively in removing SO_x, also a great part of the PM is removed but almost no NO_2. Scrubbers can only remove the particles which are relatively large in size. This means that the mass of the PM emission is reduced and not the number (Kocks, et al, as cited in den Boer & 't Hoen, 2015; Lack & Corbett, 2012).

Table 12
Performance of a scrubber.

Pollutant	Reduction
SO_x	>90%
PM	60-90%
NO_2	>10%

Note. Reprinted from; "Scrubbers – An economic and ecological assessment ", by den Boer, E., & 't Hoen, M., 2015. Retrieved from https://www.cedelft.eu/en/publications/download/1822

Even when a scrubber is used there is still the risk that nitrates, PAHs, PM, and heavy metals come into the marine environment. That is why the IMO set criteria for the turbidity, pH, PAH, and nitrate concentration of the wash water (den Boer & 't Hoen, 2015). Some heavy metals found in the wash water are not biologically degradable and therefore harmful for marine and human life. Table 13 shows the substances found in the wash water. IMO did not set any limits for the metal in the wash water. They use the turbidity of the wash water to measure the suspended solids (den Boer & 't Hoen, 2015).

Table 13
Hazardous substances in wash water

Substances in wash water
Iron, Copper, Zinc (from the scrubber)
Metals from seawater (from the sea)
Vanadium, Nickel, (from combustion)
PAH
Oil
Nitrate
Lead
Arsene
Mercury

Note. Adapted from "Scrubbers – An economic and ecological assessment ", by den Boer, E., & 't Hoen, M., 2015. Retrieved from https://www.cedelft.eu/en/publications/download/1822

Sludge is produced together with the wash water. The sludge is captured into a plastic tank till it can be disposed of to land. The produced sludge is around 0.1 to 0.4 kg/MWh and the dry weight of sludge is between 11-21%. Table 14 shows the substances and quantities which are found in the sludge of a freshwater scrubber. The sludge is hazardous due to the vanadium, nickel, and hydrocarbons. Only classified contractors may handle the sludge. Research from EMSA (in den Boer & 't Hoen, 2015) states that the sludge from scrubbers is similar to the sludge from engine rooms. However, experts say it is not smart to mix the sludge because of the low calorific value of the scrubber sludge (den Boer & 't Hoen, 2015).

Table 14
Hazardous substances in sludge

Substances in sludge	
Sulfur	max. 79 g/kg dw
THC (total Hydrocarbon)	max. 111 g/kg dw
PAH	230 mg/kg dw
Dioxins/ Furans	26 ng/kg dw
PCB	Below detection limit of 1 Qg/kg dw
Vanadium	max. 12 g/kg dw
Nickel	max. 5.4 g/kg dw
Copper	max. 1.1 g/kg dw

Note. Adapted from "Scrubbers – An economic and ecological assessment ", by den Boer, E., & 't Hoen, M., 2015. Retrieved from https://www.cedelft.eu/en/publications/download/1822

Conclusion – Gas waste stream

Most vessels use scrubbers instead of MGO to limit their sulfur emissions due to the higher cost of MGO fuel. There are three types of scrubbers in the market, open-loop, closed-loop, and hybrid-loop. Royal Caribbean uses the hybrid scrubbers on their fleet which means they can use the open-loop system at open sea and the closed-loop system in ports or emission control areas (ECA). The scrubber removes around 90% of SO_x, 60-90% PM (mass), and less than 10% of the NO_2. This means that scrubbers are effective in removing sulfur but not in eliminating all the other pollutant emissions. There are also by-products created as the wash water and the sludge which contain their own harmful substances, see table 15. The benefit of this system is that these substances do not come into the air anymore. However, there is still a possibility they end up in the sea when the sludge and wash water are not properly handled. If properly handled the sludge will be disposed to land. IMO has set some criteria for pH, nitrates, and hazardous hydrocarbons in the wash water. However, there are no criteria for heavy metals and PAHs. To prevent wash water coming into the marine environment ships should use distillate fuels as MGO or LNG. The pollution in case of an accident will also be lower in these cases.

Table 15
Substances found in HFO, wash water and sludge.

Substances in HFO	Substances in wash water	Substances in sludge
Vanadium	Vanadium	Vanadium
Nickel	Nickel	Nickel
Sulfur S	Oil	Sulfur
Ash	PAH	PAH
Hydrocarbons	Nitrate	THC (total Hydrocarbon)
	Lead	Dioxins/ Furans
	Arsene	
	Mercury	
	Iron, Copper, Zinc (from the scrubber)	

Note. Data retrieved from: den Boer & 't Hoen (2015)

4.3.2.2 Fluid waste stream

The fluid waste streams consist out of four different streams which are described in chapter 3.2.2: black water, greywater, ballast water, and bilge water. Ballast water is already treated in such a way that no harm is done to the environment. This chapter focusses on the black and grey water stream and the bilge water stream. The ballast water stream is left out.

Black and Greywater

The first part of this chapter investigates the physiochemical composition of black and grey water and gives a detailed description of the treatment system on board of the Royal Caribbean. After this is clear, research is done into the micropollutants of black and greywater.

According to the legislation, black water needs to be treated before it can be discharged into the sea. However, there is no such rule for grey water (Westhof, Köster, & Reich, 2016). The general components of black and greywater can be seen in table 16, and the physicochemical composition of black and greywater in Table 17. The legislation gives maximum numbers for BOD5, TSS, Faecal Coliform, chlorine, and a pH range see table 18. Faecal coliform is normally only found in black water. However, sometimes small amounts of faecal coliform are found in greywater when people wash their hands or clean their babies in the sink. Greywater contains oil and grease from sinks and showers which is normally not found in black water.

Table 16
General components in black water.

Black	Acc Grey	Laundry	Galley	Gdu Pulpers
Paper	Plastic	Softeners	Grease	Acids
Plastic	Hair	Lint	Fat	Fat
Solid waste	Oils	Detergent	Food waste	Food waste
Cleaners	Cleaners			

Note. Reprinted from "BLACK & GREY WATER TREATMENT SOLUTIONS USING MEMBRANE BIOREACTORS", by Bentley, A., & Ballard, I., 2007. Retrieved from http://www.dieselduck.info/machine/04%20auxiliary/2007%20MBR.pdf

Table 17
Physicochemical components in black water.

Component
Alkalinity mg/L
Ammonia Nitrogen mg/L as N
BOD5 mg/L
COD mg/L
Chloride mg/L
Conductivity uS/cm
Faecal Coliform
Hexane Extractable Material (Oil and Grease) mg/L
Nitrate mg/L
Nitrite mg/L
PH
Settable Residue mg/L
Sulfate mg/L
Temperature °C
Total Dissolved solids mg/L
Total Kjeldahl Nitrogen mg/L
Total organic carbon mg/L
Total phosphorous mg/L
Total Residual Chlorine mg/L
TSS mg/L
Turbidity mg/L

Note. Reprinted from "Graywater Discharges from Vessels", by United States Environmental Protection Agency, 2011a. Retrieved from https://www3.epa.gov/npdes/pubs/vgp_graywater.pdf

Table 18
Limits from IMO.

Parameter	MEPC 159 IMO Limit
BOD_5 (mg/l)	< 25
TSS (mg/l)	< 35
Faecal (CFU/100 ml)	< 100
Free Chlorine (mg/l)	< 0.5
pH	6.5 – 8.5

Note. Reprinted from "Graywater Discharges from Vessels", by United States Environmental Protection Agency, 2011a. Retrieved from https://www3.epa.gov/npdes/pubs/vgp_graywater.pdf

General process AWPS

Chapter 3.2.2 shows that the black and grey water streams are treated together through the advanced wastewater purification system. The cruise industry has been at the forefront of water treatment. Last few years the treatment of water received more attention in the cruise industry due to the Alaskan requirements (Bentley & Ballard, 2007). There is no standard advanced wastewater purification system (AWPS) used on cruise ships. There are multiple systems on the market that work by different processes: mechanical, chemical, and biological. These processes are often used in combination with one or the other (Koboevic & Kurtela, 2011).
Royal Caribbean has multiple AWPs from different manufacturers; Scanship, Headworks, and Evac. Evac took over the marine department of Headworks in 2014 (Headworks Bio, 2014).
The general stages of an advanced wastewater treatment system consist of four steps: 1. Filter and Holding/ mixing tank, 2. Aeration process, 3. Settlement chamber and 4. Sterilization. The first step is to filter the large particles out of the black and grey water before it comes into the first tank. Then the wastewater goes into the aeration chamber

which is filled with aerobic bacteria that clean the water. After this, the water goes into the settlement chamber where the dense heavy material sinks to the bottom and the water flows to the next tank. The last step is sterilization which can be done by UV or chlorination. These four steps can be found back in all three AWPS which are used on the ships of Royal Caribbean. This research focusses on the treatment systems of Evac including the treatment system of headworks because this system is found on multiple ships. The Scanship system works in principle the same way.

Technical process AWPS – EVAC

Headworks bio clean is installed on 7 ships of the Royal Caribbean and the systems of Evac on 3 of the bigger ships of the Royal Caribbean; Oasis of the Seas, Allure of the Seas, and Harmony of the seas, which all have a capacity of over 8000 passengers and crew. This includes a wastewater treatment system, a dry and wet waste treatment system, freshwater generation systems, and system automation, all provided by Evac (Evac, n.d.). The process of the treatment system can be seen in figure 48 and the setup in figure 49.

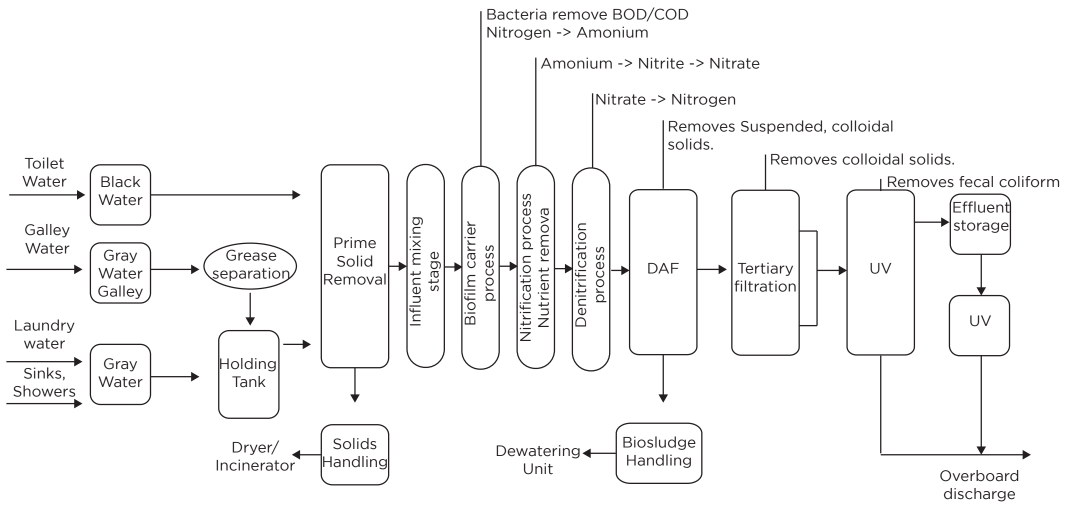

Figure 48: Process treatment system from EVAC
Note. Adapted from Evac. (2019).

Figure 49: Process treatment system from EVAC
Note. Reprinted from Evac. (2019).

The black water goes first into the Evac EcoScreen. This is a pre-screening unit that is connected to the sewage treatment plant. Most solids are mechanically separated by this pre-screening unit. The amount of organic load in the wastewater is reduced by 10-20%. When this pre-screening unit is used, the solid matter does not need to be chopped in pieces. The greywater from the galleys goes into the Evac Ecotrap grease separator. The greywater from the galleys contains a lot of grease which is harmful to the components of the wastewater treatment systems, it can cause clogging in the pumps, valves, and tanks. The grease separator is used to prevent this from happening. All the greywater comes together in a holding tank. The first solids are now removed from the wastewater. The wastewater goes into the mixing tank to ensure a constant mixture and loading process for the moving bed biofilm reactor (MBBR). The first step is the biotreatment process, also called the biofilm carrier process. This are aerated reactors filled with active biomass carriers. Air is pumped into the reactor to provide oxygen for the aerobes, which are oxygen demanding bacteria. The biomass carriers are plastic carriers which complex shapes to increase the surface. By increasing the surface, the media can absorb a higher number of substrates from the wastewater. The biomass carriers act as biofilm substratum (S. Wang, Parajuli, Sivalingam, & Bakke, 2019). Biofilms are complex communities formed by bacteria (Lopez, Vlamakis, & Kolter, 2010). Multiple habitats are formed on the biofilm which can transform constituents as carbon and nitrogen from the wastewater (S. Wang et al., 2019). Figure 50 shows the three steps of biofilm formation: attachment, growth, and detachment.

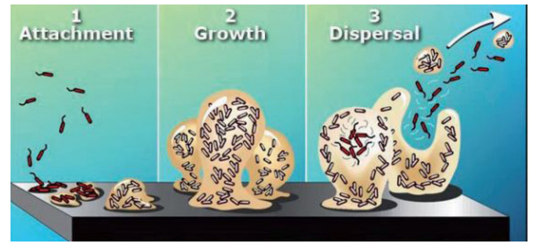

Figure 50: The steps of biofilm formation.
Note. Reprinted from S. Wang, Parajuli, Sivalingam, & Bakke (2019), p.2.

The performance of the MBBR depends on the shape, density, protected areas, and void volume of the biomass carriers. These carriers have a lower density than water, normally around 0.98 kg/L, to make sure it can be suspended in wastewater without the need for strong mixing (S. Wang et al., 2019). In the biotreatment process, organic substances as BOD and COD are removed from the wastewater, and ammonification takes place. Ammonification is the breakdown of organic nitrogen to ammonium. The ammonium is needed for the next process; nitrification (Van Haandel & Van Der Lubbe, 2007, p. 87).

Ammonification:

$RNH_2 + H_2O + H^+ \leftrightarrow ROH + NH_4^+$

*R represents the different hydrocarbon chains the nitrogen can connect to.

The conversion of ammonia (NH_4) into nitrite (NO_2) and nitrite into nitrate (NO_3) is called nitrification. This is done by aerated bacteria. The reactions are shown below (Van Haandel & Van Der Lubbe, 2007, p. 87).

$NH_4^+ + {}^{3/2}O_2 \rightarrow NO_2^- + H_2O + 2H^+$ (ammonium to nitrite)
$NO_2^- + {}^{1/2}O_2 \rightarrow NO_3^-$ (nitrite to nitrate)

After nitrification, the wastewater goes into the next tank where denitrification takes place. This means that nitrate is converted into molecular nitrogen (N_2). Organic matter is used as reductor for this process (Van Haandel & Van Der Lubbe, 2007, p. 87).
After the nitrate is converted into nitrogen the water goes into the Evac EcoDAF unit, also called the dissolved air flotation (DAF). This system removes suspended and colloidal solids by using pressure. The DAF consists out of four components: air supply, pressurizing pump, retention tank, and flotation chamber. When a liquid is under pressure the solubility of gas, such as air, increases. That is why the wastewater is pressurized by a pump. Microscopic air bubbles are released when the pressure is suddenly reduced. The suspended and colloidal solids attach themselves to the microscopic air bubbles and float to the top. A layer of sludge from these solids will arise and need to be skimmed off (L. K. Wang, Hung, & Shammas, 2004). After the DAF the wastewater will go into the Evac EcoPol which is a polishing filter. This system removes the remaining colloidal solids. The last step is sterilization. This is done in the Evac EcoRay, a UV disinfection unit. This unit removes faecal coliform. Wastewater can also be disinfected by chlorine, radicals, and ozone. Using chlorine is not recommended because it is not good for the environment (Koboevic & Kurtela, 2011; L. K. Wang et al., 2004). According to Evac (2019) the water contains now < 15 mg/L BOD, < 15 mg/L TSS <10 CFU/100 ml.

Micropollutants
Researchers have recently started focusing on the micropollutants in black and grey wastewater. Currently, there are no laws or guidelines against the discharge off micropollutants in wastewater and they are often ignored. However, micropollutants are a concern for the environment and can harm the aquatic life. Examples of micropollutants are pharmaceuticals, personal care products, anti-flame retardants, industrial chemicals, etcetera (Grandclément et al., 2017; Vicente-Cera et al., 2019; Westhof et al., 2016). It is important to reduce the number of micropollutants in wastewater for the marine environment in case it is discharged into the sea and to make reuse of the wastewater possible (Westhof et al., 2016). Micropollutants which were found in black water where oral pharmaceuticals and non-drugs as tonalite and TCCP. Diclofenac, caffeine, non-pharmaceutical residues, food residues as TCPP were found in greywater (Westhof et al., 2016). Several studies are done into the removal of micropollutants by conventional activated sludge (CAS) and membrane bioreactors (MBR) but not into the removal of micropollutants by newer treatment systems as adsorption processes, oxidation processes or membrane processes. The removal of micropollutants is compound- and process-dependent. The conventional processes are insufficient in removing micropollutants. Systems with biofilm carriers, attached growth systems, or crosslinked enzymes are better able to remove micropollutants (Grandclément et al., 2017). However, further studies are needed into possible ways to remove micropollutants from wastewater (Grandclément et al., 2017; Vicente-Cera et al., 2019; Westhof et al., 2016).

Conclusion – Black and Greywater
Table 19 summarizes the treatment process and shows which components are removed in which sub-process. When this table is compared with the general component table of black and grey water it can be seen that not all the components are removed. Some of them are properties that need to be met, as pH, temperature, conductivity, etc. Others are probably taken care of in the process but not specifically mentioned. At the beginning of the process, the wastewater is filtered which means that some solids are removed. This could indicate that the total dissolved solids are removed sufficiently. However, this is not explicitly said, that is why these components are under the subtitle not verified. Table 20 shows which components from the grey and black water are removed in the advanced wastewater purification system. However, this treatment does not focus on micropollutants. Micropollutants are a concern for the environment and can harm the aquatic life. The current processes cannot remove the micropollutants, more research is needed to remove these pollutants from the wastewater.

Table 19
Removed components per process.

Section	Removes component
Evac EcoScreen	Reduce organic Load, Solids
Ecotrap Grease separator	Grease
Bio Treatment	Carbon, Nitrogen (Constituents) BOD, COD
Ammonification	$NH_2 \rightarrow NH_4$
nitrification	$NH_4 \rightarrow NO_2 \rightarrow NO_3$
Denitrification	$NO_3 \rightarrow N2$
Evac EcoDAF	Suspended and Colloidal Solids
Evac EcoPol	Colloidal Solids
Evac EcoRay	Faecal Coliform

Table 20
Removed components from black and grey water.

Component
(partly) Removed
Ammonia Nitrogen mg/L as N
BOD5 mg/L
COD mg/L
Faecal Coliform
Hexane Extractable Material (Oil and Grease) mg/L
Nitrate mg/L
Nitrite mg/L
Total Kjeldahl Nitrogen mg/L (Nitrogen contained in organic substances and inorganic compounds)
Properties that must be met
Alkalinity mg/L (capacity to resist pH changes)
Conductivity uS/cm (capability to pass electrical flow)
Temperature °C
pH
Turbidity mg/L
Not verified
Chloride mg/L
Settable Residue mg/L
Sulfate mg/L
Total Dissolved solids mg/L (organic and inorganic substances)
Total organic carbon mg/L (Acids, fats, sugars, proteins, enzymes, and hydrocarbon fuels)
Total phosphorous mg/L
Total Residual Chlorine mg/L
TSS mg/L Total suspended solids

Fluid waste stream – Bilge water

Rincón & La Motta (2014) states that a cruise ship that sails in Alaska generates 5-20m^3 bilge water every 24h. This is equal to 35-140m^3 in a week and 1800-7200m^3 in a year. There are multiple oily water separators (OWS) in the market according to the United States Environmental Protection Agency (2011b), to treat bilge water. Which system is used by the Royal Caribbean is not made public. The company itself says that they're using an OWS where the sludge is skimmed off the top and the remaining bilge water goes through three filters, with one carbon activated filter (Royal Caribbean Cruises Ltd., 2016c). Most likely this is a combination of a gravity oil water separator in combination with a polishing treatment system.

The gravity OWS uses the different specific gravities of water and oil to separate the liquids. Oil is hydrophobic which means that it does not mix with water. Due to this property the oil rises to the top. Plates or filter coalescing are used at the bottom of the tank. These plates or filters are made of an oil-absorbing polymer as polypropylene. The oil droplets adhere to the filters when the water goes through. These droplets coalesce, break free of the filters, and rises to the top. The tank has a sensor that detects the oil and controls a pump that sends the oil to the collected oil waste

tank. Gravity OWS cannot separate emulsified oils from water and are not effective in removing colloidal metals and soluble compounds. Due to this gravity OWS cannot meet the 15 ppm requirements, a polishing treatment is needed (United States Environmental Protection Agency, 2011b).

There are multiple polishing treatment systems: absorption and adsorption, biological treatment, coagulation and flocculation, flotation, and membrane technologies (ultrafiltration). Royal Caribbean states that they skim off the sludge which could indicate that they use coagulation and flocculation. This system uses aggregation, bringing small particles together which are initially too small to settle by gravity. Emulsified oil is pumped into a mixing tank where flocculant chemicals or air is added. To make aggregation possible particles need to travel and meet other particles and they need to destabilize to attach to others. The aggregated flocks that connect to the oil are skimmed off and the bilge water goes through a filter (United States Environmental Protection Agency, 2011b).

The carbon activated filter Royal Caribbean use could indicate the use of adsorption because granular activated carbon (GAC) is often used as media in this polishing treatment to remove dissolved oil and hydrophobic organic chemicals. GAC can absorb 10-20% oil by weight and then it is saturated. GAC has a relatively low initial cost but is vulnerable to high suspended solids. Royal Caribbean use most likely a combination of these three processes.

Table 21 shows the bilge separator treatment systems the United States Environmental Protection Agency (2011b) has investigated. All systems comply with the 15 ppm standards. System E has a higher ppm because the bilge water only went through the centrifuge, if this process is combined with a polisher the value would be 0-2 ppm (United States Environmental Protection Agency, 2011b). System G combines OWS with coagulation and flocculation and granular activated carbon. Royal Caribbean states that their bilge water has an average of less than 1.5 ppm. From the 14 systems, 7 comply with this, including system G. It is likely that Royal Caribbean uses this system.

Research is also done into the other processes which are not used by the Royal Caribbean to be able to compare them.

Table 21
Effluent Oil Concentrations for Bilge Treatment. Systems.

Bilge Separator Treatment System	Effluent oil concentration (ppm) from MEPC 107 (49)
System A (OWS/PS absorber)	0.26 (0.14-0.48)
System B (OWS/Biological Reactor/Clarifier)	1.6 (1.3-1.8)
System C (DAF/coag.-flocc/DAF-skimming GAC)	<1
System D (OWS/prefilter/UF)	1.75 (1.5-2.5)
System E (Strainer/preheat/centrifuge)	9.5 (8.4-11.0)
System F (OWS/filter coalesce/AGM adsorber)	<1
System G (Descaler OWS/ coagulation-flocculation- floatation/granular media filer/ GAC)	<1
System H (Filter/preheat/OWS)	6.7 (5-10)
System I (unknown)	0.22 (0.1-0.42)
System J (unknown)	4.1 (3.4-4.7)
System K (Oil absorption filter)	<0.1
System L (Oil absorption filter)	1.7 (0.72-2.7)
System M (unknown)	0.8 (0.4-1.1)

Note. Adapted from ''Oily Bilgewater Separators'', by United States Environmental Protection Agency, 2011b. Retrieved from https://www3.epa.gov/npdes/pubs/vgp_bilge.pdf

Research is also done into the other processes which are not used by the Royal Caribbean to be able to compare them.

Biological treatment

In this process, a film is used as media for microorganisms to grow on. These microorganisms convert the oil and organic compounds into carbon dioxide, cell components. Oxygen is delivered by aerators at the bottom of the tank for the bacteria. The bacteria also need nutrients and pH adjustments to survive in the tank. By using this process organic pollutants can be degraded to low concentrations as well as emulsified oils which are hard to treat with physical and chemical treatment. Other benefits of this process are that it can remove organic pollutants as jet fuel, detergents, nitrogen, phosphates, glycols, and surfactants and it does not produce waste oil. A disadvantage is that it cannot handle loading spikes (United States Environmental Protection Agency, 2011b).

Flotation

This system is used to enhance the separation of oil and water by gravity. An example of flotation is the DAF system which is also used for the separation of black and greywater. The oil droplets and small solid particles connect to the air and float to the top. To enhance this process flocculating agents can be added as well (United States Environmental Protection Agency, 2011b).

Centrifugal separators

This system can be used instead of a gravity OWS, together with a polishing process. Like gravity OWS, centrifugal separators work with the principle of gravity and the immiscibility of oil and water. Centrifugal separators are efficient, reliable, compact, big holding tanks are not needed, and it generates little waste. Disadvantages of this system are that it uses a lot of power, the motor requires maintenance, the initial cost is relatively high, and further treatment as with a gravity OWS is still needed (United States Environmental Protection Agency, 2011b).

Membrane Technologies

Membrane technologies act as a molecular sieve and are used in the municipality and the industry. Membrane technologies have high efficiency, low energy needs, and are compact. There are three different categories: ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO). The pores where the particles must go through differ in the size. Table 22 shows the particle cut-off size and the molecular weight range. Ultrafiltration is the most common membrane technique used as polishing treatment. Water, ions, and small molecules can pass the membrane, but oil and other large molecules can not go through. The substrates which can not pass through the membrane, the concentrate, are collected and send back to the holding tank. The oil that is now de-emulsified can be treated by the oily water separator (United States Environmental Protection Agency, 2011b).

Table 22
Particle Size and Molecular Weight Ranges.

Membrane Technology	Particle Size Cutoff	Molecular Weight (MW) Ranges
Ultrafiltration	0.01 to 0.1 µm	1,000 – 100,000
Nanofiltration	0.001 to 0.008 µm (10 to 80 angstroms)	200 – 10,000
Reverse Osmosis	0.0005 to 0.0015 µm (5 to 15 angstroms)	100 – 300

Note. Adapted from ''Oily Bilgewater Separators'', by United States Environmental Protection Agency, 2011b. Retrieved from https://www3.epa.gov/npdes/pubs/vgp_bilge.pdf

Electrochemical wastewater treatment

Flotation, separation by centrifuge, filtration, and coagulation are chemical and physical processes. The disadvantage of these processes is that they have a hard time separating the emulsified oil in the bilge water (Akarsu et al., 2016; Caplan, Newton, & Kelemen, 2000; D.L. Woytowich, C.W. Dalrymple, F.W. Gilmore, M.G. Britton, in Ulucan & Kurt, 2015). The current legislation only focusses on the removal of oil from bilge water and not on the removal of heavy metals (Rincón & La Motta, 2014). Ulucan & Kurt (2015) states that electrochemical wastewater treatment is developing and most likely to be used in the future. This treatment also removes the emulsified oil, heavy metals, grease, organic matter, nitrate, arsenic, etc. from the bilge water. It can also be used for other wastewater treatment processes as, domestic, dairy, paper, and pulp wastewater (Akarsu et al., 2016; Rincón & La Motta, 2014). Akarsu et al. (2016) state that next to electrochemical wastewater treatment, the polishing treatment membrane filtrations work best in removing heavy metals. However, there will be membrane blocking and fouling without any pre-treatment.

Research into using electrochemical processes for bilge water treatment is still limited (Ulucan & Kurt, 2015). In the literature, some researches are found focussing on the process behind the electrochemical treatment, which tries to find the most efficient process to remove the emulsified solids and heavy metals (Akarsu et al., 2016; Körbahti & Artut, 2010; Rincón & La Motta, 2014; Ulucan & Kurt, 2015). Electrochemical processes involve electrocoagulation, electroflotation, and direct and indirect electro-oxidation processes. The anode electrodes aluminium and Iron dissolve into AL^{+3} and Fe^{+2} ions as a coagulant in electrocoagulation, see reaction below (Ulucan & Kurt, 2015).

Carbon steel anode:

$Fe_{(s)} \rightarrow Fe^{2+}_{(aq)} + 2e^-$

$Fe_{(s)} \rightarrow Fe^{3+}_{(aq)} + 3e^-$

Aluminium anode:

$Al_{(s)} \rightarrow Al^{2+}_{(aq)} + 2e^-$

$Al_{(s)} \rightarrow Al^{3+}_{(aq)} + 3e^-$

These ions form metal hydroxides as $Al(H_2O)^{3+}_6$ and $Fe(OH)_3$ which can connect to emulsified materials, suspended solids, and colloidal materials. The H_2 generated at the electrode can remove flocks and precipitates by floating, see figure 51. Insoluble electrodes as Ti, Ru, Pt, are needed for the oxidation. There are two types of oxidation: direct electrooxidation and indirect electrooxidation. Oxidation is needed to generate the coagulants which remove the harmful substances from the bilge water (Rincón & La Motta, 2014; Ulucan & Kurt, 2015). Electrochemical treatment must be combined with another type of treatment because it is not effective enough by itself. A possible combination is electrochemical treatment and nanofiltration. Blocking of the membrane will be prevented when these treatment processes are combined (Akarsu et al., 2016).

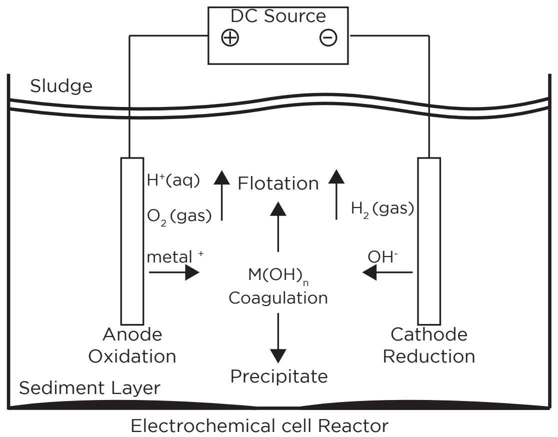

Figure 51: Schematic view of electrochemical batch reactor.
Note. Adapted from Rincón & La Motta (2014), p. 44.

Components bilge water

Bilge water contains next to petroleum, oil, and hydrocarbons also metallic impurities as zinc, lead, copper, etc. (Akarsu et al., 2016). Table 23 shows some components in bilge water.

Table 23
Composition bilge water.

Component
pH
Conductivity (QS/cm)
Absorbance at UV
COD (mg/L)
Cr (ppb)
Cu (ppb)
As (ppb)
Sr (ppb)
Mo (ppb)
Pb (ppb)
Ti (ppb)
Zn (ppb)

Note. Adapted from "Electrocoagulation and nanofiltration integrated process application in purification of bilge water using response surface methodology", by Akarsu, C., Ozay, Y., Dizge, N., Elif Gulsen, H., Ates, H., Gozmen, B., & Turabik, M., 2016, Water Science and Technology, 74(3), 566.

Conclusion – Bilge water

It can be assumed that all previously mentioned processes meet the needed requirements and remove (enough) hazardous components from the bilge water according to the current legislation. However, this legislation only focusses on the oil content and not on other harmful particles in the bilge water as heavy metals. The chemical and physical processes have a hard time removing emulsified oil. A new technique is in development which could be the bilge water treatment system of the future. This new technique is called electrochemical wastewater treatment which can remove the emulsified oil and heavy metals from the bilge water. This treatment process is still under development, but researches call it promising.

4.3.2.3 Solid waste stream

There are two types of solids waste: general non-hazardous solid waste and hazardous waste as discussed in chapter 3.2.3. This chapter examines in detail which material enters and leaves the ship, in which quantities and how the waste is treated.

Non-hazardous solid waste

The amount of solid waste generated on a cruise ship depends on the size of the ship, the number of passengers and crew, and the amount of consumption. As a guideline, it can be assumed that one person generates two pounds of solid waste and 2 bottles and 2 cans per day. This is around 7-8 tons of solid waste per week (Copeland, 2005; CELB, as cited in United States Environmental Protection Agency, 2008). However, this is only the waste generated per person on the ship. Royal Caribbean states that the ship generates next to this up to 15 tons of packing material every day and the vision class ships of Royal Caribbean discharge around 450 pounds (240kg) of aluminium cans per week. Next to this around 1,300 to 2,600 gallons of food liquid is produced per day which ends up in the grey water holding tank (United States Environmental Protection Agency, 2008). According to Polglaze (2003), food is often the largest garbage stream on ships. Table 24 shows the materials that fall under non-hazardous solid waste.

Table 24
Non-hazardous solid waste and their treatment methods.

Non-hazardous Solid Waste	Used for	Treatment	Ends up
Glass	Food and beverage jars & bottles.	Crushed	Land
Plastic	ropes, containers, bags, biodegradable plastics, poly-ethylene terephthalate plastics, high-density polyethylene plastics	Incinerated, recycled	Land, Air, (Sea)
Aluminium & Metal Cans	Soft drink cans, tin cans (food), steel cans ship maintenance	Crushed, recycled	Land
Paper	Paper and packing	Incinerated, recycled	Land, Air, (Sea)
Cardboard	Dunnage, packing	Incinerated, recycled	Land, Air, (Sea)
Food waste	Food scraps, table refuse, galley refuse, food wrappers contaminated with food.	Pulped, compressed, incinerated	Land, Air, (Sea)
Wood	Pallets, waste wood	Incinerated	Land, Air, (Sea)
Incinerator ash	Ash from packing material, paper, cardboard, etc.	-	Sea

Note. Data retrieved from: United States Environmental Protection Agency (2008).

The treatment of solid waste is depended on the type of waste. For example, food waste, plastic, cardboard, and paper goes into the incinerator, glass is crushed in a glass crusher, paper and cardboard is pulped and plastic bottles, metal cans, cardboard, and paper are stored and recycled (Butt, 2007; Copeland, 2005; United States Environmental Protection Agency, 2008). Around 75-85% of all the waste generated onboard goes to the incinerator. Most of the time the ash is discharged into the sea, in some cases it is stored and disposed to land or recycled (Butt, 2007; Copeland, 2005; United States Environmental Protection Agency, 2008). Table 24 shows the type of treatment and the final location of the waste generated onboard. Solid waste on ships is managed by source reduction, source segregation, waste minimization, and recycling (Copeland 2005; United States Environmental Protection Agency, 2008).

Hazardous solid waste
Waste is hazardous when it is on one of the four hazardous waste lists, or it has one of the four hazardous characteristics, which are ignitability, corrosivity, reactivity, and toxicity. Hazardous waste is stored onboard until it can be handed over to qualified contractors on land. Although the quantities of hazardous waste are small due to the high risk to the environment waste handling is very important (Copeland 2005; United States Environmental Protection Agency, 2008).
Activities onboard that generate hazardous waste are: photo processing, dry cleaning, and equipment cleaning. Substances that come free during these processes are: heavy metals, perchlorethylene, hydrocarbons, chlorinated hydrocarbons, and solvents. Other hazardous wastes that can be found on cruise ships are: waste of paint, aerosol liquid, incinerator ash, fluorescent and mercury vapour light bulbs, unused or outdated pharmaceuticals, and batteries (United States Environmental Protection Agency, 2008). Table 25 shows the hazardous materials which can be found on cruise ships.

Table 25
Hazardous waste found on cruise ships.

Hazardous waste	Hazardous waste Substances
Paints waste	Perchlorethylene
Incinerator ash	Hydrocarbons
Fluorescent and mercury vapour light bulbs	Chlorinated hydrocarbons
Batteries	Heavy metals
Medical waste	Solvents
Photo waste	Silver
Explosives	Aerosol liquids
Chemical	

Note. Data retrieved from: United States Environmental Protection Agency (2008).

Table 26 shows the amount of generated hazardous waste from 17 ships of the Royal Caribbean in 1999. Most likely these numbers are not representative anymore because of the actions taken to reduce waste in the last 20 years. However, they are given to get an idea of the quantities. Actions taken by the cruise industry are using more effective digital photo technologies, non-toxic printing ink, and alternative dry-cleaning processes. CLIA also states that member cruise lines want to reduce the use of incineration (United States Environmental Protection Agency, 2008).

Conclusion – Solid waste
All the generated solid waste ends up in the sky and sea through incineration or on land when it is disposed of. The cruise industry is already focusing on source reduction, source segregation, waste minimization, and recycling but there is still more to gain. Incineration should be the very last option to handle waste because of the harm done to the environment. If possible, this process should be eliminated at all. Hazardous waste is always disposed to land which is, in this case, the best and only option. The most important step here is to minimize the generation of hazardous waste by using sustainable alternative materials or perhaps stop facilitating some products or facilities.

Conclusion –Treatment systems
Figure 52 shows the outcome of this detailed research. It summarizes what comes into the cruise ship, the connected treatment processes, and what comes out of the cruise ship.

Table 26
Generated hazardous waste on cruise ship fleet.

Type of Hazardous waste	Royal Caribbean Cruises Ltd (17 vessels) 1999	
Photo waste	1300 gallons/ week	~4921 L/ week
Discarded and expired chemicals	2050 lbs./ week	~930 kg/ week
Medical Waste	80 lbs./ week	~36 kg/ week
Batteries	550 lbs./ week	~250 kg/ week
Fluorescent Lights	270 lbs./ week	~122 kg/ week
Explosives	12 lbs./ week	~5 kg/ week
Spent paints and thinners	255 gallons/ week	~965 L/ week

Note. Data retrieved from: United States Environmental Protection Agency (2008).

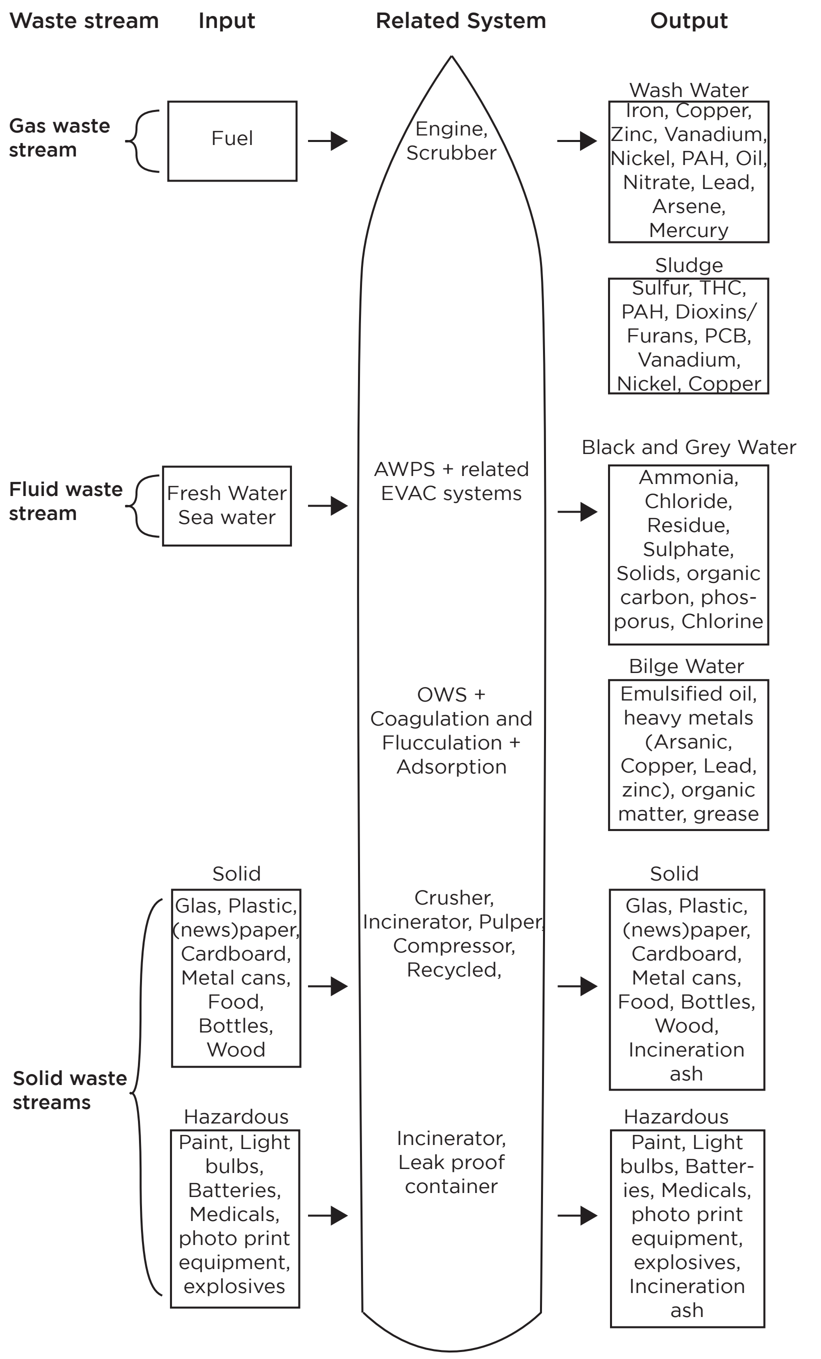

Figure 52: Overview input, output and related systems of the waste streams.

4.3.3 Detailed research improvements

A distinction is made between ships that undergo retrofitting, called retrofit ships, and newly built ships. A cruise ship has an average life span of 30 years (Golden, 2018). The fleet of Royal Caribbean consists at this moment of twenty-seven ships and is still growing. The ships are built between 1990 and today (iCruise, n.d.). See appendix C for the list of Royal Caribbean cruise ships with their building year and the expected end of life year. It is important to investigate improvements for retrofit ships and newly built ships.

4.3.3.1 Gas waste stream

Chapter 4.3.2.1 shows that emissions come free and hazardous substances as wash water and sludge are generated when ships sail on HFO fuels with scrubbers. This chapter looks into promising alternative types of fuels that can be used on retrofit ships and newly built ships. This chapter starts with an overview of the most common and promising fuels and engines. Their advantage and disadvantages are discussed, including their emissions. Then explanations and examples of renewable electric energy sources in the marine industry are given.

Potential engines and fuels

Today, the most common engine in the marine industry is still the combustion engine. Other engines with great potential are the dual-fuel engine and the fuel cells, see chapter 3.2.1. Diesel engines use most of the time HFO fuel and dual-fuel engines use diesel and LNG. However, these engines can run on multiple types of fuel. A combustion engine can run besides diesel theoretically also on hydrogen (García-Olivares, Solé, & Osychenko, 2018; Hua, Wu, & Jin, 2008; Royal Academy of Engineering, 2013; Turner, 1999), biofuels as (bio)methanol (IRENA, 2015; Verhelst, Turner, Sileghem, & Vancoillie, 2019) and on natural gas (Royal Academy of Engineering, 2013). Dual fuel engines can run on several types of biofuels as LNG, (IRENA, 2015) methanol, (Coulier & Verhelst, 2016; IRENA, 2015; J. Liu, Yao, & Yao, 2015) natural gas (Royal Academy of Engineering, 2013) and hydrogen (Korakianitis, Namasivayam, & Crookes, 2010; Tsujimura & Suzuki, 2017. Also, the fuel cell can run on different fuels as hydrogen (García-Olivares et al., 2018; Hua et al., 2008; IRENA, 2015; Royal Academy of Engineering, 2013; Turner, 1999), some biofuels (García-Olivares et al., 2018; Kraaij, Specchia, Bollito, Mutri, & Wails, 2009) as methanol (Hua et al., 2008; Mathiesen et al., 2015; Royal Academy of Engineering, 2013), and methane (García-Olivares et al., 2018; Royal Academy of Engineering, 2013). Table 27 shows the engines and their fuels.

Table 27
Engines and their fuels.

Engine	Fuel
Combustion Engine	-Natural gas
	-Biofuel as (bio) methanol
	-Hydrogen
Dual Fuel	-Biofuels as LNG and methanol
	-Hydrogen
Fuel Cell	-Hydrogen
	-Biofuels as methanol
	-Methane

Which type of fuel is most sustainable to use depends on several aspects;

Q.1. How is the fuel made, are emissions released in this process?

Q.2. Can the fuel be used in one or more engines?

Q.3. Are emissions released during the process when this type of fuel is used?

Q.4. What needs to be adjusted for this type of oil?

When choosing the most suitable type of oil, questions 1 and 3 weigh the most in this study because the most important aspect is to reduce the emissions into the air. It is beneficial when question 2 is applicable. Question 4 is something that most likely needs to happen because the world needs to change drastically to make this transition happen. Hydrogen, methanol, and biofuels are according to the literature the most promising fuels for the maritime industry.

Hydrogen

(Q.1) There are three main ways to form hydrogen: reforming of hydrocarbons, using biofuels, and electrolysis of water. The most common process is producing hydrogen from conventional fuels such as methane, a natural gas (Hua, et al., 2008; IRENA, 2015; Royal Academy of Engineering, 2013; Turner, 1999; Volger, 2019). It is also possible to use methanol for this process, this is seen as a more sustainable fuel (Hua, et al., 2008). The reaction of reforming hydrocarbons to hydrogen is shown below (Volger, 2019, p.15).

$CH_4 + H_2O <-> CO + 3 H_2$

It can be seen that this process is not emission free, CO comes out as pollutant emission.

Hydrogen can also be made from biomass. There are multiple methods to produce hydrogen from biomass (Balat & Kırtay, 2010; Nath & Das, 2003). There are two main categories: thermochemical and biological methods. Examples of thermochemical processes are pyrolysis and gasification (Balat & Kırtay, 2010; Lam, Loy, Yusup, & Lee, 2019). Gasification is one of the most promising methods to produce syngas from biomass. Gasification of the biomass microalgae consists out of 3 steps: removal of moisture, devolatilization, and oxidation. When the biomass decomposes, H_2 is generated together with CO and CO_2. Some CO comes free as an emission (Aziz & Nuran Zaini, 2017; Lam, Loy, Yusup, & Lee, 2019). Pyrolysis is a thermochemical process that occurs at high temperatures 600-900 °C and does not need oxygen. During this process, the noncondensable gases H_2, CO, and CO_2 are formed (Lam et al., 2019). The advantages of chemical processes are that it has a higher overall efficiency and lower production cost. However, the disadvantages are the formation of char and tar from the decomposition of the biomass (Balat & Kırtay, 2010; Lam et al., 2019). Examples of biological methods are direct and indirect biophotolysis of water, dark fermentation and a hybrid system. Direct biophotolysis splits water in H_2 and O_2 by using sunlight. There are no emissions formed during this process. Indirect biophotolysis consists of two stages, the growing stage with light and the dark fermentation stage. During fermentation, several by-products were produced as CO_2, acetate, ethanol, and glycerol. Dark fermentation can be coupled to direct biophotolysis, a hybrid system. The produced CO_2 during the fermentation can be used to grow the microalgae in the firsts stage. This eliminates the emission of CO_2. It is a new process that is not yet commercially available but promising according to several types of research (Lam et al., 2019). The biological methods require less energy and are more environmentally friendly (Balat & Kırtay, 2010). Using algae as a biofuel has several advantages, they do not compete with the food sector, have a high growth rate, growth density and consist out of lignin (Aziz & Nuran Zaini, 2017).

Hydrogen can also be made when renewable energy is used for the electrolysis. This is seen as a sustainable method to produce the fuel (IRENA, 2015; Royal Academy of Engineering, 2013; Turner, 1999; Volger, 2019). The total reaction is shown below (Volger, 2019, p.15).

$2H_2O -> 2H_2 + O_2$

There are no pollutant emissions formed in this process. Table 28 summarizes the processes and their emissions.

Table 28
Emissions per process – Hydrogen.

Emissions per process – Hydrogen	
Reforming Hydrocarbons	CO
Gasification - Algae	CO
Pyrolysis - Algae	CO, CO_2
Direct biophotolysis - Algae	-
Dark fermentation – Algae	CO_2
Hybrid - Algae	-
Electrolyse + Renewable energy	-

(Q.2) Hydrogen can be used in fuel cells (García-Olivares et al., 2018; Hua et al., 2008; IRENA, 2015; Khooban, Vafamand, & Boudjadar, 2019; X. Liu et al., 2020; Royal Academy of Engineering, 2013; Turner, 1999), theoretically in conventional combustion engines (Hua et al., 2008; Royal Academy of Engineering, 2013; White, Steeper, & Lutz, 2006) and in dual-fuel engines (Korakianitis, Namasivayam, & Crookes, 2010; Tsujimura & Suzuki, 2017). There are some advantages when it is possible to use hydrogen in a conventional engine. There is no need to install new engines which reduces the cost and combustion engines do not require pure hydrogen (Tsujimura & Suzuki, 2017). Research is still conducted into improving the use of hydrogen directly into a combustion engine and a duel fuel engine (Korakianitis et al., 2010; Tsujimura & Suzuki, 2017; White et al., 2006). The easiest option is to use hydrogen in a fuel cell (Royal Academy of Engineering, 2013).

Q.3 A neat hydrogen engine only produces water and does not produce significant amounts of other pollutant emissions, e.g. CO, HC, SO_x, CO_2 (Das, 1991, p. 768).
Hua et al (2008) state that theoretically hydrogen can be more effective than fossil fuels when used in an internal combustion engine. However, some issues may raise because hydrogen needs more storage space (Royal Academy of Engineering, 2013). Hydrogen has unique combustion characteristics which makes it a clean and efficient fuel for low engine loads. However, in high engine loads, unscheduled combustions occur with high temperature which leads to a higher NO_x production. The production of nitrogen oxides is the only pollutant emissions of concern that comes free. Other emissions as CO, CO_2, HC, and SO_x are not found in significant amounts (Das, 1991; White et al., 2006).
A dual fuel engine uses two types of fuels, in this case, diesel and hydrogen. The hydrogen is mixed with an intake gas and compressed. Then diesel is injected for the combustion (Tsujimura & Suzuki, 2017). The advantage of using hydrogen is the improvement of thermal efficiency and the reduction of CO_2 and HC emissions. However, there is an increased production of NO_x which comes free together with some smoke. Multiple types of research are conducted to reduce the number of emissions and improve the duel fuel engine (Korakianitis et al., 2010; Tsujimura & Suzuki, 2017).
Fuel cells powered by hydrogen have a zero-tailpipe emission. The fuel cell converts hydrogen and oxygen to direct power (Khooban et al., 2019; X. Liu et al., 2020). In this scenario, the entire marine power system would be seen as a direct current (DC) microgrid. Most of the time ships have a constant speed. Constant power is needed to provide this. The challenge of a hydrogen fuel cell is to stabilize the voltage and current. Research has been done into a DC/DC converter to eliminate the fluctuations (Khooban et al., 2019). Table 29 shows the emissions that come free.

Table 29
Emissions per engine type – Hydrogen.

Emissions per engine type – Hydrogen	
Combustion engine	NO_x
Dual Fuel engine	Increase in NO_x Decrease in HC, CO_2, and smoke
Fuel Cell	-

Q.4 Multiple conducted researches conclude that hydrogen will be the fuel of the future (García-Olivares, et al., 2018; Hua et al., 2008; Turner, 1999). However, big changes in the worldwide infrastructure are needed to support this fuel. New technologies need to be developed to produce, store, and distribute the hydrogen. The very low density of the hydrogen makes this difficult (García-Olivares et al., 2018; Hua et al., 2008; IRENA, 2015; Royal Academy of Engineering, 2013; Turner, 1999). Special storage space needs to be designed because of the high flammability of hydrogen (Royal Academy of Engineering, 2013; Volger, 2019). Next to this hydrogen is not yet cost-effective (IRENA, 2015). Hydrogen can become the fuel of the future when the step is made to a hydrogen economy. Hydrogen will then not only be used as fuel for the marine industry but also for other types of transport (García-Olivares et al., 2018; Royal Academy of Engineering, 2013). Another option would be to produce the hydrogen directly on board so no special infrastructure system is needed when hydrogen is only used for the marine industry.

Methanol
Q.1 Methanol can be produced from natural gas, renewable energy and hydrogen, and from biomass. The most common process is the production of methanol from natural gas with gasification. The syngas used, consist of CO, CO_2, and H_2. Fossil fuels are used in this process and carbon dioxide is generated (Bellotti, Rivarolo, Magistri, & Massardo, 2017). This makes this process not emission-free. The reaction is shown below (Bellotti, Rivarolo, Magistri, & Massardo, 2017).

From methane to syngas:
$CH_4 + H_2O \rightarrow CO + 3H_2$

From syngas to methanol:
$CO + H_2O \rightarrow CO_2 + H_2$
$CO_2 + 3H_2 \rightarrow CH_3OH + H_2O$

Bio methanol can be made with syngas which is the result of the gasification of second-generation biomass. The production of second-generation biofuels does not compete with food production (Molino, Larocca, Chianese, & Musmarra, 2018). In principle this is the same reaction as the reaction above, instead of using syngas from methane, the syngas comes from second-generation biomass. By doing this no fossil fuel is used.
Methanol can also be produced from renewable energy sources and hydrogen. The hydrogen is made by the electrolysis of water, which is an emission free process when renewable energy sources are used. To obtain the needed CO_2 for the process, flue gas of traditional power plants is used (Bellotti et al., 2017). See the reaction below:

Electrolyse:
$2H_2O \rightarrow 2H_2 + O_2$ (water + renewable energy)

Hydrogen to methanol
$3H_2 + CO_2 \rightarrow CH_3OH + H_2O$

This process does not use fossil fuel to produce methanol and there are no harmful emissions. Next to this, this process mitigates the CO_2 emission (Bellotti et al., 2017). Table 30 shows the emissions that come free during the production process.

Table 30
Emissions per process – Methanol.

Emissions per process – Methanol	
Gasification natural gas	CO
Gasification 2nd generation biomass	CO
Renewable energy and hydrogen	-

Q.2 The produced methanol can be used in internal combustion engines (IRENA, 2015; Verhelst, Turner, Sileghem, & Vancoillie, 2019; Zhen & Wang, 2015) in a dual fuel engine (Coulier & Verhelst, 2016; IRENA, 2015; J. Liu, Yao, & Yao, 2015) and in a fuel cell (Höhlein, von Andrian, Grube, & Menzer, 2000; Hua et al., 2008; H. Liu et al., 2006; Mathiesen et al., 2015; Papavasiliou et al., 2018; Royal Academy of Engineering, 2013).

Q.3 When diesel is combined with methanol the fuel can be used in a dual fuel engine. A reduction in smoke, PM, NO, and NO_x emission can be seen but there is an increase in the emission of CO and HC (Coulier & Verhelst, 2016; J. Liu et al., 2015; Yao, Cheung, Cheng, & Wang, 2007). It is safer to use methanol than the commonly used LNG because methanol is in its liquid form and the flammability of methanol lies close to that of diesel which makes it safer than gases or liquid hydrocarbons. Next to this, it is also easier to store methanol on board because there are no complications of cryogenic storage (Verhelst, Turner, Sileghem, & Vancoillie, 2019). There are already vessels in operation that can sail on methanol and conventional fuels in combination with a dual fuel engine (Marinvest, n.d.).
Methanol can also be used in an internal combustion engine without blending the fuel. A reduction in NO_x, CO_2, and PM can be seen. Other emissions that come free are CO and HC (Verhelst, Turner, Sileghem, & Vancoillie, 2019; Zhen & Wang, 2015). Methanol is commonly used as fuel for racing cars, but not yet in the marine industry (Hagen, 1977). This is most likely possible in the short future.
There are two ways to use methanol with a fuel cell. It can be directly used to generate electricity, or it can be transformed into hydrogen. CO_2 is emitted into the air when methanol is directly used as fuel for the fuel cell. Other emissions as PM, NO_x, CO are close to zero (Höhlein et al., 2000). The efficiency of methanol is higher when methanol is directly used because then there is no energy loss in processing the fuel to hydrogen. However, there are also some small issues: the reaction of methanol is kinetically hindered, the methanol oxidizes at the cathode and not all the fuel can be used for power which decreases the efficiency (Höhlein, von Andrian, Grube, & Menzer, 2000). Due to this hydrogen fuel cells have a higher efficiency then methanol fuel cells (Antonucci, Aricò, Cretı, Ramunni, & Antonucci, 1999). To produce hydrogen from the liquid methanol, a fuel processor unit is needed which uses steam. It can be seen in the reaction below that (a small amount of) CO_2 is created during this process (Papavasiliou et al., 2018).

$CH_3OH + H_2O \leftrightarrow CO_2 + 3H_2$

The emissions that come free when methanol is used in a combustion engine, dual-fuel engine, and fuel cell can be seen in table 31.

Table 31
Emissions per engine type - Methanol.

Emissions per engine type – Methanol	
Combustion engine	CO, HC Decrease in NO_x, PM, CO_2
Dual Fuel engine	Increase in CO, HC, NO_2 Decrease in PM, NO, NO_x, smoke, CO_2
Fuel Cell – direct use methanol	CO_2
Fuel Cell – Hydrogen **$CH_3OH \rightarrow H_2$**	- CO_2

Q.4 Methanol is used in a liquid state, which can be easily stored, transported, and dispensed (H. Liu et al., 2006; Papavasiliou, Słowik, & Avgouropoulos, 2018). Due to this, there is no high investment cost to change the infrastructure as with hydrogen. Other benefits of methanol are that it is the simplest fuel that is liquid at atmospheric conditions and that no scarce recourses are needed for the production. This means that the production of methanol can easily be scaled up (Verhelst et al., 2019).

Biofuels
There are three types of biofuels: first generation biofuels, second generation biofuels, and third generation biofuels. First-generation biofuels directly compete with the food sector and land use (IRENA, 2015; Mathiesen et al., 2015). That is why first-generation biofuels are not seen as sustainable fuel in this research. Second-generation biofuels are biofuels that are made of lignocellulosic biomass, for example, agricultural and forest waste, energy

crops, municipal and construction waste, and vegetable oils. Second-generation biofuels do not directly compete with the food sector. However, they do use large number of land that could be used for food production (Antizar-Ladislao & Turrion-Gomez, 2008; IRENA, 2015; Mathiesen et al., 2015; Molino, Larocca, Chianese, & Musmarra, 2018). Also, some of these products have a higher value when they are used for other purposes as food and fibre production and soil conservation. Next to this, other industries also need bioenergy in the future to generate heat and power. When possible, the use of this should be limited in the transport sector (Mathiesen et al., 2015). This research only investigates the use of organic waste to produce biofuel because these fuels do not compete with the food sector, cannot be used for other purposes, and otherwise end up in landfills. Examples of organic waste are: paper waste, animal fats, recycled cooking oils, and municipal solid waste (MSW) which includes kitchen waste and paper/card. There are three main methods to treat second generation biomass: thermochemical, biochemical processes, and extraction of vegetable oils. Thermochemical includes combustion, gasification, pyrolysis, liquefaction, and hydrothermal upgrading. Biochemical methods are fermentation and anaerobic digestion. Biofuel made through anaerobic digestion and gasification can be used in fuel cells, gas engines, and gas turbines. Biofuel made through fermentation can also be used in fuel cells and as liquid motor fuel. That is why this research focusses on these three methods. As seen in the hydrogen chapter, during fermentation and gasification CO and CO_2 are formed (Antizar-Ladislao & Turrion-Gomez, 2008; Lam et al., 2019). Bioethanol is made through the fermentation of organic matter (Antizar-Ladislao & Turrion-Gomez, 2008). Syngas is released through the gasification of biomass. This syngas can be converted into methanol which then can be converted to dimethyl ether, see chapter biofuel production on land for the reaction (Speight, 2011). Dimethyl ether can be used in all three types of engines. However, when used in a combustion engine there is an increase in HC and CO emissions and a decrease in NO_x emission (Song, Huang, Qiao, & Wang, 2004). There is also an increase in HC and CO emissions when dimethyl ether is used in a dual-fuel engine and a decrease in NO_x and PM (Y. Wang, Liu, Huang, & Liu, 2016). Hydration of dimethyl ether is needed to form methanol, then through steam reforming hydrogen is made. The hydrogen can be used in a fuel cell. During the formation of H_2, CO_2 and CO are also formed (Badmaev & Snytnikov, 2008). Anaerobic digestion is a cost-effective treatment because it has almost no environmental effect and it recovers high amounts of energy. Organic matter is decomposed in an anaerobic, oxygen-free, environment to produce biogas. During this process, some CO_2 comes free through natural mineralization. It is possible to pre-treat the organic matter to increase biogas production and solubilization and reduce the volatile solids. There are three types of reactors: batch reactors, one-stage reactors, and two-stage reactors. Which reactor works best, depends on the material to be digested. In the two-stage reactor, the material becomes more stable. A two-stage reactor haves a higher performance than a one-stage reactor but also higher investment and maintenance cost. Next to the biogas also some waste material is formed, the digestate, which can be used fertilizer. As mentioned before MSW can be treated by anaerobic digestion. However, some pre-treatment is needed to remove plastic metals glass, etc. Also, fruit and vegetables, industrial waste, and wastewater as catering waste, and sewage sludge are easily degraded in an anaerobic digester. The industrial waste can later be treated in aerobic circumstances to meet the criteria (S, Ibrahim, Quaik, & Ismail, 2016). This are all sources that are found and produced on a cruise ship. By implementing this process, the waste onboard can be immediately treated and produce energy at the same time. If the use of second-generation biofuels becomes globally used a new infrastructure should be developed for harvesting, transporting, storing, and refining (Antizar-Ladislao & Turrion-Gomez, 2008). Biogas is already used in wastewater treatments to power fuel cells. Pre-treatment is needed to get access to the sugars needed for fermentation. The hydrogen in the biogas can be used after steam reforming, dry reforming, or catalytic partial oxidation. To prevent the forming of CO, steam, and oxygen contents have to be optimised together with the catalyst (Galvagno, Chiodo, Urbani, & Freni, 2013; Papurello, Lanzini, Tognana, Silvestri, & Santarelli, 2015; Trendewicz & Braun, 2013). It is assumed that biogas can be used in the near future for marine applications. It is also possible to use biogas in a dual fuel engine where biogas is the main fuel and diesel the pilot fuel. The NO_x emissions are reduced, the CO and CO_2 emissions are dependent on the operation loads and the HC emissions are increased. However, the power output is lower when biogas is used instead of natural gas. More research is needed into the exhaust gas emissions of this process (Mustafi, Raine, & Bansal, 2006). A dual fuel biogas diesel engine is tested in a tractor. This led to higher HC and CO emissions, a decrease in PM, and a constant NO_x (Owczuk, Matuszewska, Kruczynski, & Kamela, 2019). It is assumed that biogas can be used in the near future in dual fuel engines. Research is done in using biogas for conventional marine diesel engines. To make this possible the diesel engine must be transformed into a dual fuel (biogas-diesel) engine. Which is almost the same as the dual fuel engine, but it has two independent speed regulators. Because this method is still theoretical, it is assumed that this is only possible in the late future

(Nguyen, Thiep Cao, & Do, 2019).

Third generation biofuels are made from aquatic autotrophic organisms, like algae. The technology to make biofuel from algae is still in development but very promising for the marine industry because it could be produced close to ports (IRENA, 2015). Algae can produce more energy per unit area than first generation biofuels. The process to make biofuel from algae is not yet effective in cost and environmental impact. There are two different types of algae: microalgae and macroalgae. The production of biodiesel from algae can be separated into four steps: microalgae cultivation, biomass harvesting/concentration, processing and extraction, and transesterification to produce biodiesel. The cultivation of microalgae can take place in three different installations: circular ponds, photo-bioreactors (PBR), and stirred tank bioreactors (STRs). The algae can grow in three different conditions: phototrophic, heterotopic, and mixotrophic modes. In phototropic conditions, CO_2 from the air or from flue gases are used together with light and macro- and microelements. Microalgae can bond 10-50 times more CO_2 than plants, which makes algae more effective. An alternative source of CO_2 for algae can come from anaerobic digestion installations (AD) which are previously mentioned. Heterotrophic and mixotrophic cultivation is a substitute from photoautotrophic cultivation. The need for an external CO_2 source is not needed or minimized. This improves the economic feasibility. Heterotrophic cultivation is an aerobic process, which means that oxygen is needed. Some advantages of this process are a higher growth rate, higher biomass and lipid productivity, and low-cost harvesting. Mixotrophic cultivation is a combination of photoautotrophic and heterotrophic cultivation. Microalgae that grow in heterotrophic conditions can do this in freshwater but also in wastewater from multiple industrial operations. This wastewater contains nutrients as phosphor and nitrate which algae can remove from the wastewater and use for their own growth. Microalgae could be coupled to these waste streams. There are multiple techniques to harvest the microalgae e.g. settling, filtration, flocculation, dissolved air flotation, centrifugation, coagulation, etc. Harvesting is responsible for 50% of the energy consumption. After the microalgae are harvested, the lipid needs to be extracted through a mechanical, physical, chemical, or biological method. The last step is the conversion of free fatty acids (FFAs) or triacylglycerols (TAGs) into fatty acid methyl ester (FAME), this process is called transesterification. The TAG content and fatty acids profile determine the quality of the biodiesel. The biodiesel create from algae has an advanced combustion efficiency but has also lower energy content and there is an increase in NO_x emission compared to petroleum diesel. The emissions of PM, HC, CO, and CO_2

are reduced. There are already some solutions to reduce this emission to the needed levels (Avagyan & Singh, 2019; Demirbas, 2005). Research is also done into using biodiesel in a fuel cell for vehicles. A processor is needed to make this possible (Kraaij et al., 2009). In this paper, it is assumed that the use of biodiesel in fuel cells is not possible in the near future for the marine industry. Theoretical and experimental research is also done into using biodiesel in dual fuel engines. The biodiesel is mixed with natural gas and air which led to promising results (da Silva, de Lima, da Costa, Filho, & Grilo, 2013). The increase and decrease in emissions differ per research. Korakianitis et al. (2010) showed that the NO_x emission increases, the CO_2 emission decreases, and HC and CO emission stay constant in the current work. It is most likely that sailing on biodiesel in a dual fuel engine is possible in the near future.

The production of biofuel from macroalgae happens off-shore, near-shore, or onshore. Macroalgae can also be used to treat wastewater. It removes around 90% of the nitrogen and phosphor. Harvesting of macroalgae has a negative effect on the marine ecosystem. The harvested algae must be treated to remove alien substances. Bio-oil and lipids are retrieved from the macroalgae which are diverted into biodiesel. Microalgae have a higher lipid content than macroalgae and received more attention in research and development. Next to this macroalgae consist out of K, Na, Ca, and Mg ions which negatively influence the fuel quality (Avagyan & Singh, 2019). This research focusses on the use of microalgae.
There is actually a fourth-generation biofuel which use photosynthetic mechanisms to generate biohydrogen and bioelectricity (Antizar-Ladislao & Turrion-Gomez, 2008). An example of this is the production of hydrogen from algae, which is discussed in the hydrogen chapter.

Biofuels could play an important role in the transition of sustainable transport (Royal Academy of Engineering, 2013). Especially second-generation biofuels made through anaerobic digestion, third generation biofuels made from microalgae, and fourth-generation biofuels that produce hydrogen.

Table 32 gives an overview of what type of biofuel can be made with second generation biomass (organic waste) and algae. It also shows which process is involved and the emissions that come free during this process. Table 33 shows which type of fuel can be used in which engine. Biodiesel (FAME) and Dimethyl ether (DME) are also called drop-in fuels, this means that these types of fuels can be used in a combustion engine with some small modifications (IRENA, 2015). Hydrogen, biogas and (bio) methanol can also be used in a combustion engine. Dual fuel engines can run on (bio) methanol, biogas, dimethyl ether, and bioethanol (IRENA,2015; Y. Wang et al., 2016). Fuel cells can run on biofuels which are made through anaerobic digestion, fermentation, and gasification. In these processes, H_2 comes free (Antizar-Ladislao & Turrion-Gomez, 2008). This means that the fuel cell can run on, hydrogen, methanol, bioethanol, biogas, and dimethyl ether. Fuel from second generation biomass (organic waste) and third generation biomass (algae) can be used as fuel in a combustion engine and in a dual fuel engine. The type of emissions that come free are shown in table 34. The emissions are reduced compared to conventional fuels but there are still emissions coming free.

Table 32
Overview related processes with type of biofuel and emissions.

Material	Process	Biofuel	Emission
Organic waste	Anaerobic digestion	Biogas	CO_2
Organic waste	Fermentation	Bioethanol	CO_2
Algae	Fermentation	Hydrogen	CO_2
Organic waste	Gasification (syngas)	Methanol	CO
Algae	Gasification (syngas)	Hydrogen	CO
Organic waste	Gasification (syngas)	Dimethyl ether	CO_2
Algae	Phototrophic	Biodiesel (FAME)	-
Algae	Heterotrophic	Biodiesel (FAME)	-
Algae	Mixotrophic	Biodiesel (FAME)	-

Table 33
Possible combinations between engine and fuel.

Biofuel	Combustion engine	Dual Fuel	Fuel Cell
Hydrogen	√		√
Bio Methanol	√	√	√
Biodiesel	√		√
Dimethyl ether	√	√	√
Bioethanol		√	√
Biogas (biomethane)	√	√	√

Table 34
Emissions per engine – Biofuels.

Emission per engine	Biodiesel	Dimethyl ether	Biogas
Combustion Engine	High: NO_x Low: PM, HC, CO, CO_2	High: HC, CO Low: NO_x	n.a.
***Dual Fuel**	High: HC, CO Low: NO_x	High: HC, CO Low: NO_x, PM	High: HC Low: NO_x CO, CO_2 depends on the load
Fuel Cell	-	-	-

*Depends on the combination of fuels
-The emissions shown in this table are only the emissions that were researched in the used references. There could be more emissions coming free, but these are not mentioned.

Conclusions – Hydrogen, methanol, and biofuels

The fuel and engine which generates the least amount of emissions is the fuel cell with hydrogen. However, due to the high investment cost for a new infrastructure, several types of research concluded that methanol is a good alternative (Mathiesen et al., 2015, p. 150; Royal Academy

of Engineering, 2013). The downside of using methanol in a fuel cell is the emission of CO_2, which is not the case when hydrogen is used (Höhlein et al., 2000). This is shown in table 35 where the emission of a car running on methanol and hydrogen is compared (Höhlein et al., 2000).

Table 35
Comparison emission of a methanol and hydrogen car.

	CO (g/100km)	NO_x (g/100km)	CH_4 (g/100km)	VOC (g/100km)	SO_2 (g/100km)	PM (g/100km)	CO_2 (g/100km)
Methanol	0.1	0.01		0.1		0	7500
Hydrogen	0	0	0	0	0	0	0

Note. Adapted from '' Critical assessment of power trains with fuel-cell systems and different fuels", by Höhlein, B., von Andrian, S., Grube, T., & Menzer, R., 2000, . Journal of Power Sources, 86(1–2), 248.

There is no need for a special hydrogen infrastructure when the hydrogen is directly generated on board. Hydrogen can be produced through reforming hydrocarbon, gasification, pyrolysis, biophotolysis, fermentation, hybrid system, and electrolyse. Table 36 shows that no emission comes free when the production methods direct biophotolysis, direct biophotolysis and dark fermentation, and electrolyse are used in combination with a fuel cell. It should be taken into account that algae need sunlight to grow and produce hydrogen. A special algae system needs to be designed which can come to the surface of the ship. The other option of producing hydrogen is through electrolysis. This is done in an electrolyser. This electrolyser could be placed onboard of the ship. The ship itself can provide the electrolyser with water together with renewable energy to generate hydrogen. The hydrogen can then directly go into the fuel cell or dual fuel engine without the need of transport. The other two methods of generating hydrogen can still be used in a hydrogen economy where storage and distribution of hydrogen is not a problem.

Table 36
Combinations of the production process of hydrogen and engines which emit pollutants.

Hydrogen	Combustion Engine	Dual Fuel Engine	Fuel Cell
Reforming Hydrocarbons	X	x	X
Gasification - Algae	X	X	X
Pyrolysis - Algae	X	X	X
Direct biophotolysis - Algae	X	X	
Dark fermentation – Algae	X	X	X
Hybrid - Algae	X	X	
Electrolyse + Renewable energy	x	X	

Methanol could be used instead of hydrogen when it is not possible to produce the hydrogen directly on board and the needed infrastructure is not there. Methanol can be easily transported in the current infrastructure. This means that there are no high investment costs for the transportation of methanol. However, to reduce transport emissions and create a circular cruise ship this research also considers the possibility of producing methanol onboard. Table 37 shows that the production of methanol with renewable energy and hydrogen is the most sustainable option in combination with a fuel cell. To produce methanol from hydrogen CO_2 is needed. This CO_2 can come from the CO_2 that comes free when methanol is directly used in the fuel cell. If there is a processor unit onboard the methanol can be converted into hydrogen. During this process, a small amount of CO_2 is also emitted.

Table 37
Combinations of the production process of methanol and engines which emit. pollutants emissions

Methanol	Combustion Engine	Dual Fuel Engine	Fuel Cell Methanol	Fuel Cell Hydrogen
Gasification natural gas	X	X	X	X
Gasification biomass	X	X	X	X
Renewable energy and hydrogen	X	X		

• A small amount of CO_2 is emitted when hydrogen is used in a fuel cell

It is assumed that emissions come free when biomass, hydrogen, and methanol are used in a combustion engine and in a dual fuel engine. Table 36, Table 37, and Table 38 shows which combinations of fuels and engines emit pollutants emissions. Fuel from second generation biomass (organic waste) and third generation biomass (algae) can be used as fuel in a combustion engine and in a dual fuel engine. The benefit from 3rd generation biomass compared to 2nd generation biomass is that algae use CO_2 from the air or from flue gases during their process. Due to this, it is more sustainable to use algae for the production of biofuels. Algae can be used to treat wastewater and produce biofuel at the same time. The only question that arises is, is there enough biodiesel made for the propulsion of the ship, or are there external fuels needed. There are no emissions released during the process of making hydrogen and methanol and using them in a fuel cell. Literature does not report that emissions are released during the production of biodiesel from algae, this is therefore assumed in this research. Biodiesel can not be used in combination with a fuel cell. However, it is possible to run a fuel cell on biomass from organic matter. Hydrogen comes free through the gasification of the biomass; this can be used to power a fuel cell.

Table 38
combinations of the production process of biofuels and engines which emit.

Biofuel	Combustion engine	Dual Fuel	Fuel Cell
Hydrogen	X	X	
Bio Methanol	X	X	
Bioethanol	X	X	
Biodiesel	X	X	n.a.
Dimethyl ether	X	X	
Biogas (biomethane)	X	X	

Biofuel production on land

The text above focusses on the production of the biofuels onboard of the cruise ship. It is also possible to produce these fuels on land or in the harbour when there is not enough space or material input onboard.

Biogas can be produced onboard with an anaerobic digester. This is also possible on land. As with the production onboard this research only focusses on the use of organic waste as food waste, catering waste, and wastewater. The biogas production on land works similarly as the biogas production onboard. The food waste or wastewater comes into the anaerobic digester and biogas and the digestate come out. The biogas can be transported to the ship as fuel or used to generate electricity. The digestate can be used as fertilizer or for landscaping (S et al., 2016). This process can be seen in figure 53.

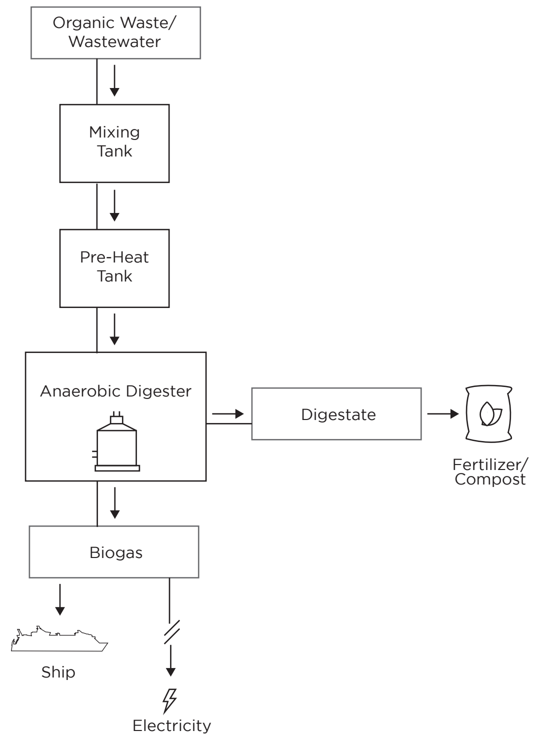

Figure 53: Biogass process.

As mentioned before, dimethyl ether can be formed from biomass. The first step is to form the syngas from biomass through gasification. This syngas is converted into methanol with a catalyst. The methanol is dehydrated with another catalyst to form dimethyl ether, see figure 54. The two-step reaction is shown below (Speight, 2011).

$2CH_4+O_2$ -> $2CO+4H_2$	(Gasification; Syngas)
$CO+2H_2$ -> CH_3OH	(catalyst 1; Methanol)
$2CH_3OH$ -> $CH_3OCH_3 + H_2O$	(catalyst 2; Dimethyl ether)

It is also possible to produce dimethyl ether through direct synthesis with a dual catalyst. Both processes are used on land. The two-step process is commonly used due to its simplicity and low start-up cost (Speight, 2011).

Biodiesel can be formed with the help of microalgae from plant oil and cooking waste. This research focusses on the use of algae. The production of biodiesel from algae can be separated into four steps: cultivation, harvesting/ concentration, processing and extraction, and transesterification, see figure 55 (Avagyan & Singh, 2019). This whole process with the different types of installations is explained in the biofuel chapter. The process onboard and on land is the same. However, it is easier to install this process on land or in the harbour because of the needed space and light. Figure 56 shows an example of the cultivation of algae.

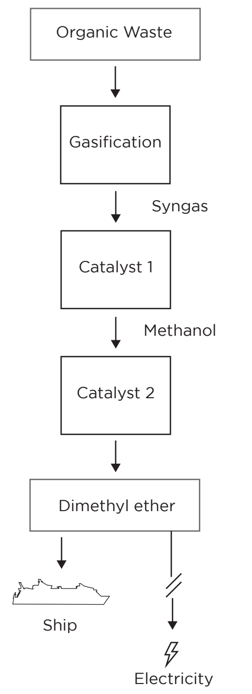

Figure 54: Formation of dimethyl ether.

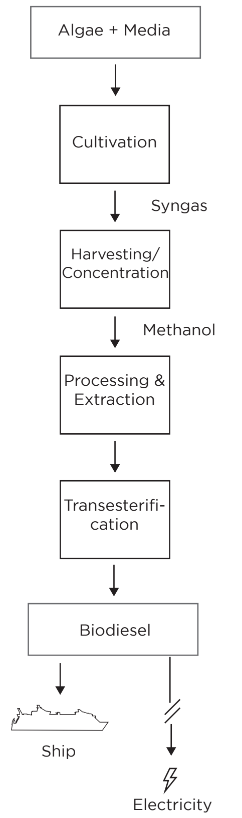

Figure 55: Production of biodiesel.

It is possible to produce all three types of biofuel on land. During the production of biogas and dimethyl ether, CO_2 comes free. This is not the case during the production of biodiesel from algae. All three fuels can be made close to the harbour which reduces transport costs and emissions. More research is needed to find out what the preferred


Figure 56: Algae cultivation.
Note. Reprinted from Qualitas (n.d.).

Figure 57: Soft sails
Note. Reprinted from IRENA (2015), p. 18

Figure 58: Fixed rotors
Note. Reprinted from IRENA (2015), p, 19

Figure 59: Flettner rotors
Note. Reprinted from IRENA (2015), p. 20

Figure 60: Kite sails
Note. Reprinted from IRENA (2015), p. 21

option is. This can differ per land and port.

Renewable electric energy – Onboard

Renewable electric energy sources do not release exhaust pollutants. Sources that could be used on ships are wind (soft sails, fixed wings, rotors, kites, and wind turbines), solar photovoltaics, and wave energy together with a battery (IRENA, 2015; Royal Academy of Engineering, 2013). These sources can be applied to newly built ships and retrofits. The energy can be used for primary, hybrid/ or auxiliary propulsion and for the onboard energy use. There is no dependency on oil when renewable energy is used (Royal Academy of Engineering, 2013). This chapter starts with an explanation of the renewable electric sources and their advantages and disadvantages.

Wind

The first ships sailed on a renewable energy source, the wind. The wind is a well understood renewable energy source. The downside of the wind is that it does not deliver constant power and that the power also differs when you sail in or close to the wind. There are five ways to capture wind energy: with soft sails, fixed sails, rotors, kite, and turbine technologies (IRENA, 2015).

Soft sails are a proven technology to capture the wind and is historically the oldest technique (IRENA, 2015; Royal Academy of Engineering, 2013). Nowadays soft sails can be used as primary or auxiliary propulsion for newly built and retrofits. Greenheart is one of the current market leaders, see figure 57.

A fixed sail is a sail that is attached to a rotation mast. These sails can be combined with photovoltaic panels. OCIUS an Australian company powers harbour ferries by implementing these fixed sails with photovoltaics, see figure 58 (IRENA, 2015).

Flettner rotors are rotating cylinders placed on board of the ship, see figure 59. When the wind passes the Magnus Effect is created, which is used for the propulsion of the ship. The force created has a linear relationship with the wind speed. This technique is used to assist the propulsion of the ship (IRENA, 2015; Royal Academy of Engineering, 2013).

A kite sail looks like a conventional kite and is attached to the bow of the ship, see figure 60. With this technique, the cargo ship MS Beluga Skysails is partially powered.

Wind turbines are often used on land and are a well-known technique. Till today there is no ship with this technique. Lessons can likely be learned from this technique which can be used later in the marine sector (IRENA, 2015).

Although the power generated from wind energy is not enough for the sole driver of the propulsion it can contribute to a big share of the required power (Traut et al., 2014).

Wind can never be the sole driver for the propulsion system because in the absence of any other system and wind the ship will lay still (Royal Academy of Engineering, 2013).

Solar

Photovoltaic (PV) cells are an evolving technique that can be used in the marine sector. Better energy storage techniques need to be developed to make it possible to fully power the propulsion system with PV cells. A large deck surface is needed which is not used or covered. This could be a limitation to generate enough energy (IRENA, 2015; Royal Academy of Engineering, 2013). The generated energy also depends on solar radiation. Which is dependent on latitude and longitude, elevation, time of the day, and day in the year (Diab, Lan, & Ali, 2016; Royal Academy of Engineering, 2013). Today some ships use PV cells with batteries for auxiliary propulsion. Batteries can be implemented for hybrid solutions as the fixed sails with PV cells, see figure 61. However, even when the maximum attainable power of the sun is used with 100% efficient PV cells and the limited deck area, the power generated would not be enough as the sole driver for the propulsion of the ship, only as support (Royal Academy of Engineering, 2013).

Figure 61: Example of fixed sail with PV cells.
Note. Reprinted IRENA (2015), p. 23.

Wave

The thought behind wave power is to mimic the manner of dolphins and fish for the propulsion. Underwater flaps (fins) are attached to the ship and use wave energy to mimic the tail movement of dolphins for the propulsion and to generate electricity and hydraulic power. Wallenius Wilhelmsen Logistics designed a ship with 12 underwater flaps to generate electricity (IRENA, 2015).

Batteries

Batteries can play a key role in hybrid solutions and reduce exhaust emission by reducing fuel consumption (Diab et al., 2016; IRENA, 2015; Royal Academy of Engineering, 2013). Batteries do not produce CO_2, NO_X, SO_X, volatile organic matter, or particulate emissions. However, it is important that when the battery is recharged this energy is made from renewable energy, and no land base emissions are produced elsewhere. There are multiple batteries in the market the conventional lead-acid batteries, zinc-carbon dry cell batteries and nickel-cadmium batteries, and the newer metal-air batteries, lithium-ion batteries, magnesium-ion batteries, and all-electron batteries. The conventional batteries do not meet the requirements for marine propulsion. From the metal-air batteries, the lithium-air battery is most promising. They are very light but need to get rid of their exhaust air as fossil-fuelled engines. A downside of lithium-air and lithium-ion batteries it the scarcity of raw lithium. The alternative is using magnesium,

which is more common, to create magnesium-ion batteries (Royal Academy of Engineering, 2013). More research is needed to make batteries efficient for the maritime industry. Researches think that batteries can play an important role in the propulsion of small and medium-size ships (IRENA, 2015; Royal Academy of Engineering, 2013). However, for bigger ships, they could support the energy need.
There are already several ships sailing which use batteries. Lloyd designed a Scandlines ferry that uses liquid hydrogen to power a fuel cell together with a battery system and in Norway, the Siemens Zerocat 120 is powered by a lithium battery (IRENA, 2015).

Conclusion – Renewable electric energy onboard
The renewable electric energy sources of today are unusable into providing enough energy for the propulsion of the ship. However, they can be implemented in a hybrid system. A combination of technology is needed to reduce the emissions in the marine industry, a hybrid system. Batteries are needed, to make this hybrid system possible. Research is done into optimizing batteries for marine use. Multiple renewable energy sources can be coupled to the battery. In the short future, the techniques to generate energy from renewable energy are insufficient for the propulsion of the ship as the sole energy driver. A combination can be made between renewable energy sources and a fuel cell connected to a battery. Renewable energy generated from the wind with soft sails, fixed wings, rotors, and kites and renewable energy generated with PVs has the most potential. Renewable energy generated from wave power is still in its infancy.

Renewable electric energy – Private Island
The bigger cruise lines have their own private island in the Caribbean. These islands could be used to produce renewable electric energy. This research investigates the following options, wind energy, solar energy, geothermal energy, and hydrokinetic energy.

Private Island
Royal Caribbean leases two private islands, Labadee in Haiti and Cococay in the Bahamas, see figure 62 and 63. Royal Caribbean cruises use these islands as beach gateway where the passengers can relax or do activities as going off a zip line and sliding of waterslides. Cococay is a flat island from 140-acre (0.56 km^2) in the Bahamas and Labadee is a resort from 260 acres (1.05 km^2) on the island of Haiti (Cruise Critic., 2019).

Figure 62: Labadee
Note. Reprinted from Royal Caribbean International (n.d.-f).

Figure 63: Cococay
Note. Reprinted from Cruisemapper (n.d.)

Wind
As previously mentioned the wind can be used the generate renewable electric energy. Wind turbines can be used on land. There are two main types of wind turbines, horizontal axis, and vertical axis wind turbines, see figure 64. The most commonly used wind turbines are the horizontal turbines with two or three blades. Horizontal wind turbines have an efficiency of 47% and can be connected to the grid for commercial use. Some disadvantages of horizontal wind turbines are, high capital cost due to the tower, difficult to maintain, and protection is needed to prevent over-speeding. Vertical wind turbines have an efficiency of 37% and do not need a high tower. Due to this, the capital cost is lower, the maintenance is easier, and no over speed protection is needed. However, because this type of wind turbine does not use the higher wind speed because of its lower height, the power coefficient is lower. A general disadvantage of wind turbines is the optical distortions, as shadows and noise. The infrastructure cost can be reduced by placing multiple wind turbines in one area (Al-Bahadly, 2009).
Wind turbines can be connected to the main grid if they generate a constant output frequency, otherwise, an asynchronous generator or electric frequency converters are needed. Small turbines can directly be connected to the grid network at 0.4kV. Big megawatt turbines can be connected to the city electricity share distribution of 10-30kV. In remote areas, there is no electricity share distribution. In this case, the wind park developers must create one. Wind parks in Germany are connected to the electrical grid at 110 kV (Wagner, 2013). Wind turbines can be used on the private island to generate electricity. To decided which wind turbine, more research is needed into the conditions of the island and wind turbines.

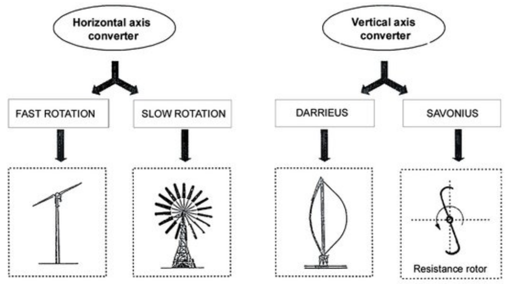

Figure 64: Example horizontal and vertical axis wind turbines
Note. Reprinted from Wagner (2013), p. 2.

Solar
Solar energy uses the inexhaustible and free energy of the sun. Around 30% of the solar energy that comes to the earth is scattered or reflected, 70% can be harvest and captured. The intensity of solar radiation differs around the world, see figure 65 (Kabir, Kumar, Kumar, Adelodun, & Kim, 2018). There are passive and active solar energy technologies. Passive systems do not transform the thermal or light energy into another form of energy. This type of energy can be used for the heating of homes. Active systems convert solar energy into heat and electric power. A distinction can be made between photovoltaic technology which is previously mentioned and solar thermal technology. Photovoltaic technology can convert sunlight directly into electrical energy. There are different types of photovoltaic technologies, wafer-based cells, commercial thin-film cells, and new thin-film technologies. Solar thermal energy is

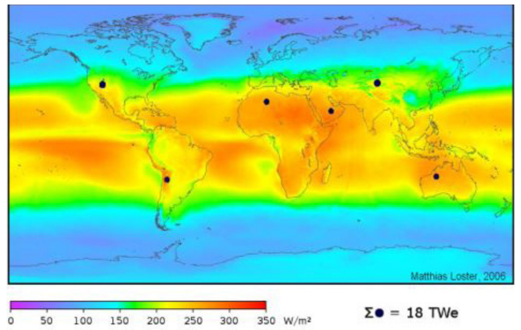

Figure 65: The intensity of solar radiation.
Note. Reprinted from Kabir, Kumar, Kumar, Adelodun, & Kim (2018), p. 895.

used for commercial applications as heating, cooling, and cooking. However, concentrated solar power (CSP) can generate electricity. This system uses mirrors to concentrate the solar energy, the heat is used to power a steam turbine. There are four types of CSP technology parabolic troughs, fresnel mirrors, power towers, and solar dish collectors (Kabir et al., 2018).
The downside of solar power is the high initial installation cost, low efficiencies (10-20%), sensible to dust, algae, and water intrusion and made from rare or precious metals. However, the benefits of solar power are the unlimited potential of the sun, it is non-polluting, reliable, free of noise pollution, and easily installed on all kind of surfaces (Kabir et al., 2018). It is possible to use photovoltaic technologies and concentrated solar power to generate electricity on the private island. More research is needed to find out which system is most suitable for the islands.

Geothermal Energy
Geothermal energy is the contained heat in the interior of the earth. The heat is transferred through conduction and convection from the depth to the sub-surfaces of the earth. Geothermal energy can directly be used for heating and indirectly to generate electricity. The efficiency of producing electricity from geothermal energy is between 10-17%. The earth consists out of three zones: crust, mantle, and core. The lithosphere is the earth's crust together with the upper part of the mantle and it is divided into plates. These plates move slowly to each other, away from each other, or slide past each other. The boundaries between the plates are the place with the highest energy potential. Geothermal activity as hot springs, steam vents, and geysers are an indication of warm subsurface rocks. Next to this, a reservoir is needed from permeable rocks on drilling depth to form a productive geothermal resource. There are four types of geothermal systems, hydrothermal, hot dry rock, geopressured, and magmatic (Barbier, 2002). The first system is already exploited, the latter three may be possible in the future. Hydrothermal systems can be subdivided into water-dominated or vapour dominated. Water dominated fields are hot water fields and wet steam fields. Hot water fields have the lowest temperature and can be used for heating. Wet steam fields can be used to generate electricity. The heat transfer from vapour fields is higher than in wet steam fields. These fields produce half of the geothermal electric energy generated in the world. However, geothermal energy is not a renewable energy source. With good reservoir management, the geothermal source can be used for several decades. Next to this, geothermal energy has also some other negative effects on the environment. Gases as CO_2, H_2S, NH_3, CH_4, N_2, and H_2 come free into the atmosphere. These gases do not come in

the environment when binary plants are used. Next to this, water pollution, land subsidence, and noise are side effects of geothermal energy (Barbier, 2002). This needs to be taken into account when considering geothermal energy. To use the geothermal energy a hole needs to be drilled into the earth, see figure 66. This has a huge impact on the area, especially for a small island. If a geothermal source is found on the island it could be used to produce electricity. However, more research is needed into these possibilities and environmental impacts.

Hydrokinetic
Hydrokinetic and hydrostatic methods are both ways to generate hydropower. Hydropower is one of the largest and cheapest renewable energy sources on the planet. A hydrostatic method is, for example, a dam. However, this is not an option, due to the environmental impact and the type of location. Compared to solar and wind, hydrokinetic energy is more predictable. Using hydrokinetic energy is a good option for off-grid places. However, a downside of hydrokinetic technology is the low power coefficients and the maximum efficiency of 59.3%. The technology used to generate hydrokinetic energy is similar to that of wind energy. River, tidal, and wave energy are the three sources that can be used for hydrokinetic energy. Tidal movements and river flows are better to predict than wave movements. The downside of using wave energy are the harsh conditions the turbines must operate in. The turbines should be designed to overcome these forces. There are two main categories of hydrokinetic technologies, the current energy conversion (CEC), and the wave energy conversion (WEC) systems. The CEC systems can be divided into horizontal axis, vertical axis, helical, and ducted turbines. Most of these systems use two or three rotating blades. The horizontal axis turbine is most commonly used. The WEC system can be divided into oscillating water columns (OWC), overtopping devices (OTD), and wave activated bodies (WAB). All these systems float in the sea and use the movements of the wave to generate energy. Hydrokinetic systems do not have a huge environmental impact in contrast to the conventional hydrostatic systems. However, it is possible that the turbines can hit aquatic organisms, generate noise, vibration, and turbulence which can negatively influence the aquatic environment. Sensitive areas should be avoided, and more research is needed in these effects (Güney & Kaygusuz, 2010; Yuce & Muratoglu, 2015). The first hydroelectric systems produced DC, but today AC generates can be used. AC is used when the hydroelectric system is connected to the grid. For this synchronous and asynchronous generator can be used. Synchronous systems are used for big hydroelectric systems. Asynchronous generators cannot regulate the voltage thus a stationary water regime is

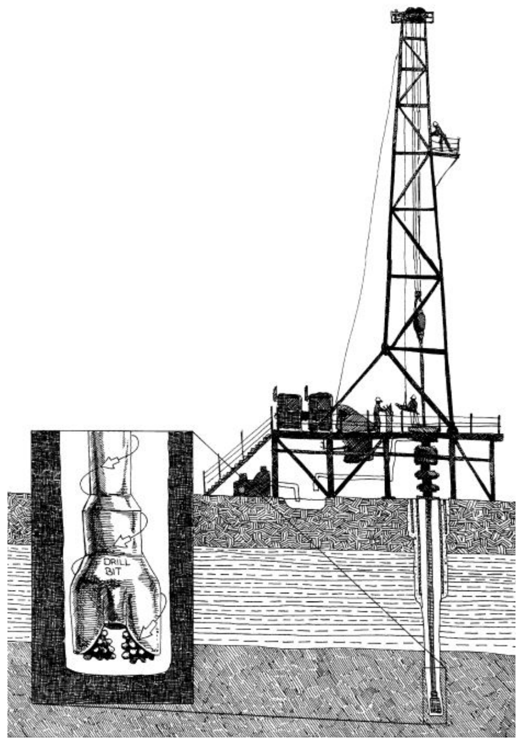

Figure 66: A drill and drill bit digging into the ground.
Note. Reprinted Barbier (2002), p. 32.

needed. Which generator is chosen depends on the size of the power system. Hydrokinetic energy can be used to generate power on the private islands (Güney & Kaygusuz, 2010). More research is needed into the most efficient and suitable system for the private island of Royal Caribbean. Figure 67 shows two types of tidal systems and two types of wave systems.

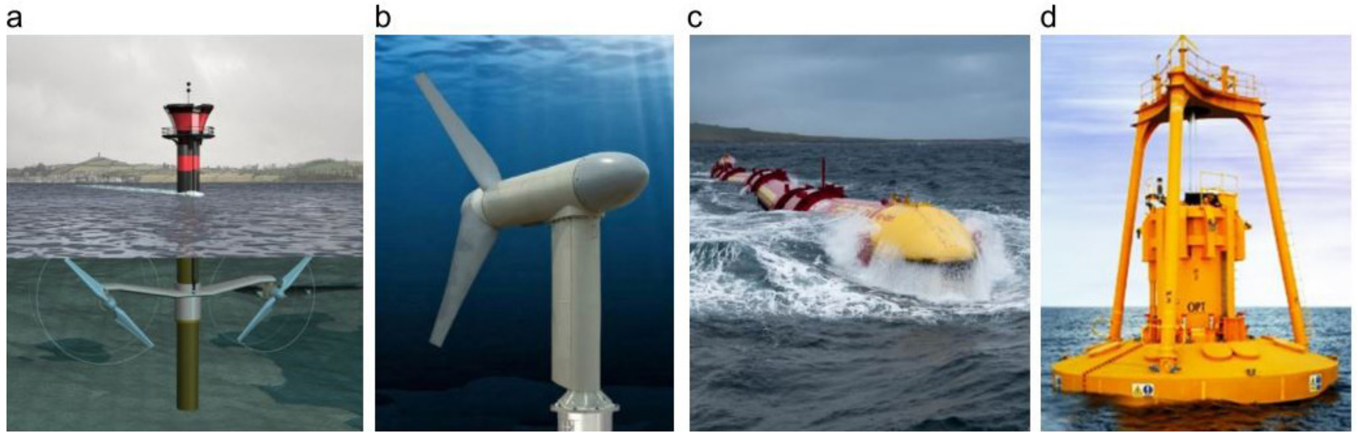

Figure 67: Examples of tidal and wave systems. A. Horizontal axis bidirection two bladed proppelor, B. Three-bladed rotor, C. Wave energy conversion, D. two body heaving mechanism (wave energy).
Note. Reprinted from Yuce & Muratoglu (2015), p. 77.

Conclusion – Renewable electric energy private islands

Wind energy, solar energy, geothermal energy, and hydrokinetic energy are all options to produce electricity on the private island of the Royal Caribbean. Solar and wind energy are more common and known ways to produce electricity. Photovoltaic technology can be installed on roofs or on empty areas on the island. Horizontal or vertical wind turbines can also be placed on the island. Which system should be used depends on the amount of usable space. Tidal movement and wave energy can be used as sources to produce hydrokinetic energy. However, more research is needed into which systems. Geothermal energy can only be used if there is enough geothermal activity to produce electricity. However, the downside of this is the environmental impact and required space to extract the heat. This takes up a lot of space compared to the relatively small island.

All the systems should be connected to the grid of the island to make sure the power can be transferred to the ships. The generated electricity can only be used for the ships that dock on the islands. The question that arises is: Should this energy be used for cruise ships or for the island itself? This depends on the amount of generated energy. It is better to use the power for the island itself when the generated electricity is relatively little compared to the needed electricity for the propulsion or hotel load of the ship.

4.3.3.2 Fluid waste stream

Chapter 4.3.2.2 shows that black and grey water is treated together with the systems of Evac. By using this system, the discharged wastewater complies with the current legislation set by IMO. This legislation focusses on BODs. TSS, faecal coliform, free chlorine, and ph. From some other components, it is not verified that they are taken out. Black and grey water also contain micropollutants that are not removed by the treatment systems. This means that pollutants still enter the sea when wastewater is discharged. Research is still being conducted in new treatment systems which can remove or reduce the number of micropollutants, heavy metals, nutrients, phosphorous and nitrogen in the current discharged wastewater (Bentley & Ballard, 2007; Grandclément et al., 2017; Koboevic & Kurtela, 2011; Vicente-Cera et al., 2019; Westhof et al., 2016). The discharged bilge water also complies with the current legislation of the IMO, which only focusses on the oil content and not on other harmful particles. This means that the bilge water still contains some hazardous components as emulsified oil and heavy metals which come back into the environment. In this research, the systems from Evac are used as the base and it is assumed that this is the best treatment system on the market. This research looks into the possibility of small beneficial adjustments or additions for the black and grey water stream and new wastewater treatment for the bilge water stream.

Black and Greywater - Adjustment and additions

Chapter 4.3.2.2 showed that wastewater can be treated by implementing algae and anaerobic digestion. Biodiesel and biogas are simultaneously produced during this process. Figure 68 shows the Evac system which is now used on board of the Royal Caribbean cruise ships. It can be seen that the black and grey water is treated together and that two streams are left over, the solids and the bio sludge. Solids are the bigger solid parts of human faeces and solids from galley water. Bio sludge is the sludge that is skimmed off in the DAF. Bio sludge consists most of the time of heavy metals, pathogens, organic pollutants, and nutrients as phosphor, nitrate, and ammonium (Lundin, Olofsson, Pettersson, & Zetterlund, 2004).

Black and Greywater - Anaerobe digestion

Wastewater from food waste and sewage sludge can be treated by an anaerobic digester. Figure 69 shows that in the wastewater treatment plant of Ryaverket, Gothenburg, Sweden the anaerobic digestion happens after the first phase (Börjesson, Melin, Matussek, & Lindgren, 2009). This could mean for the wastewater treatment process of the Royal Caribbean that the anaerobic digester can be connected to the solid handling, see figure 70. By doing this, useful components are removed from the sludge before it goes, in this system, to the incinerator.

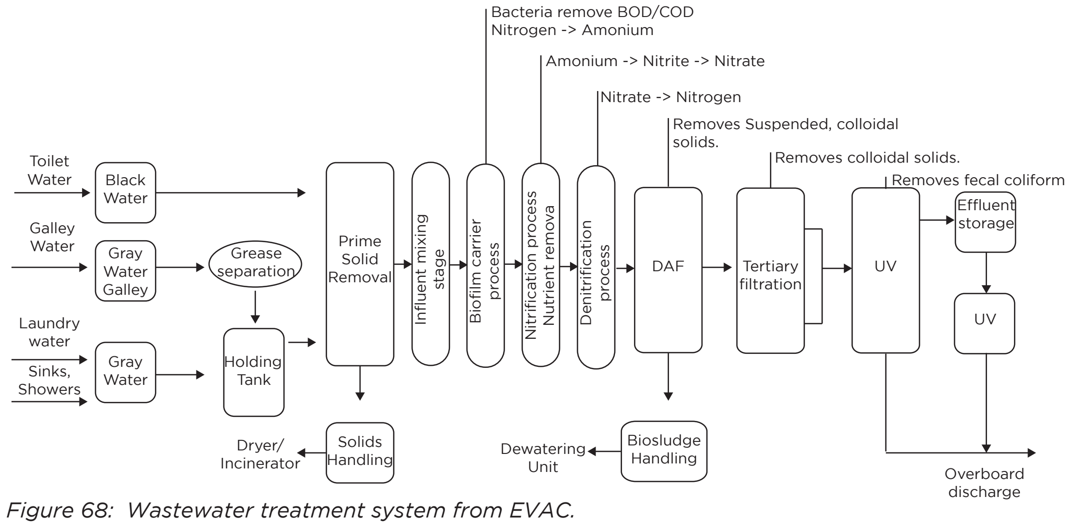

Figure 68: Wastewater treatment system from EVAC.
Note. Adapted from Evac (2019).

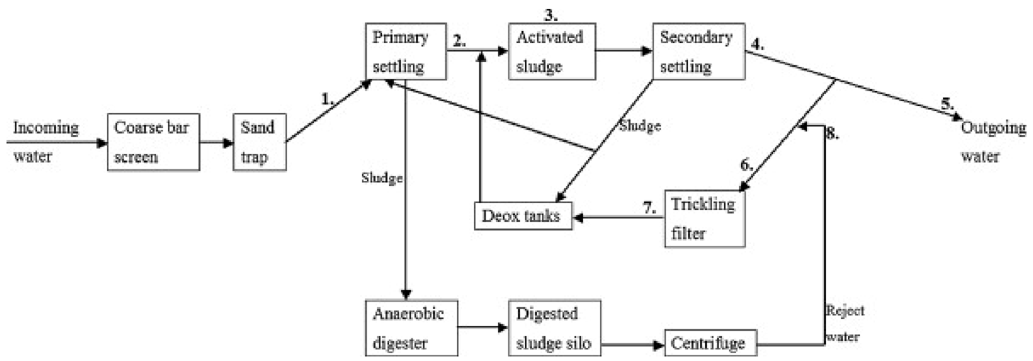

Figure 69: Schematic drawing wastewater treatment plant Ryaverket.
Note. Reprinted from Börjesson, Melin, Matussek, & Lindgren (2009), p. 926.

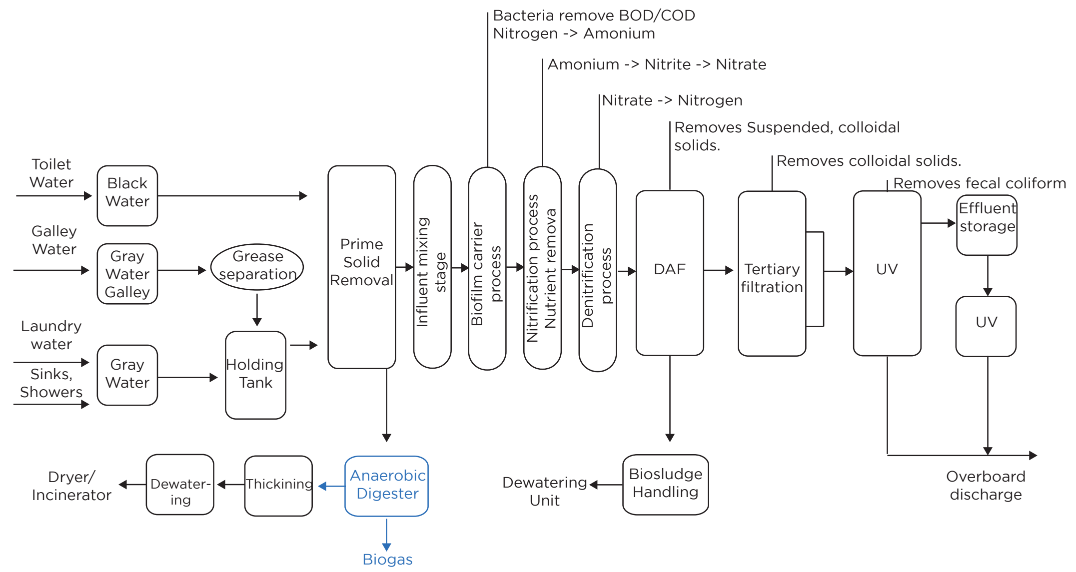

Figure 70: Wastewater treatment system from EVAC with anaerobic digester.
Note. Adapted from Evac (2019).

Black and Greywater - Struvite removal

Phosphor and nitrogen are important nutrition's for agriculture and can be recovered by precipitating of struvite (NH_4MgPO_4 $6H_2O$), also called magnesium ammonium phosphate. In most wastewater treatment plants the precipitating of struvite is connected to anaerobic digestion. By doing this a higher phosphor concentration is created in the digester effluent, which is returned to the beginning of the plant, see figure 71 (Sena & Hicks, 2018). However, this is not the only place where phosphor can be recovered. Figure 72 shows the possible places to recover phosphor. The light blue bar (sewage sludge) has the highest recovery potential according to figure 73. The sludge is formed by anaerobic digestion and can be collected after this process (Egle, Rechberger, Krampe, & Zessner, 2016). The struvite recovery can be implemented in the wastewater treatment process of Royal Caribbean together with anaerobic digestion, see figure 74. The ship produces biogas and struvite by implementing these two processes. These products can be used onboard or on land.

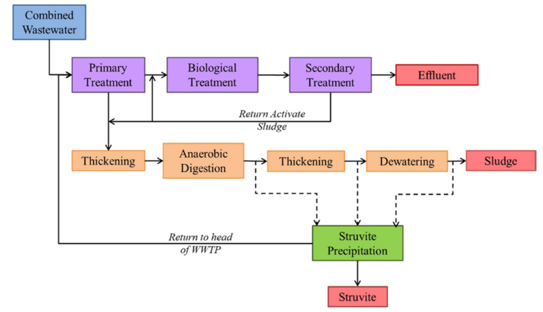

Figure 71: General layout of struvite precipitation in a wastewater treatment plant.
Note. Reprinted from Sena & Hicks (2018), p. 197.

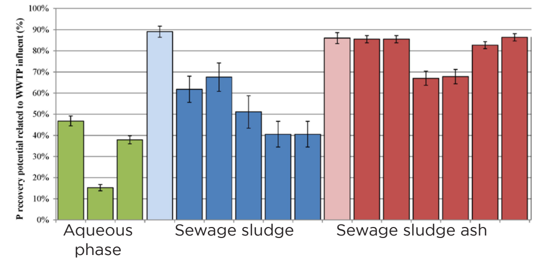

Figure 72: Various possible points for P recovery.
Note. Adapted from Egle, Rechberger, Krampe, & Zessner (2016), p. 523.

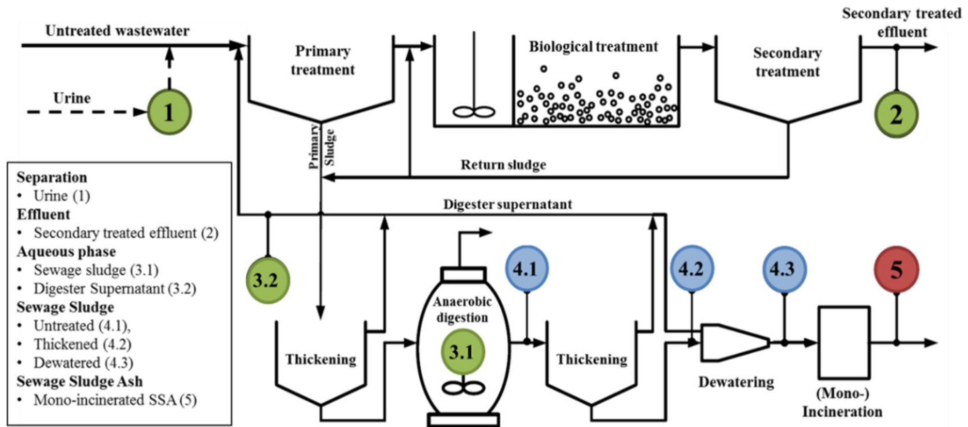

Figure 73: P recovery potential.
Note. Reprinted from (Egle, Rechberger, Krampe, & Zessner (2016), p. 532.

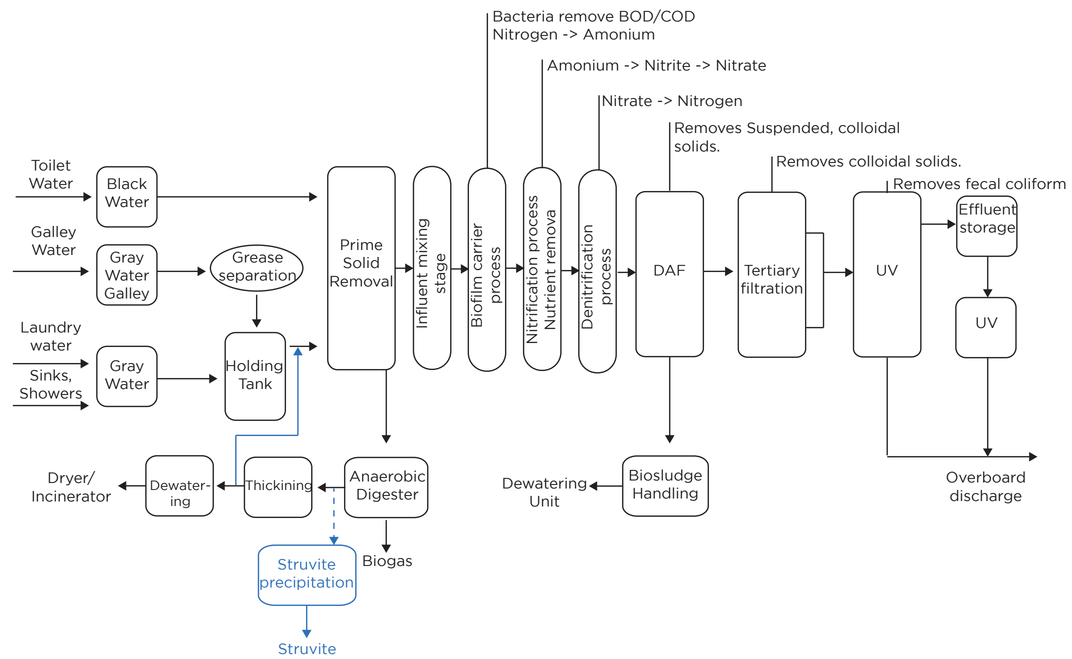

Figure 74: Wastewater treatment system from EVAC with anaerobic digester and struvite precipitation.
Note. Adapted from Evac (2019).

Algae

Another option to clean the wastewater is by algae, which produce biodiesel. Algae can remove nitrogen and phosphor from the wastewater. These nutrition's are found in the (bio) sludge (Avagyan & Singh, 2019; Lundin et al., 2004). However, the sludge is most likely to compact and to dry for microalgae to grow. Algae can be applied in the wastewater treatment process after the denitrification process and before the DAF. All the required nutrients are then still in the wastewater and the wastewater is still in its liquid form, see figure 75. However, to make this possible the water and algae that flow through the pipes must receive sunlight. A special design must be made to make this possible. For example, a pipe system visible on the side of the ship, around the chimney, or under the helicopter deck. After the algae removed the nitrogen and phosphor the wastewater can go into the DAF which removes the suspended and colloidal solids.

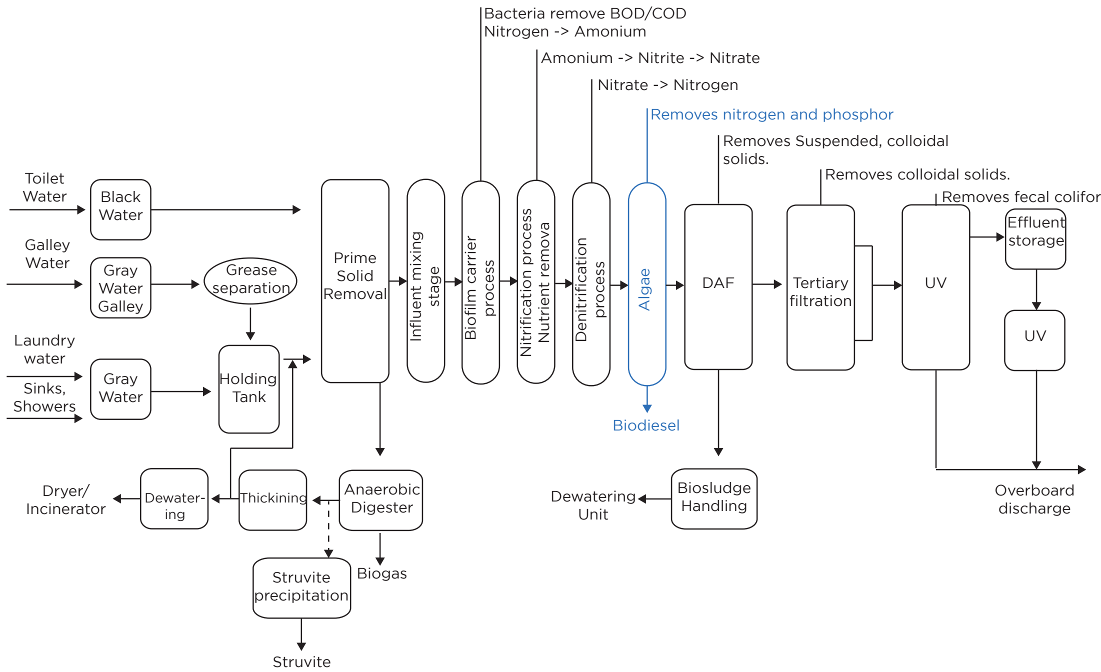

Figure 75: Wastewater treatment system from EVAC with anaerobic digester, struvite precipitation and algae.
Note. Adapted from Evac (2019).

Black and Greywater - Heat recovery

Besides using the chemical energy from wastewater, thermal energy can also be recovered. In fact, the potential of thermal energy is higher than chemical energy (Hao, Li, van Loosdrecht, Jiang, & Liu, 2019). Both black and greywater can be used for heat recovery. The wastewater from showering, laundry, cleaning, and cooking (grey water) has a high temperature which can be recovered. This is done in a project called waterschoon in the Netherlands (Urban green-blue grids, n.d.). A heat exchanger can be used to recover the heat from showers and immediately use it. This is the only process where the inflow of cold water and outflow of hot water happens at the same time. This

research looks into separately treating shower water from the other waste streams because of that reason.

The cold water that goes to the shower is preheated by the warm water that comes out of the drainage. By doing this less energy is needed to heat the water to the desired temperature. The pipe with hot wastewater is made from materials that can exchange the heat, for example, aluminium or copper (McNabola & Shields, 2013). Figure 76 shows how the cold-water pipes are wrapped around the hot water drain. There are horizontal and vertical heat exchangers on the market. Vertical heat exchangers have a higher efficiency but require a space of 1-2m below the shower. When this is impossible to install, a horizontal heat exchanger can be used. The wastewater can be used to preheat the hot water, preheat the cold and hot water, or to preheat the cold water. Horizontal heat exchangers mostly use the wastewater to preheat the cold water. Vertical heat exchangers can preheat the hot water, and the cold and hot water (Bertrand, Aggoune, & Maréchal, 2017; McNabola & Shields, 2013). Detailed research should be conducted to find out which options work best on a cruise ship. Figure 77 shows the wastewater treatment process including the heat recovery of the greywater stream.

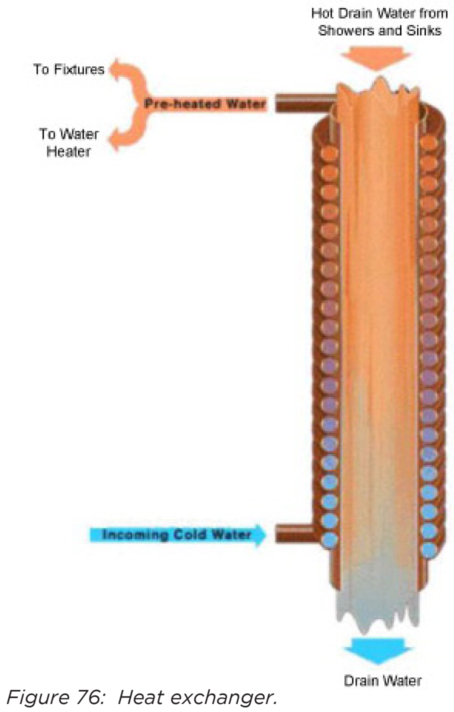

Figure 76: Heat exchanger.
Note. Reprinted from McNabola & Shields (2013), p. 45.

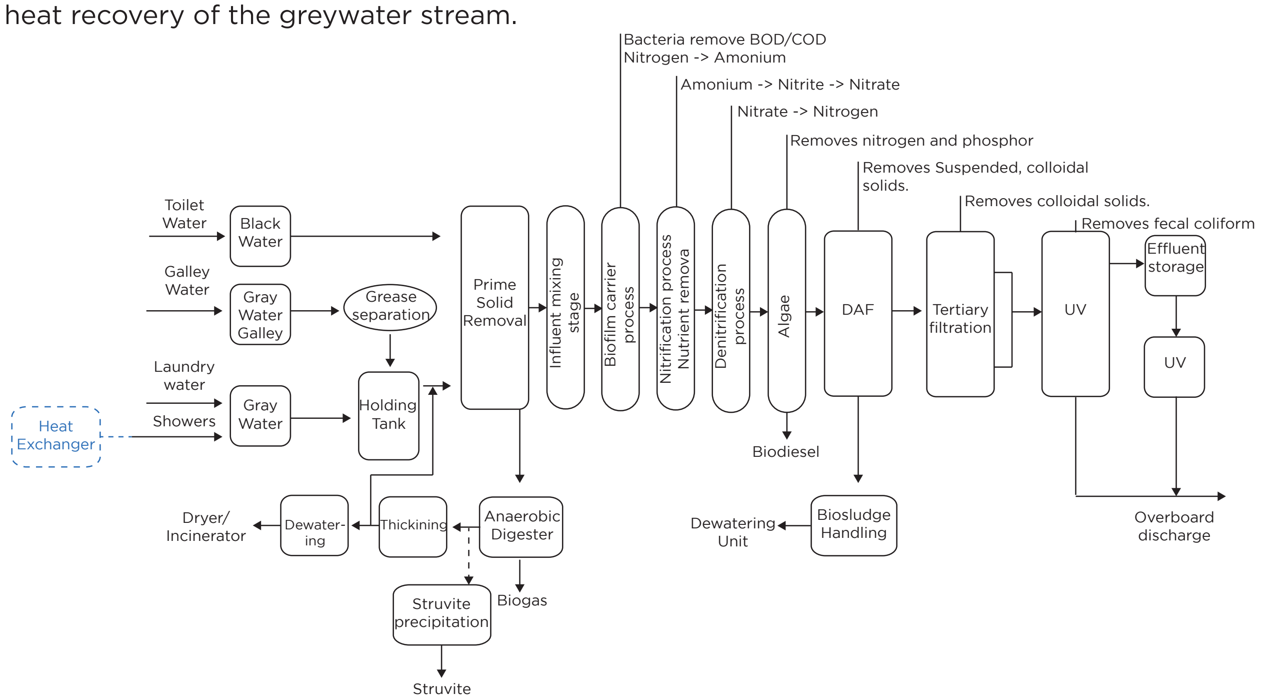

Figure 77: Wastewater treatment system from EVAC with anaerobic digester, struvite precipitation, algae and heat exchanger.
Note. Adapted from Evac (2019).

The heat from the remaining grey water streams and the black water stream is recovered after the streams are brought together. Culha et al. (2015) state that there are multiple options to place the wastewater heat exchanger for buildings, see figure 78. When translated to a cruise ship this could mean per single or group of cabins, all the cabins together before wastewater treatment, and after the wastewater treatment. Option 2 and 3 remain to treat

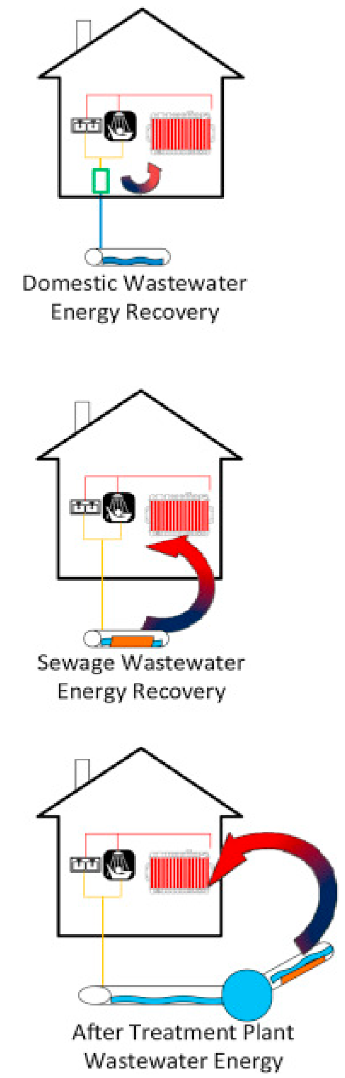

Figure 78: Possible places for wastewater energy recovery.
Note. Reprinted Culha, Gunerhan, Biyik, Ekren, & Hepbasli (2015), p. 223.

the remaining grey and black wastewater. Extracting the heat in the sewage system, option 2, is the most common system used in urban areas. There is a continuous stream of wastewater that contains high heat energy. The downside is that the treatment process of the sewage treatment plant can be negatively affected by this (Culha, Gunerhan, Biyik, Ekren, & Hepbasli, 2015). Research should be done into the optimisation of the energy recovery without decreasing the efficiency of the wastewater treatment process. There are different types of heat exchanges to recover the heat from the sewage system, external, integrated, modular, and specially designed. The heat exchanger can be installed outside the sewage system. The piping system is not inside the channel which prevents biofouling. The heat exchanger can also be integrated into the sewage system, which is easier in case of a newly built system. The modular heat exchanger can be installed in the sewage channel and designed according to the existing dimensions. The heat exchanger can also be placed after the wastewater is treated. In this case, the wastewater treatment system is not affected by the heat exchanger. The recovered energy from the wastewater after the sewage treatment process is higher compared to the domestic and sewage heat exchangers (Culha et al., 2015). Next to this, research shows that some problems can occur during the heat recovery of black water, like blockage, corrosion, and biofouling. Because of that Hao at al (2019) states that treated sewage water is the preferred place for heat recovery. However, in urban areas, a lot of heat is lost because the treatment plants are far away from the end-user (Culha et al., 2015). This is not the case by a cruise ship. Based on this information it is advised to install the heat exchanger after the wastewater treatment process, see figure 79. However, more extended research is needed into this topic.

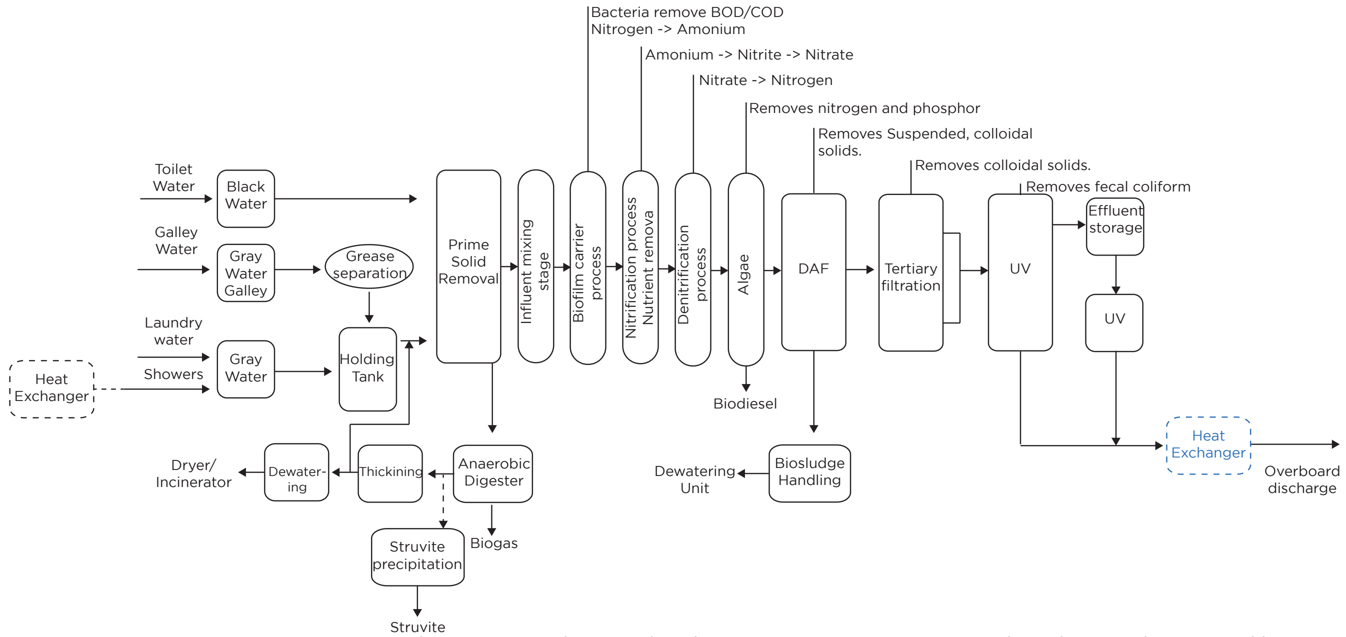

Figure 79: Wastewater treatment system from EVAC with anaerobic digester, struvite precipitation, algae, heat exchanger and heat recovery.
Note. Adapted from Evac (2019).

Bilge water

Chapter 4.3.2.2 showed that the current wastewater treatment system used for the treatment of bilge water comply with the rules of IMO. However, the legislation only focusses on the oil content and not on other harmful particles in the bilge water as heavy metals. This research looks into the possibility of implementing electrochemical wastewater treatment into the current system, see figure 80.

Treatment systems

A new wastewater treatment is under development, called electrochemical wastewater treatment. According to the literature, this is a very promising method that can remove emulsified oils, heavy metals, grease, organic matter, etc. When this treatment is fully developed it can be installed on newly built cruise ships. However, this method is insufficient in removing all the pollutants by itself. A combination with for example a membrane is needed, see figure 81. More research is needed for the most effective combination. This research only looks into the possibility of using electrochemical treatment for bilge water and not for other wastewater streams.

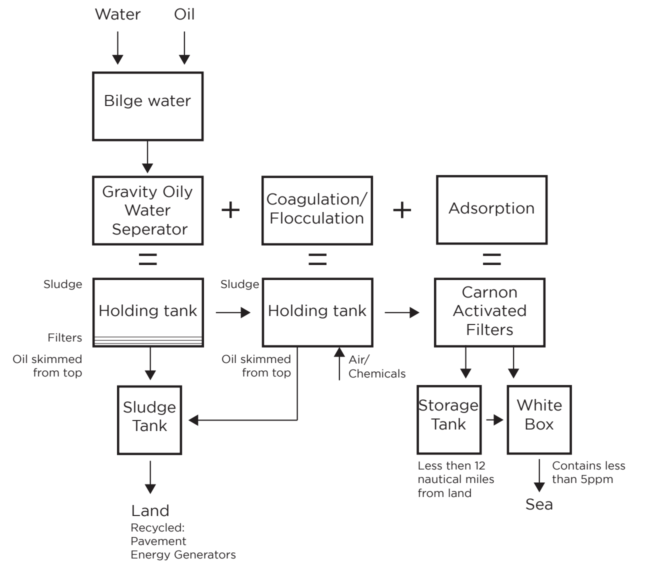

Figure 80: Current bilge water process.

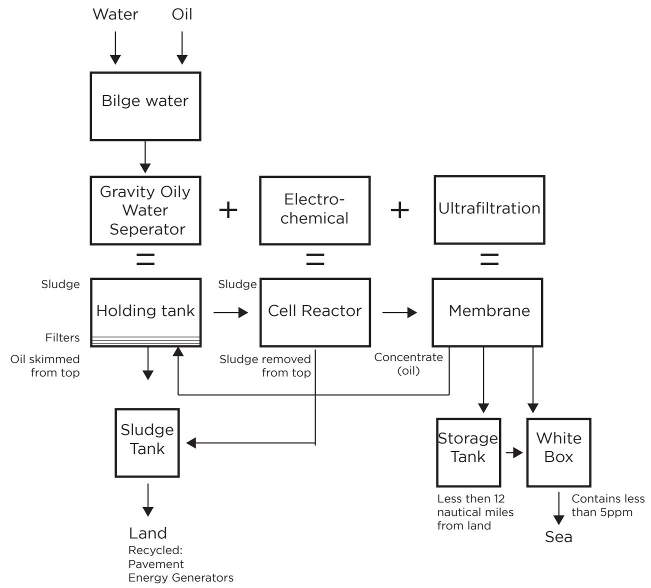

Figure 81: Bilge water process with electrochemical treatment.

Ballast water

There is no need for a new ballast water treatment system because no hazardous substances come back in the environment.

Sludge and wastewater treatment on land

Several by-products are formed during the treatment of black and grey water and bilge water. Sludge and bio sludge (biosolids) are left after black and grey water treatment and (oily) sludge remains after bilge water treatment. Next to this, both waste streams discharge the treated

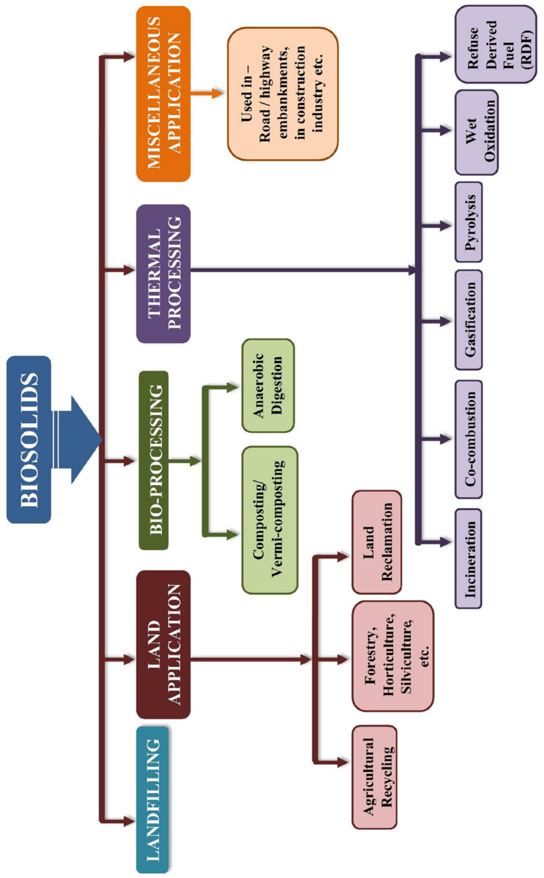

Figure 82: Waste management options for biosolids.
Note. Reprinted from Sharma, Sarkar, Singh, & Singh (2017), p. 121.

wastewater, with a small amount of pollutants into the sea. This research investigates the possibilities of storing the sludge and treated water until it can be disposed of to land where it can be recycled in a sustainable way.

Black and grey water sludge

Biosolids is another name for sludge given by the Water Environment Federation to convince people something good can be done with the remaining wastewater. Biosolids is sludge that comes from wastewater treatment and is produced in such a way that it can be used as land application and improve soil quality. There are several laws for the disposal of sludge. Since 1988 it is not allowed to dump sludge into the sea and there are concentration limits for pathogens, metals, and nutrients in the sludge. Biosolids can come in different forms: liquid, cake, and pellet. Liquid sludge is not dewatered or dried and comes directly from the digester. Cake sludge can be compared to a wet sponge and is created with (un)digested liquid sludge with quicklime or hydrated lime. Lastly, pallet biosolids are heated and have a solid content of 90%. Liquid biosolids release nutrients faster than dewatered biosolids (Lu, He, & Stoffella, 2012; Swierczek, Cieslik, & Konieczka, 2018). Sewage sludge contains out of organic matter, mineral components, nutrients (as N and P), and inorganic (heavy metals) and organic (pesticides, surfactants, hormones, pharmaceuticals, nanoparticles, etc.) contaminants. With appropriate treatment, the number of pathogenic and parasitic organisms can be reduced (Kacprzak et al., 2017). There are multiple options for biosolids disposal: landfilling, land application (agricultural, horticultural, silvicultural, and land reclamation), bio-processing (composting and anaerobic digestion), thermal processing (incineration, co-combustion, gasification, etc.) and miscellaneous applications, see figure 82 (Sharma, Sarkar, Singh, & Singh, 2017). Landfill should be avoided because of direct CO_2 emissions and leachate production which is bad for the environment. Special guidelines are made to restrict the amount of sludge sent to landfill. Agricultural use, landfill, and incineration are most often used for sludge disposal. Agricultural use is seen as the best practicable environmental option (BPEO). However, this is not always possible due to the restrictions of sludge use for agricultural purposes. Contaminants could accumulate in the soil when sludge is used for a long time. The sludge must be analysed before it can be used for this purpose. Some countries implemented stricter limits for contaminations, and others banned the use of sludge for agricultural use completely. However, other countries as Norway recycle 80% of the biosolids to farmland (Kacprzak et al., 2017). Guidelines are made to regulate the use, prevent harmful effects, and encourage the use of biosolids for agricultural purposes (Kelessidis

& Stasinakis, 2012). Sharma et al., (2017) concluded that sludge can be a good substitute for inorganic fertilization. Using biosolids is good for the health of the soil, enriching the soil with nutrients and increasing the pH. However, the use of biosolids should be done cautiously. The sludge can also be used for horticulture and to restore degraded land. Bioprocesses as composting and digestion reduce the amount of organic N due to mineralization and an increase in P and trace metals. The composted biosolids can be used as the replacement of inorganic fertilizers. The benefit of using biosolids is that they release the nutritions at a slow pace. Next to this, it also reduces the number of pathogens (Lu et al., 2012). Incineration is one of the options under thermal processing. When the quality of the sludge does not comply with the legislation or the biosolids cannot be used on land the sludge goes most of the time to the incinerator. Energy is recovered in this process and the sewage sludge ash remains. Gasification and pyrolysis are used to produce solid fuel and co-incineration means that the sludge is burned together with other solid waste or fuels. The downside of pyrolysis is that it requires more energy to be heated and has subsequent treatment costs (Kacprzak et al., 2017; Smol, Kulczycka, Henclik, Gorazda, & Wzorek, 2015; Swierczek et al., 2018). Smol et al., (2015) state that incineration is not the last step in the management of sludge due to the remaining ash. They investigated the possibility of using sewage sludge ash in the construction industry. The ash consists of hazardous and toxic waste. The sewage sludge ash can be used in cement production, ceramic and glass production, brick production, and road construction. Holland America line is designing an “ash bricking” system to bag incinerator ash (Herz & Davis, 2002). Biosolids can also be used for other applications. The raw sewage sludge itself can be used in the construction industry (Swierczek et al., 2018). When sludge is used for the production of a product, the environmental threat is taken away. The raw sewage sludge can be used to produce cement mortars and concretes. Dried sewage sludge can be used for example in the production of bricks and tiles, and for concrete with lightweight aggregate. The sewage sludge can be used in lightweight aggregates and ceramics when it is sintered, which requires a lot of energy. However, the product itself is more durable than commercial aggregates (Swierczek et al., 2018).

Bilge water sludge

In the case of the bilge water stream, the oily sludge is skimmed off and stored in a tank. The remaining oily sludge consists out of oil products, water, and mechanical impurities as clay, sand, and metal oxides. The oily sludge can be used as asphalt extender, binder for paved and unpaved road mixes, material for the composition of asphalt concretes, and as roadbed material. Research is also done into the use of oily sludge for waterproofing, this is still under investigation (Al-Abdul Wahhab & Dalhat, 2014; Kopylov & Burenina, 2019; Xiao, Yao, & Zhang). When oily sludge is used as a material into the mixture for asphalt concretes, the amount of required bitumen can be reduced because the internal pores are filled with the oils and resins. By implementing the oily sludge into these products an alternative treatment is provided with economic and environmental benefits (Kopylov & Burenina, 2019; Xiao, Yao, & Zhang). The sludge is not incinerated in these cases which reduces the emissions into the air.

Discharged wastewater

The wastewater that is discharged into the sea complies with the legislation set by IMO. However, it still contains some amount of pollutant substances. Per person per day 65.0 litres of black water is discharged into the sea together with 146.6 litres of greywater. It is assumed that an average cruise ship has a capacity of 3000 guests. This results in 634,800 litres of black and greywater per day. It is impossible to store all this treated wastewater onboard of a cruise ship. Today around 20% of the wastewater is reused. The cleaned water can be used for flushing the toilets, laundry, and watering the plants.

A cruise ship that sails in Alaska generates around 5-20m^3 bilge water per day, which is equal to 35-140m^3 (35,000-140,000 litres) in a week (Rincón & La Motta, 2014). It is assumed that it takes a cruise ship one week to return to the homeport. This means that the ship must store 35-140m^3, treated bilge water including the sludge, which is impossible. The only possibility is to discharge the treated bilge water into the sea and store the sludge. Figure 83 shows the treatment process with the end location of the waste products.

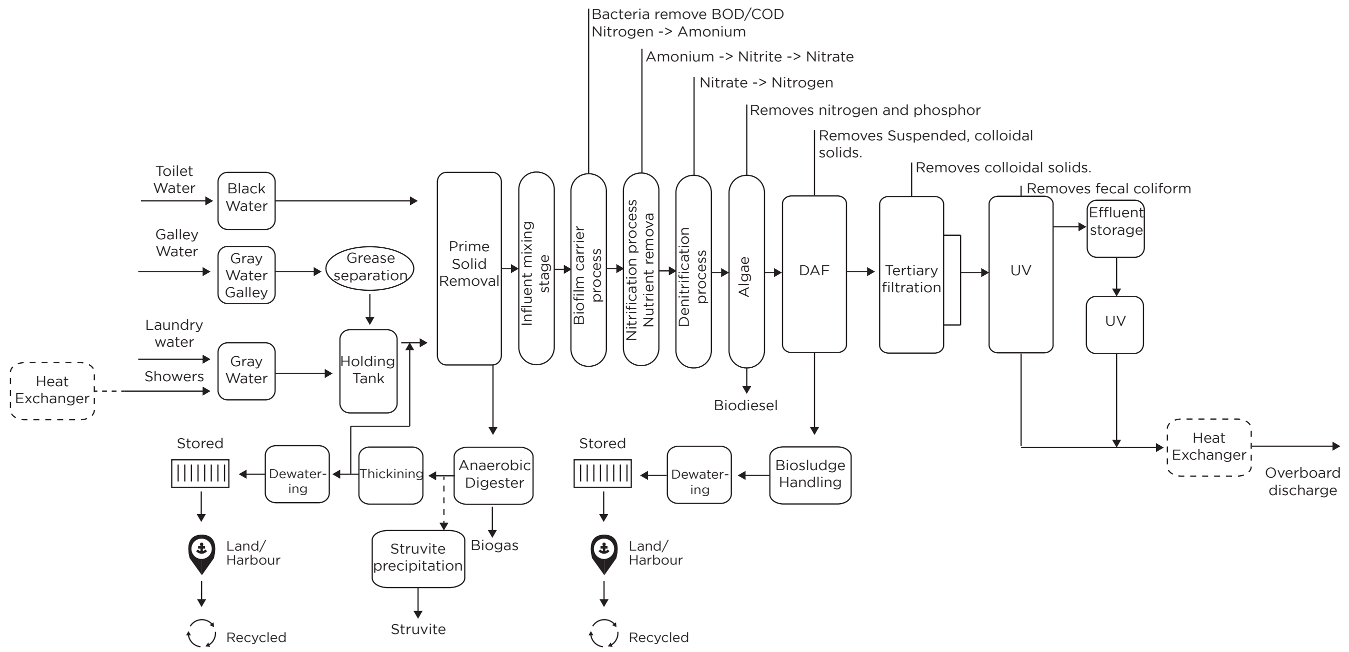

Figure 83: Wastewater treatment system from EVAC with recycle options. Note. Adapted from Evac (2019).

Biodiesel, biogas, and struvite

Biogas, biodiesel and struvite are formed in this new wastewater treatment system. The biogas and biodiesel can be used as fuel for the ship. When this is not possible because the ship uses other fuels, the biodiesel and biogas can be disposed of to land. Both are sustainable fuels which can be used in other industries and reduce the CO_2 emission of that industry. The wastewater would contain more pollutants when these new systems (anaerobic digestion and algae) are not implemented, these pollutants would end up in the environment. The struvite can be used for the greenery onboard. Especially on the future cruise ships which have more greenery onboard including food production. The struvite can be disposed of to land when too much has been produced to use onboard. This research did not investigate the cost of installing these techniques but focusses on the best-case scenario for the environment.

4.3.3.3 Solid waste stream

Chapter 4.3.2.3 showed what types of non-hazardous solid waste and hazardous solid waste are found onboard. There are several treatment methods on board to manage solid waste, like crushers, pulpers, compressors, and incinerators. However, with none of these methods, the solid waste is fully taken care of. The first three options are to prepare the waste for disposal to land and the latter burns the waste, but the ash remains. The hazardous solid waste is stored until it can be disposed of to land. This research looks into the possibility to reduce, reuse, and sustainably recycle the waste.

Non-hazardous solid waste

The solid waste stream cannot be fully eliminated due to the need for products on board. The best way to improve this waste stream is by reducing the need for products, reusing the products when possible, and eventually recycle the products. The common non-hazardous solid waste products onboard of the ship, where they're used for, their treatment method, and where they end up can be seen in table 39. The first three treatments are used to reduce the volume of the waste so it can be stored and off-loaded to land, the latter burns the solid waste. By doing this, emissions come free and pollutant ash is left. Other solutions should be found to treat this waste.

Table 39
Non hazardous solid waste and their treatment methods.

Non-hazardous Solid Waste	Used for	Treatment	Ends up
Glass	Food and beverage jars & bottles.	Crushed	Land
Plastic	ropes, containers, bags, biodegradable plastics, poly-ethylene terephthalate plastics, high-density polyethylene plastics	Incinerated, recycled	Land, Air, (Sea)
Aluminium & Metal Cans	Soft drink cans, tin cans (food), steel cans ship maintenance	Crushed, recycled	Land
Paper	Paper and packing	Incinerated, recycled	Land, Air, (Sea)
Cardboard	Dunnage, packing	Incinerated, recycled	Land, Air, (Sea)
Food waste	Food scraps, table refuse, galley refuse, food wrappers contaminated with food.	Pulped, compressed, incinerated	Land, Air, (Sea)
Wood	Pallets, waste wood	Incinerated	Land, Air, (Sea)
Incinerator ash	Ash from packing material, paper, cardboard, etc.	-	Sea

Note. Data retrieved from: United States Environmental Protection Agency (2008).

Reduce, Reuse, Recycle

Glass, aluminium, and plastics are used to package beverage. Single used plastic should be fully eliminated on board of cruise ships. This is already done for straws and stirrers but not for plastic bottles and garbage bags. Norwegian Cruise Line is implementing this strategy by the beginning of 2020 (Glusac, 2019). Passengers often take plastic water bottles with them into the city because they are light, easy to carry, and resealable. Instead of using single used plastic bottles cruise lines give 1 reusable plastic bottle per person. The passengers can refill their bottles for free on the ship and leave them after their holiday. The bottles are cleaned and reused for the next passenger. By doing this, single used plastic bottles are banned, and the need for plastic bottles is reduced. The plastic bottles are disposed to land and recycled when they reach the end of their lives. Other plastics products that are found onboard should not go to the incinerator. When they reach the end of their lifespan, they should be disposed to land and recycled. The used bottles are often recycled into new bottles. However, the plastic bottles can also be recycled into sheets, non-food bottles, and strapping (Welle, 2011).

The usage of drinking cans should be reduced onboard. Drinks from cans should be delivered in liquid form and stored onboard in big tanks. The fluid can be distributed over the ship in large reusable barrels and from there directly poured into a glass without the need of the cans itself. The same goes for liquids that come per serving in a glass bottle. The liquid can be stored in bigger barrels/ containers and then directly poured into the glass of the passenger. By doing this the use of glass bottles and cans is reduced. Aluminium cans that are used can be compressed and recycled on land into new cans, see figure 84 (Baeyens,

Brems, & Dewil, 2010). The glass bottles that are used per serving should be cleaned and refilled with the same liquid. When the glass bottles cannot be reused anymore the glass is disposed to land and recycled.

Paper and cardboard are both used for packaging. Cruise ships have a constant supply of products that are carefully protected by paper and cardboard. An agreement should be made with the supplier about reusing the cardboard and paper protection. By doing this the supplier does not need to buy new materials, which reduces their cost. When the product is safely onboard the paper and cardboard protection can be sent back to the supplier which reuses these materials for the next cargo. Paper is also used for leaflets and daily onboard programmes. However, the daily programmes and other information can also be found on onboard screens and on the app. There is no need for paper leaflets and programmes. These leaflets and programmes should be eliminated which reduces the need for paper. The paper that is used should be collected and recycled on land. Almost all types of papers can be recycled if they are kept separate from other waste. Wood fibres can be reused 4 to 6 times. The recycled fibres are mixed with new fibres after they are cleaned to produce recycled paper (Baeyens et al., 2010).

Food waste is one of the larges garbage streams onboard. The food waste generated onboard is pulped or compressed and send to the incinerator (United States Environmental Protection Agency, 2008). There are two types of restaurants onboard of the ship, a la carte, and buffet. In the restaurant, passengers can order the food they would like to eat. A solution to reduce the food waste is by serving smaller portions on smaller plates. The passengers pay a set amount for their food every day. It does not matter how much or how many times they order. By reducing the portion size, the amount of food waste is likely reduced. Passengers do not get the feeling that they receive less for their money because the can always order more for ‘‘free’’. The food waste from the buffet can be reduced by eliminating plastic trays and smaller plates. Due to this people cannot stack and carry that many foods at once. Next to this, external cues can be used to encourage guests to take less food at once (Kallbekken & Sælen, 2013). Kallbekken & Sælen States (2013) that a sign which says: ‘‘Welcome back! Again! And again! Visit our buffet many times. That's better than taking a lot once’’ (p. 326) shows guest that they can come more often and that it is socially acceptable to do. These signs should be used together with the smaller plates to reduce food waste. The food waste generated onboard is pulped or compressed and send to the incinerator (United States Environmental Protection Agency, 2008). Instead of this, the food waste could be used to produce biogas with an anaerobic digester, see chapter 4.3.3.1. In the future ships

Figure 84: Crushed metal cans on a Royal Caribbean cruise ship.
Note. Reprinted from Svaetichin, 2016, p. 17.

should also be able to grow their own food and cultured meat. This makes them less dependent and it is a step into the direction of a circular cruise ship.
The wood that is found onboard is mainly from pallets that are used to transport products onboard. There are different types of pallets on the market which are made from different materials. Bengtsson & Logie (2015) did a life cycle assessment (LCA) of the following pallets: pooled softwood pallets, pooled hardwood pallets, plastic pallets, one-way softwood pallets, and one-way cardboard pallets. Pooled pallets are pallets that are reused several times and repaired when needed. The wooden pooled pallets have a lower environmental impact compared to the one-way plastic pooled panels. The softwood panels are favoured over the hardwood panels due to their lower embodied energy and lower transport loads. The pooled softwood panels are also favoured over the one-way softwood panels and one-way cardboard pallets. Pallets are always repaired when the repair cost is lower than buying a new pallet. The unusable pallets are dismantled and reused to repair other pallets. When this is not possible the wood is recycled for example into woodchips and particleboards (Bengtsson & Logie, 2015). Cruise ships should use the pooled softwood panels. The panels that are not needed anymore should be sent back to bring a new load. A collaboration between the cruise line and supplier needs to be established.
In the future cruise ships are not allowed to incinerate materials due to the released emissions. Table 39 shows that plastics, paper, cardboard, food waste, and wood are incinerated. Around 80% of the waste is incinerated onboard (United States Environmental Protection Agency, 2008). The products should be disposed to land and recycled when the materials cannot be reused anymore, instead of going to the incinerator. The incinerator ash that is produced is not really ash, it can contain glass, brick, rubble, sand, grit, metal, stone, concrete, ceramics, and ash and slag (Ramesh & Deepak, 2015). The generated ash onboard is normally discharged into the sea (United States Environmental Protection Agency, 2008). Instead of discharging the ash into the sea the ash should be collected and disposed to land. The ash can be recycled in cement production, ceramic and glass production, brick production, and road construction (Ramesh & Deepak, 2015; Smol et al., 2015).

Table 40
List of hazardous solid waste.

Hazardous waste
Paints waste
Fluorescent and mercury vapour light bulbs
Batteries
Medical waste
Photo waste
Explosives
Chemical
Incinerator ash

Note. Data retrieved from: United States Environmental Protection Agency (2008).

Hazardous solid waste

Currently, the hazardous waste is stored onboard until it can be handed over to qualified contractors on land. Processes that produce hazardous waste are: photo processing, dry cleaning, and equipment cleaning. Table 40 shows the hazardous materials which can be found on cruise ships. As with the general solid-waste stream, it is often impossible to fully eliminate the waste stream. This research looks into

the options to reduce the use of hazardous products and into the possibility to use other sustainable alternatives. Next to this it investigates reusing and recycling these waste streams.

Reduce, Reuse, Recycle

As with the non-hazardous solid waste stream, the best way to improve this stream is by applying the reduce, reuse, recycle principle.
Cruise ships are day and night in operation, causing wear and tear. The ship must be painted now and then. There are two types of paints, inside paints and anti-fouling paints for the outside of the ship. In the past tin-based marine coatings as (TBT) were used as anti-fouling paint. However, this paint is toxic to the environment. Research is done into new paints as copper-based paints, synthetic biocide paints, silicon-based paints, and electrochemically active coatings. The latter does not use biocides but changes the pH value of the hull which prevents fouling. This process looks promising as new anti-fouling paint, but more research is needed (Royal Academy of Engineering, 2013). The cruise industry should also choose sustainable paints for the inside of their ship. These paints are primarily made from plants instead of fossil-based components. Next to this, the number of toxic components in the paint is reduced, for example with the zero-VOC paints (DSM, n.d.). Sustainable paints should be used instead of the conventional paints. By doing this, non-fossil-based components are used and the product self is less toxic for the environment and people. The paint should be carefully handled to minimize spills and waste. There are no companies found that reuse or recycle paint. Research should be done into this.
LED lights should be favoured over incandescent bulbs and fluorescent light because it consumes less energy, eliminates the use of mercury, and is long-lasting (Pimputkar, Speck, DenBaars, & Nakamura, 2009). Material use is reduced, due to the longer life span of 10-15 years. Research is done into reducing the environmental impact by looking into remanufacturing and recycling components of LED lights. Manufactures should look into designing LED lights and include principles as design for disassembly, replaceable parts, minimal material types, and a proper take-back system. When the LED lights are broken, they are collected and recycled on land (Hendrickson, Matthews, Ashe, Jaramillo, & McMichael, 2010).
Different types of batteries can be found on a cruise ship, small batteries for a camera, and large batteries for generators. The following batteries can be found on a cruise ship: lead-acid, nickel-cadmium, lithium, and alkaline batteries. The nickel cadmium and lithium batteries are qualified as hazardous materials and in some states alkaline batteries as well (United States Environmental Protection

Agency, 2008). Lithium is a scarce material, as previously mentioned in this research. Research is done into batteries that use other materials as magnesium. It is not possible to eliminate this source because there will always be a need for batteries. More research needs to be done into the production of sustainable batteries and the best options to reuse and recycle them. There are already some different recovery processes for batteries. However, there is a need for efficient recycling technologies that recover the metals and help with the disposal of the harmful substances (Larcher & Tarascon, 2014). Batteries that reached their end-of-life should be stored and recycled on land.

Some pharmaceuticals are classified as hazardous. These pharmaceuticals become hazardous solid waste when its off-specification or exceeded the shelf life. These pharmaceuticals are incinerated on board of the ship. It is important to safely dispose the medical waste due to the risk of poisoning and suicide. Reusing medicines is seen as something unethical. However, more and more people suggested to reopen this discussion (Mackridge & Marriott, 2007). The medical waste should go into the incinerator on board or on land as long as there is no other option. The medicines should be disposed of to land when it is possible to reuse or recycle the medicines. To reduce the amount of expired medicines a registration system should be made to find the optimal amount of needed medicines onboard.

Hazardous waste is created during the production of photos and during printing. A few years ago all the pictures shot during a cruise where printed and displayed. Today, the pictures are digitally displayed and only printed when the passenger buys the photo. By doing this less hazardous waste is produced. The cartridges, ink, and toner from printers are not standard classified as hazardous waste, only in a few states. There are cartridge remanufacture companies that take back cartridges and reuse and sell them (Matsumoto, Nakamura, & Takenaka, 2010). The cruise line should collect the used cartridges and toners and dispose them to land (Matsumoto, Nakamura, & Takenaka, 2010).

Explosives that are found onboard are for celebration, theatre productions, and emergency purposes as flares for lifeboats. It should be considerd if explosives for celebration and theatre production are really necessary and outweigh the environmental cost. Cruise line companies should ban explosives for pleasure and only keep them for flares.

Chemicals are used during maintenance as painting, dry cleaning, and in photography labs. This paragraph focusses on dry cleaning because paints and photo processes are already discussed. The most common chemical used during dry-cleaning is perchloroethylene (PERC). However, this chemical has a bad impact on human health and the environment. Research is done into alternative chemicals as hydrocarbons, Greenearth©, acetal, and liquid carbon

dioxide (CO_2) and wet-cleaning. The other solvents have similar effects on the environment and health. Wet cleaning is a good alternative because it is energy efficient (lowest electricity consumption) and reduced the production of hazardous waste. The solvents used with wet cleaning are non-toxic, pH-neutral, biodegradable, and can be discharged into the sewage (Troynikov, Watson, Jadhav, Nawaz, & Kettlewell, 2016). Cruise organisations should use wet-cleaning instead of drycleaning. When this is not possible, for example on retrofits, they should choose the most sustainable solvent with the least chemicals and negative health effects.

Incinerator ash can contain high concentrations of heavy metals. In this case, the incinerator ash is considered as hazardous waste. The use of the incinerator should be banned on cruise ships. However, the first step is to prohibit the burning of hazardous waste in incinerators. CLIA states that cruise lines agreed to recycle more waste and reduce the production of incinerator ash. The incinerator should be primarily used for food waste, cardboard, plastic, trash, and wood according to CLIA and not for hazardous waste (United States Environmental Protection Agency, 2008). The second step is to eliminate the general solid waste stream to the incinerator to reduce this generation of (hazardous) ash, see chapter 4.3.3.3 Non-hazardous solid waste

This research states that all the products that reached the end of their life should be stored and disposed to land when possible. However, it must be investigated whether this is possible in terms of storage.

4.4 Roadmap

4.4.1 Introduction

This research answers the sub question: “How can the sustainability goals be reached” for the 3 levels of sustainability a cruise ships can strive to: 1. Fully Circular, 2. Collaboration Ship & Harbour, and 3. Positive effect on the environment. This chapter uses the conclusion drawing of chapter 4.3.2, the overview of what comes in and out of the cruise ship, and the conclusion drawing of chapter 3.4, the conclusion drawing of the measures already taken by the Royal Caribbean, as input for the roadmap. The roadmap describes which steps need to be taken to comply with the specific level of sustainability from that roadmap. Ultimately, a combination of the roadmaps is made to form the most optimal cruise ship. The principle of reduce, reuse, and recycle is applied to every waste stream. This principle is already used today but more can be done. The technique of back casting is used to create the roadmaps. This means that for every sustainability level an optimal cruise ship is envisioned to strive to. It starts with the end vision and then works backwards to find out what is required to get there. Instead of working from the current scenario to the end. These techniques are used on all thee roadmaps.

4.4.2 Roadmap A – Fully circular

4.4.2.1 Introduction

The principle used in this scenario is: Clean in = Clean out. This means that as many clean and sustainable alternative products should be used, pollutant fuels and hazardous waste are not allowed onboard anymore. All the waste streams use the reduce, reuse, recycle principle to minimize the generated waste, and prevent it from coming into the environment. A part of the waste stream can only leave the ship into the environment if it is clean (not harmful for the environment), or it has a positive effect on the environment. Figure 86 shows the most optimal vision of how a future cruise ship will look in the fully circular scenario including the principles previously mentioned. Figure 86 shows the current state of a cruise ship; what comes in and out of the cruise ships, which treatment systems are used, which processes of producing and reducing are used, and the two additional steps that have already been taken (oceanographic equipment and creating awareness). This figure is made from the two conclusion drawings. In the following chapters, a distinction is made between the future cruise ships and steps that could already be taken for retrofits.

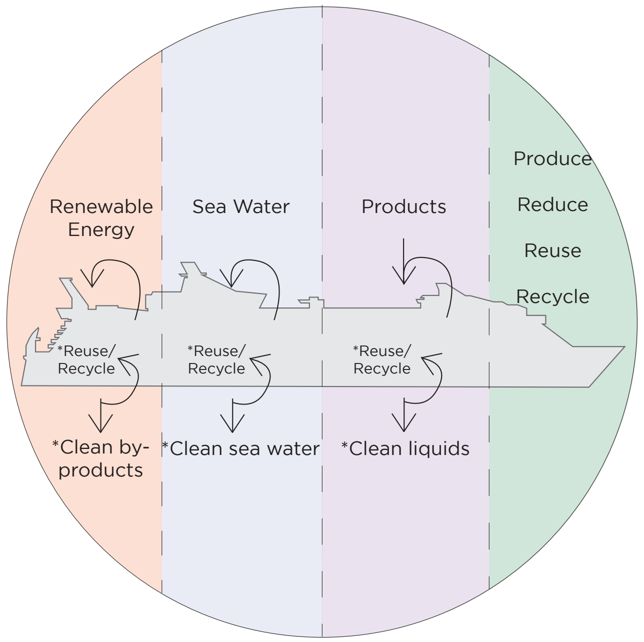

Figure 85: Vision of Roadmap A.

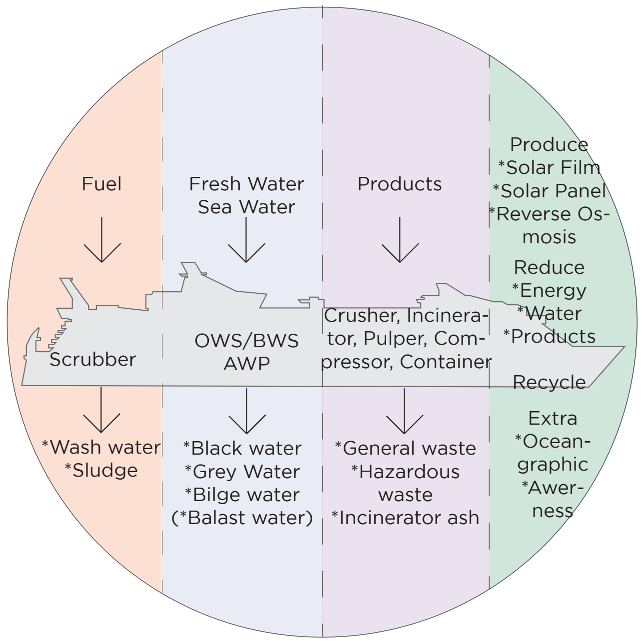

Figure 86: Overview of the current waste streams.

4.4.2.2 Roadmap A – Gas stream

The main principle indicates that something clean must go into the ship to make sure something clean can come out of the ship. This of course also depends on the processes the stream goes through. A sustainable circular future cruise ship sails on renewable energy, with hydrogen as backup fuel. Cruise ships are not allowed to use HFO fuels and scrubbers due to the pollutant emissions that come free during this process. To start the transition some in-between steps are needed to comply along the way to the legislation and reach the end goal. From chapter 4.3.3.1 can be concluded that there are 3 options to produce sustainable fuel onboard a cruise ship without the help from land. These three options are discussed below, (1) Hydrogen, (2) methanol, (3) biofuel, (4) renewable electric energy.

Fuel generated onboard

Option 1.1: Hydrogen is sustainably produced onboard, so there is no need for a special hydrogen infrastructure. The hydrogen is produced through electrolysis of water, see figure 87. No emission comes free throughout the whole process of producing and using hydrogen in a fuel cell. Hydrogen can also be used in a dual fuel engine. The usage of hydrogen instead of HFO reduces the emission for both engines.

Option 2.1: Methanol is sustainably produced from the onboard generated renewable energy and onboard generated hydrogen through electrolysis, see figure 88. The needed CO_2 for this reaction comes from the released exhaust emissions when methanol is used in a fuel cell, dual fuel engine, or combustion engine. By doing this no CO_2 comes back into the environment. Emissions are reduced when methanol is used instead of conventional fuel.

Option 4.1: The ship sustainability produces hydrogen onboard through electrolysis. This is stored together with the onboard generated renewable electric energy from the wind, sun, and wave power in a battery, which is connected to the fuel cell.

Roadmap

Which option is best to use today and in the future? Table 41 shows which combinations are possible now, in the near future, and in the late future. The decision whether the combination of fuel and engine falls under the near future of the far future is an educated guess. Hydrogen is a very sustainable fuel and perfect to use in newly built ships that generate their own hydrogen to power fuel cells. Most likely hydrogen can be used in the short future in dual fuel engines. However, not in combustion engines. Methanol can be sustainably produced onboard by combining the

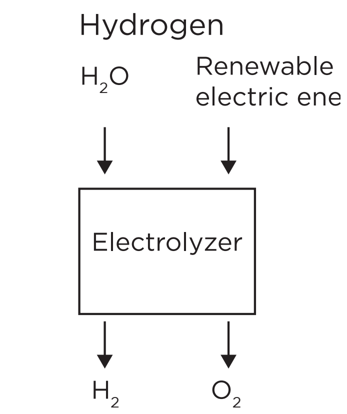

Figure 87: Production process of hydrogen.

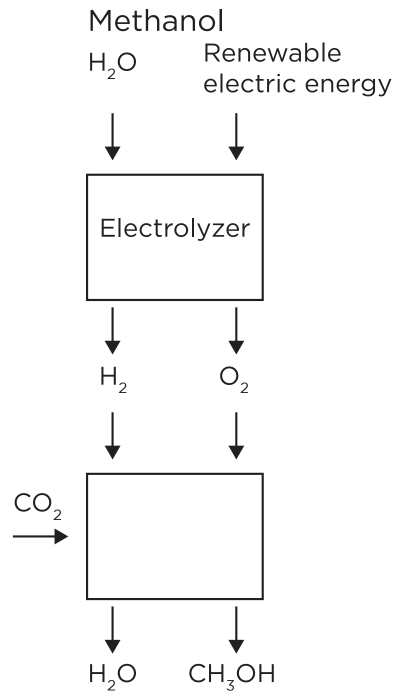

Figure 88: Production process of methanol.

produced hydrogen, renewable energy, and CO_2. Methanol can be used in fuel cells and dual fuel engines. It is most likely that methanol can be used in the short future in combustion engines. Biodiesel, biomass, and biogas are not applicable for roadmap A because the production onboard is not high enough for the propulsion of the ship and it cannot be combined with the other fuels. These fuels are discussed in roadmap B. Renewable energy can be directly used to power a fuel cell. Renewable energy can be stored in a battery in case of a dual fuel engine and combustion engine.

Table 41
Overview of possible combinations of fuel and engine in relation to time – Roadmap A.

	Hydrogen	Methanol	Biodiesel	Dimethyl ether	Biogas	Renewable Energy Ship
Fuel Cell			n.a	n.a.	n.a.	
Dual Fuel Engine			n.a	n.a.	n.a.	
Combustion Engine			n.a.	n.a.	n.a.	
Now	Near future	Late future				

Note. Data retrieved from: United States Environmental Protection Agency (2008).

There is a distinction made between retrofit ships and newly built ships. It is assumed that in the future all ships are made with fuel cells because they are the most sustainable option. The older ships which are still in use have most likely a combustion engine and the newer ships a duel fuel engine.

Retrofit:

- Combustion Engine -> Biodiesel/ Biomass -> Methanol
- Dual Fuel -> Methanol->Biodiesel/biogas/Hydrogen

According to Table 40 biodiesel can be used in combination with a combustion engine. However, this must be in combination with a biodiesel production on land. The same applies to the production of dimethyl ether from organic waste. This option is not applicable for this roadmap. In the short future, it is possible to use methanol to power a combustion engine, which is option 2.1, see figure 89.

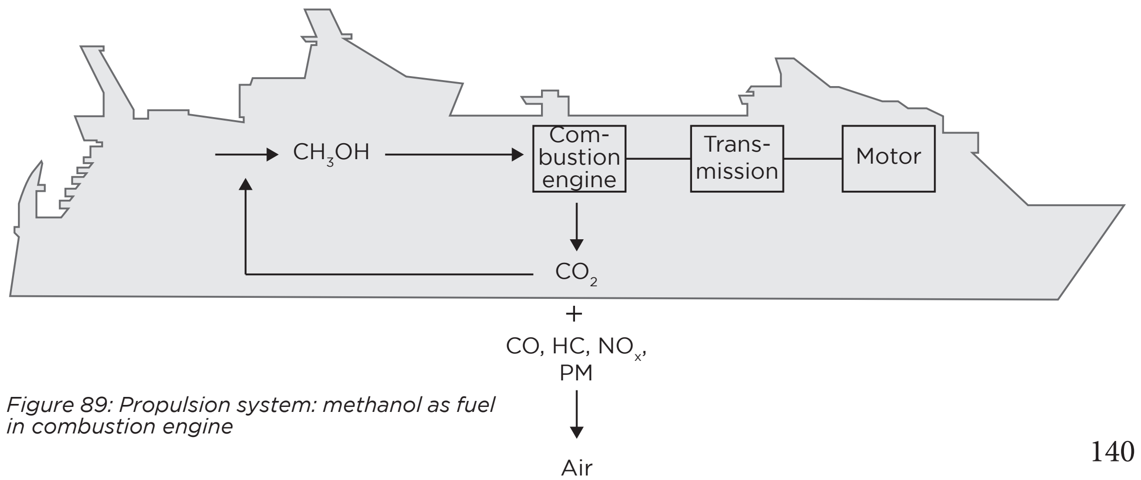

Figure 89: Propulsion system: methanol as fuel in combustion engine

Methanol can also be used for ships that currently sail with a dual fuel engine, option 2.1, see figure 90. If desired, hydrogen can be used in the near future to power the dual fuel engines and reduce the emissions, option 1.1, see figure 91.

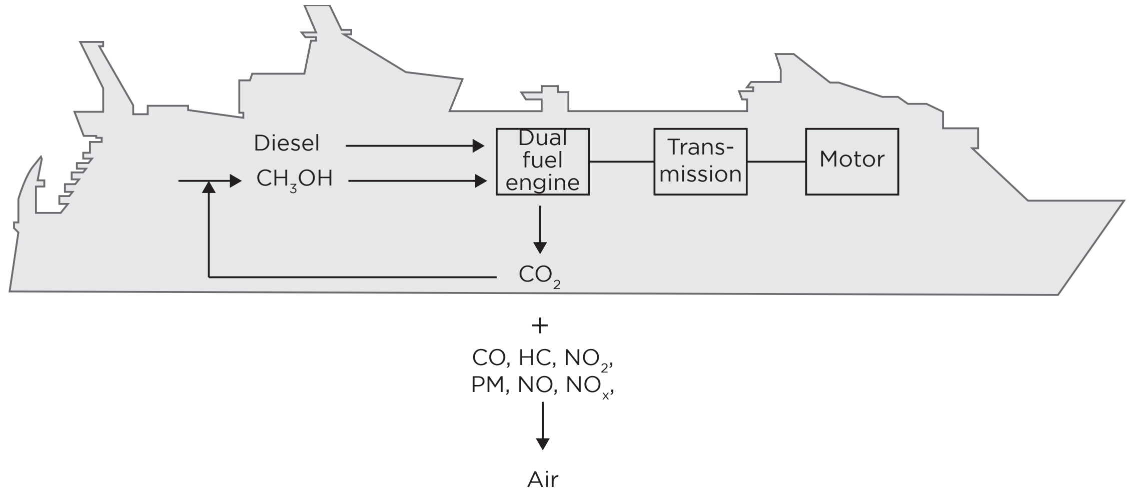

Figure 90: Propulsion system: methanol as fuel in dual-fuel engine.

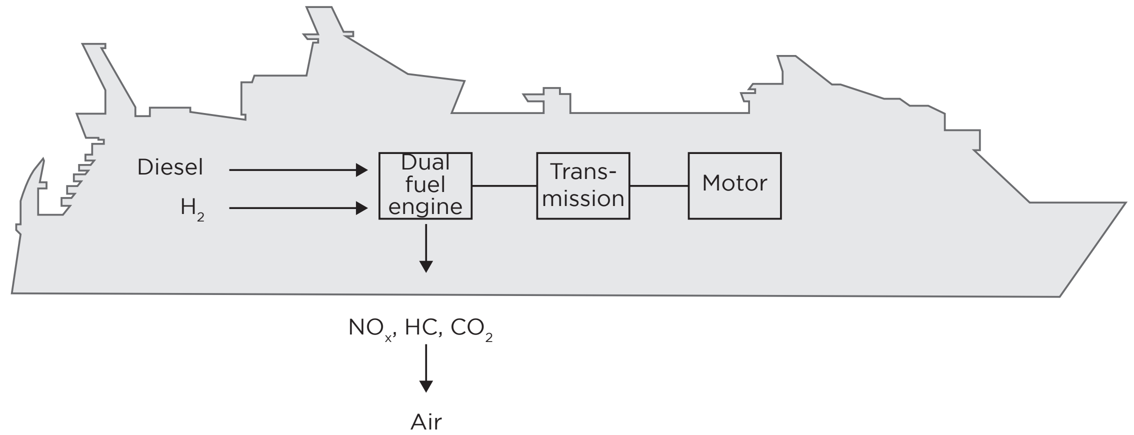

Figure 91: Propulsion system: hydrogen as fuel in dual-fuel engine.

Newly built

1. Fuel Cell -> Hydrogen
   + Renewable energy
   +Battery
2. Fuel Cell -> Renewable energy
   + Hydrogen (backup)
   + Battery

All the newly built ships have a fuel cell and a battery onboard for the propulsion and hotel load of the ship. Hydrogen is used as the main fuel source. Next to this, the ship generates its own renewable energy by using the wind, sun and wave power, which is stored in a battery, option 4.1, see figure 92.
In the last step, a switch is made between the main energy source (hydrogen) and the backup source (renewable energy). In the future, most of the needed energy is generated by using wind, sun, and wave power. When needed the hydrogen is used backup source, option 4.1

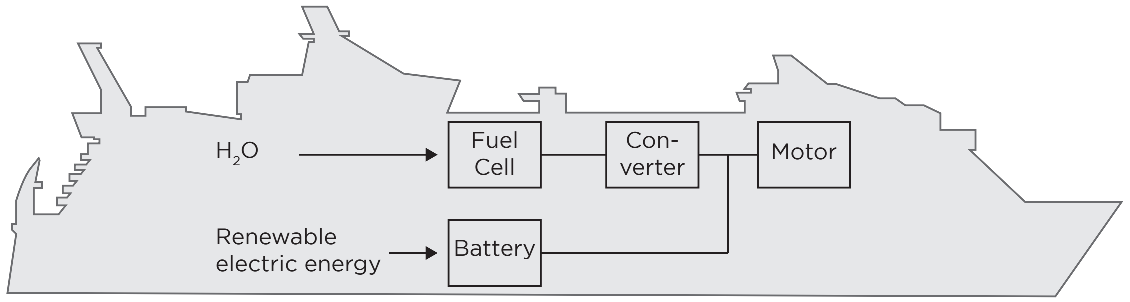

Figure 92: Propulsion system: Hydrogen as fuel in fuel cell.

Reduce, Reuse and Recycle

This chapter gives a short overview of the measures found in the literature to improve the energy efficiency of cruise ships.

Extra measures should be taken to increase the energy efficiency of the ship to reduce the emissions. Measures that are already taken to improve the efficiency of the ship can be seen in figure 38. There are a lot of studies done into the energy conservation of marine energy systems (Ancona et al., 2018; Baldi, Maréchal, & Tammi, 2017; El Geneidy et al., 2017; Royal Academy of Engineering, 2013). The energy demand can be subdivided into four aspects: mechanical energy, electrical energy, thermal energy, and cooling energy (Ancona et al., 2018). The energy need for a cruise ship is different than the energy needs for other marine vessels as a tanker. The mechanical energy need for the propulsion of the ship and the navigation and transportation system is almost the same. However, the electrical energy need is different. A cruise ship has to deal with higher electrical needs due to the high hotel load. This includes energy consuming applications as pools, food services, and entertainment (El Geneidy et al., 2017). The power plant in the ship is responsible for the distribution of the electricity. Another important aspect is the thermal energy and cooling energy which is needed for heating and cooling within the ship. These loads are depended on the temperature and scheduling of hotel load systems, like pools, galleys, and laundry (El Geneidy et al., 2017). There are a lot of studies done on energy conservation measures, see table 42.

Table 42
Overview energy conservation measures.

	Measures
Mechanical	Weather routing (management system) (Ancona et al., 2018; Royal Academy of Engineering, 2013)
	Sailing at a slower speed for fuel-saving (Royal Academy of Engineering, 2013)
	Type of propulsor (Royal Academy of Engineering, 2013)
	Machinery conditions (Influence the performance of the ship) (Royal Academy of Engineering, 2013)
Electrical	Fuel cell in combination with energy storage device (Ancona et al., 2018).
Thermal (heating and cooling)	Waste heat recovery system (LT/HT) (El Geneidy et al., 2017)
	Dual pressure steam system (waste heat recovery system) (El Geneidy et al., 2017)
	Organic Ranking Cycle (waste heat recovery) (Ancona et al., 2018; Baldi, Maréchal, & Tammi, 2017; El Geneidy et al., 2017)
	Using waste heat for ballast water treatment (difficult) (El Geneidy et al., 2017)
	Cold seawater used for cooling in combination with chillers (El Geneidy et al., 2017)
Other	Battery for energy load leveling (Baldi, Maréchal, & Tammi, 2017).
	Hull coatings to reduce friction, anti-fouling (Royal Academy of Engineering, 2013)
	Hydrodynamic (hull) design (Royal Academy of Engineering, 2013)
	Reduce ship resistance by polishing hull and propeller (Ancona et al., 2018).

It can be seen that most of these measures are already used on cruise ships of the Royal Caribbean. However, there is still room to improve these methods (Royal Academy of Engineering, 2013).

4.4.2.3 Roadmap A – Fluid stream

The principle of roadmap A is clean in is clean out. The fluid streams that come into the ship are seawater and freshwater from land, which are both clean. However, a circular ship does not use freshwater from land. Cruise ship should produce their own fresh water from seawater as the only source. The four streams that come out of the ship are grey water, black water, bilge water, and ballast water. Pollutants still come back into the environment, when the current treatment systems for black and grey water and bilge water are used. This can be seen in the overview drawing of chapter 4.3.2. Chapter 4.3.3.2 showed that several adjustments and additions can be done but the wastewater will still contain hazardous substances. Because the sludge and solids are incinerated onboard or disposed to land, and hazardous pollutants are discharged into the sea these streams cannot be seen as sustainable nor circular. The additions and adjustments of these two streams are discussed in roadmap B.

Ballast water

Ballast water is used to stabilize the ship, by doing this, plants, animals, and viruses are transferred into new environments. These non-native, exotic species can cause harm to the aquatic ecosystem. Royal Caribbean uses a ballast water treatment system to prevent this from happening. No harmful substances and non-native species enter the environment when this system is used. There are no adjustments needed for this stream to create a circular ship. A drawback of this system is that living organisms are killed during this process. Treated black and grey water that can be reused on board should be used as ballast water, instead of ballast water from the sea, see figure 93. By doing this a bigger amount of treated water can be stored as a buffer and there is no need to store seawater. When the ballast water is not needed anymore the treated water can be used onboard or discharged into the sea.

Retrofit
- Treated black and grey water as ballast water.

Newly built
- Treated black and grey water as ballast water.

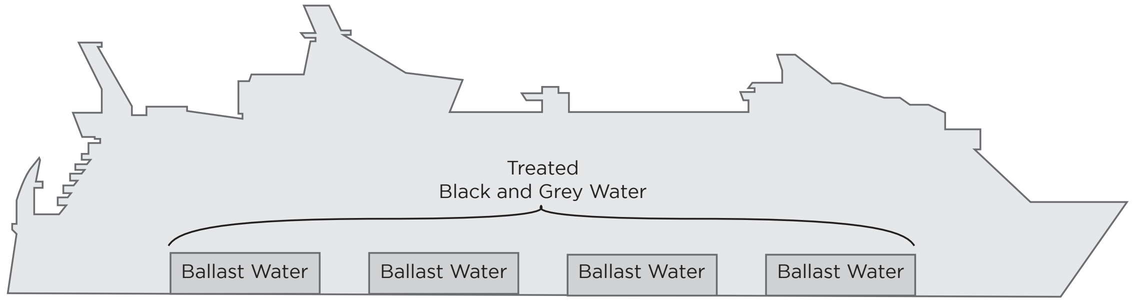

Figure 93: Treated black and grey water as ballast water.

4.4.2.4 Roadmap A – Solid stream

There are two types of solid waste streams, non-hazardous solid waste, and hazardous solid waste. The principle of roadmap A is clean in is clean out. However, not all the products that come onboard are clean. Future cruise ships should handle their own waste without the need of sending it to land or to an incinerated onboard. Chapter 4.3.3.3 investigated the possibility of sustainable substitutes and ways to reduce, reuse, and recycle the (non-) hazardous solid waste. It is today and in the future impossible to make a cruise ship fully circular concerning the solid waste streams. Not all the products that reached the end of their lives can be recycled onboard and need to be disposed of to land. Only the food stream of the non-hazardous solid waste and the explosives, incinerator ash, and dry-cleaning of the hazardous solid waste can be seen as circular streams. It is impossible to become circular for the other waste streams due to the need for products and the recycling possibilities on land. These options are discussed in roadmap B.

Non-hazardous solid waste

Only the food waste stream can become fully circular in the future. Newly built cruise ships in the future can grow their own food on board of the ship. New techniques are used to grow vegetables and cultured meat. The food waste is reduced by using smaller plates, eliminate trays, and use cues to stimulate passengers, see table 43. The food waste that is left is used to generate biogas, see figure 94. The biogas can be used onboard or send to land.

Table 43
Reduce, reuse, recycle principle – Food waste.

Non-hazardous Solid Waste	Reduce	Reuse	Recycle
Food	Use smaller plates and eliminate trays for portion control and show cues to stimulate passengers.	-	Produce biogas from the organic matter with an anaerobic digester.

Retrofit
- Use smaller plates, eliminate trays, and show cues.

Newly built
- Use smaller plates, eliminate trays, and show cues.
- Grow own food on board.
- Food waste is sent to an anaerobic digestor to produce biogas.

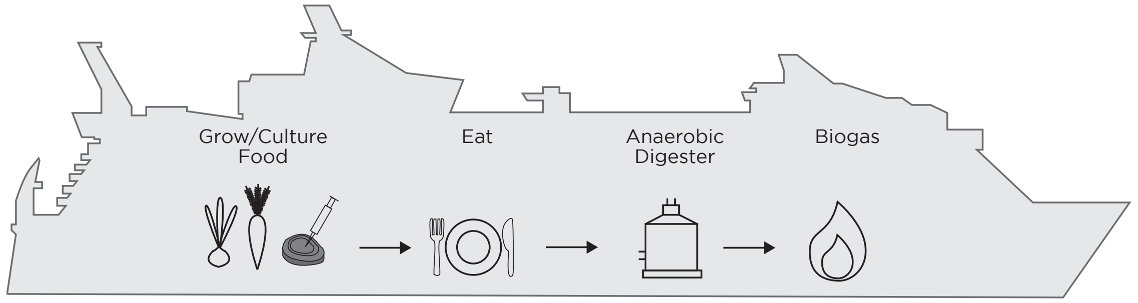

Figure 94: Food waste stream newly built ships.

Hazardous solid waste

The stream of explosives, the incinerator ash, and dry cleaning can be seen as circular streams on a cruise ship because these streams are eliminated. Explosives should not be used for pleasure onboard of a ship. Only in exceptional cases, flares are used in emergencies. Next to this, it is prohibited to incinerate hazardous waste onboard. Cruise ships should use the technique of wet cleaning instead of dry-cleaning. No hazardous chemicals are used during wet cleaning and the wastewater can be treated by the wastewater treatment system, see table 44. Due to these measures, these streams are no longer created onboard. Figure 95 shows the measures that can be implemented on retrofit ships, figure 96 shows the measures for newly built ships.

Table 44
Reduce, reuse, recycle principle – Explosives, Incinerator ash, and chemicals.

hazardous Solid Waste	Reduce	Reuse (onboard)	Recycle
Explosives	Eliminated the explosives use onboard for pleasure.	There are no explosives used on board	There are no explosives used on board
Incinerator ash	Prohibit the burning of hazardous waste on board.	There is no hazardous ash produced on board.	There is no hazardous ash produced on board.
Chemical	Use wet cleaning instead of dry-cleaning. (no-toxic chemicals)	It is no longer hazardous waste. (discharged into wastewater treatment).	It is no longer hazardous waste. (discharged into wastewater treatment).

Retrofit

- Eliminate explosive use for pleasure.
- Prohibit the burning of hazardous waste.

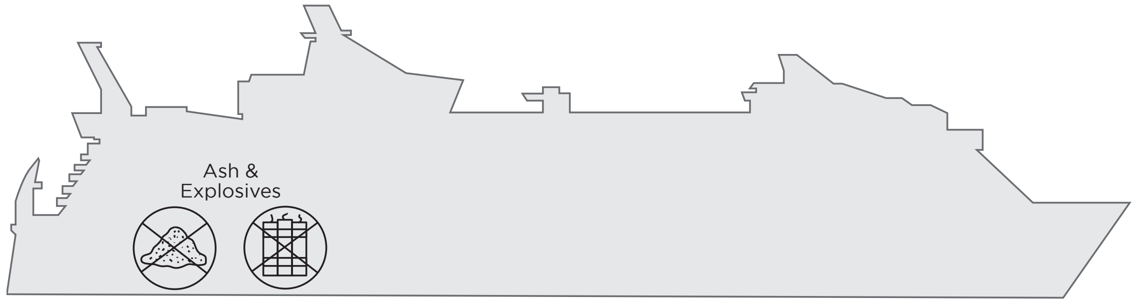

Figure 95: Eliminate ash and explosives on retrofit ships.

Newly built

- Eliminate explosive use for pleasure.
- Prohibit the burning of hazardous waste.
- Install wet cleaning facilities.

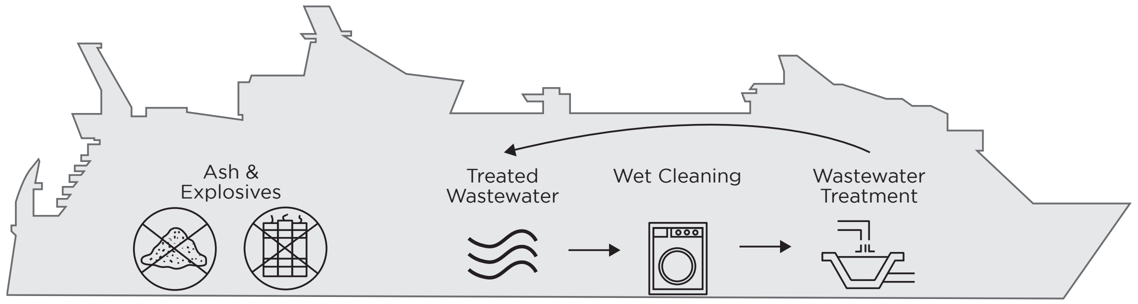

Figure 96: Eliminate ash and explosives and wet cleaning on newly built ships.

Roadmap A – Conclusion

A circular sustainable cruise ship is a ship that does not emit any pollutant substances into the environment and does not need any help to sustain itself. The ship can generate and treat everything the ship needs without damaging the environment. This chapter showed that this is impossible in the short future (retrofit ships) and far future (newly built).

The retrofit ship cannot become fully circular for any of the waste streams. By using methanol in a combustion engine and methanol or hydrogen in a dual fuel engine the emissions are reduced. Next to this, the ship can generate its own fuel without the need for land. This is the first step into the direction of a circular gas stream. For the fluid waste stream, the cruise ship produces its own freshwater from seawater through reverse osmosis and does not buffer freshwater from land. This water is treated and used as drinking water. The need for ballast water is eliminated by using treated black and grey water as ballast. The environment is not affected by this in any way. However, the bilge and black and grey water contain harmful substances and produce hazardous byproducts as sludge. The ship itself can not eliminate these substances or take care of the byproducts. This stream is not circular. Also, the solid waste stream is not circular. The products come from land, are used, and should

be taken back to land. Two streams of the solid waste are eliminated; it is prohibited to incinerate hazardous waste and use explosives on board. To conclude, the circular retrofit ship is making steps in the good direction; the ship does not need to import fuel, releases less emission into the air, produces its own drinking water, does not use seawater as ballast water, and prohibits burning hazardous waste and using explosives. However, emissions still come back into the air when a combustion engine or dual fuel engine is used, black and grey water and bilge water contain harmful substances after treatment which come back into the sea and create harmful byproducts, and the ship cannot take care of the products the ship needs without help from land. This can be seen in figure 97.

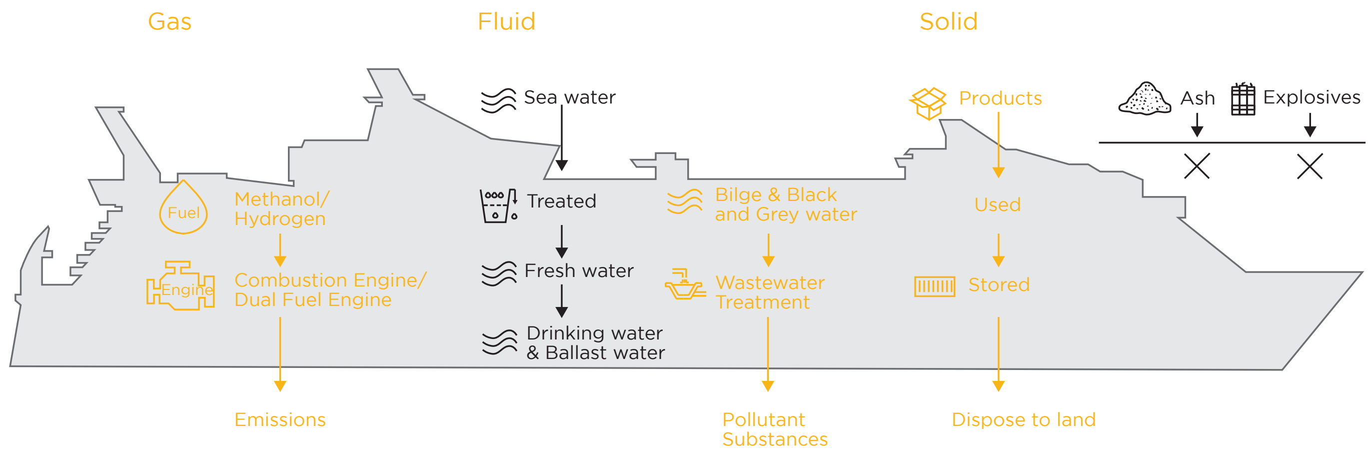

Figure 97: Conclusion drawing waste streams roadmap A, retrofit.

The cruise ships that are newly built can also not become fully circular, except for the gas waste stream. Hydrogen and self-generated renewable energy are used to power the fuel cell. A battery is used to temporarily store the renewable energy when needed. The ship can generate its own fuel and no emissions come free during this process. As with the retrofit ship the newly built cruise ship only uses seawater to produce fresh water. It also uses the treated black and grey water as ballast water. It is impossible to treat the bilge water and black and grey water to eliminate all the harmful substances and by-products. The only difference in the solid waste stream is that a future cruise ship can take care of its own food stream and dry cleaning. The ship can grow and culture the needed food onboard and use an anaerobic digester to make biogas from it. Instead of using the method of dry-cleaning which uses hazardous chemicals the ship uses the technique of wet cleaning. By doing this no hazardous chemicals are needed, and the wastewater can be treated onboard. To conclude, a future cruise ship can be circular in its gas stream but not for the fluid and solid waste stream as a retrofit ship, see figure 98.

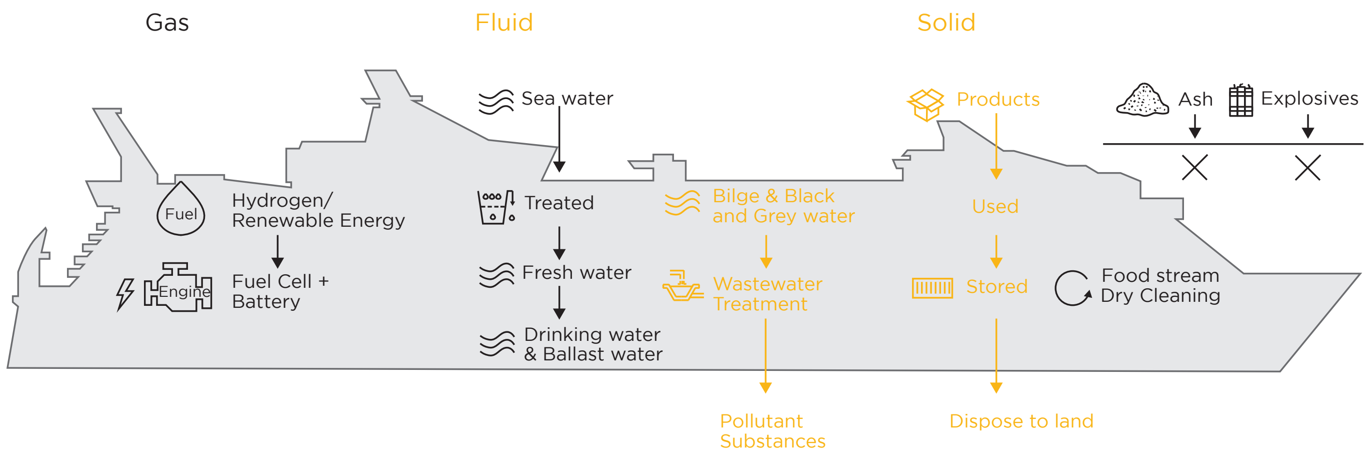

Figure 98: Conclusion drawing waste streams roadmap A, newly built.

4.4.3 Roadmap B – Collaboration Ship and Harbour

4.4.3.1 Introduction

In principle roadmap A and roadmap B have the same purpose, to create a sustainable cruise ship. The difference is that roadmap A strives to a circular cruise ship. This means that the cruise ship cannot receive anything from land or dispose to land. In the scenario of roadmap B, ships can collaborate with the harbour or companies on land to get rid of unavoidable and untreatable waste, provided this is done in a sustainable manner. Next to this, the ship can receive the needed supplies they cannot generate by themselves. The same produce, reduce, reuse, and recycle principles are used as in roadmap A. The cruise ship can use the private island from the cruise line organisation to produce energy. Figure 99 shows the vision of roadmap A and figure 100 shows the vision of roadmap B.

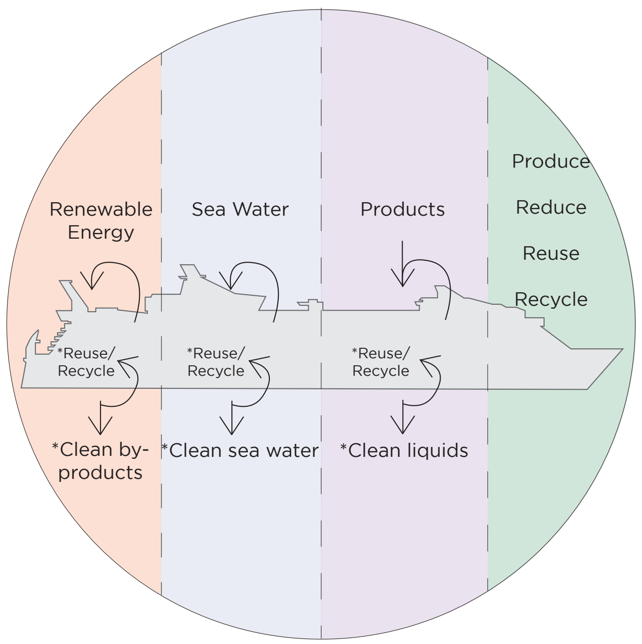

Figure 99: Vision of Roadmap A.

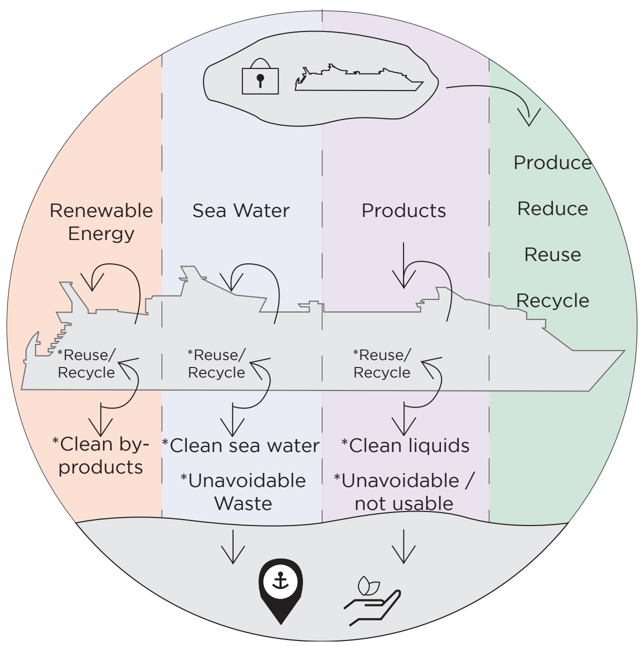

Figure 100: Vision of Roadmap B.

4.4.3.2 Roadmap B – Gas stream

Roadmap A shows that hydrogen and methanol are the best fuel options for a retrofit ship and hydrogen with renewable energy for a newly built ship. However, in this roadmap, the fuel must be generated onboard. Sustainable future cruise ships can produce its own fuel onboard in combination with a fuel production on land. By doing this it is possible to use the biofuels. This roadmap shows which biofuel can be used on which kind of ship.
From chapter 4.3.3.1 can be concluded that there are 6 options to produce sustainable fuel on land or on land and onboard. These 6 options are discussed below, (1) Hydrogen, (2) methanol, (3) biofuel, (4) renewable electric energy.

Fuel generated (partly) on land

Option 1.2: Hydrogen is sustainably produced on land and preferably in the harbour from algae, see figure 101. This can be in combination with a specially designed algae structure onboard of the ship which receives direct sunlight, see figure 102. When the hydrogen is made in the harbour there is no need for a global hydrogen infrastructure. In this scenario, the hydrogen can be used in a fuel cell without any emissions and reduces the emissions in a dual fuel engine.

Option 1.3: The hydrogen is sustainably produced on land through electrolysis or algae, see figure 101 and figure 103. In this scenario, there is a global hydrogen economy which makes it possible to transport the hydrogen from places further away. The hydrogen can be used in fuel cells and dual fuel engines.

Option 3.1: Biodiesel is sustainably generated onboard by algae which are coupled to the wastewater stream, see figure 104. The algae use the wastewater to grow and simultaneously clean the water. However, it is assumed that not enough biofuel can be generated onboard. That is why a biodiesel production on land is needed, see figure 105. The biodiesel can be used in combination with a combustion engine and a dual fuel engine. The CO_2 that comes free is used for algae growth. In the far future biofuel can be used to power fuel cells.

Option 3.2: Biomass from organic waste and wastewater from the cruise ship can be used to produce biogas, see figure 106. The organic waste can also be used to produce dimethyl ether, see figure 107. Dimethyl ether can be used to power a combustion engine, or a fuel cell. Biogas can be used to power a dual fuel engine or fuel cell. However, this is not enough for the propulsion and hotel load of the ship. A combination with a biogas or dimethyl ether production on land is needed.

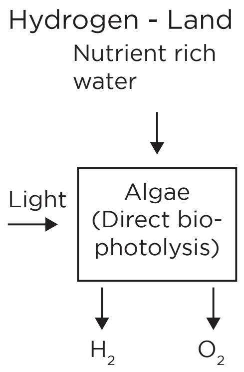

Figure 101: Hydrogen production from algae on land.

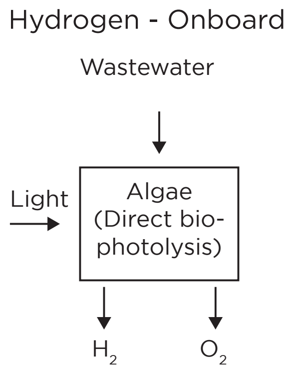

Figure 102: Hydrogen production from algae onboard.

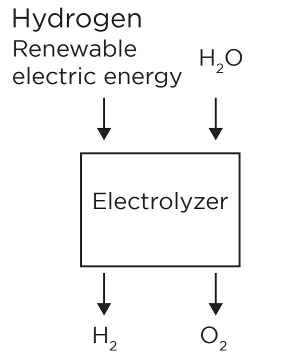

Figure 103: Hydrogen production through electrolysis.

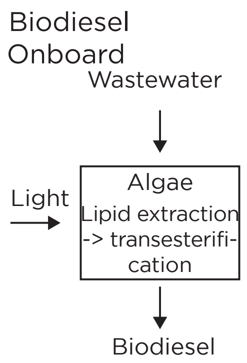

Figure 104: Biodiesel production onboard.

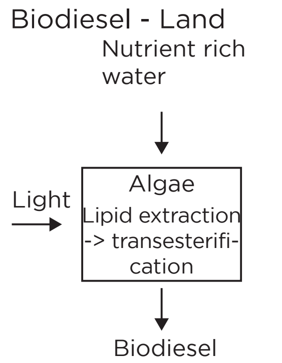

Figure 105: Biodiesel production on land.

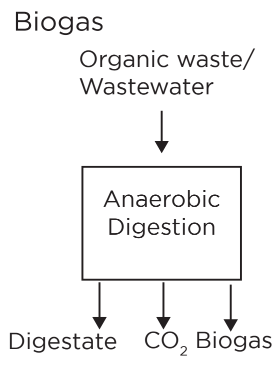

Figure 106: Biogas production.

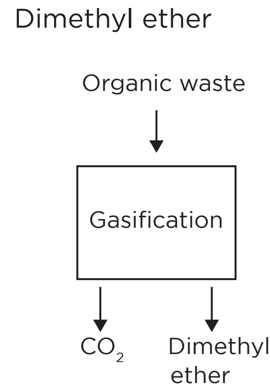

Figure 107: Dimethyl ether production onboard.

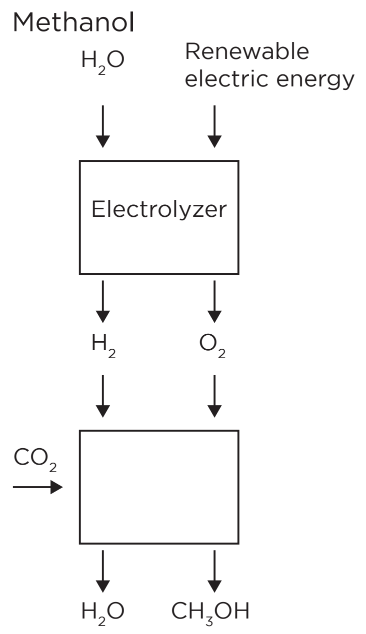

Figure 108: Production process of methanol.

Option 3.3: Methanol is sustainably produced on land through electrolysis and renewable energy, see figure 108. The needed CO_2 can come from on land generated flue gases. The methanol is transported to the ship where it is converted into hydrogen and then used in the fuel cell. The CO_2 that is released in this process is used for algae growth. The algae can clean the wastewater and use it for their growth. Hydrogen can be made through direct biophotolysis to power a fuel cell, see figure 102.

Option 4.2: The ship generated renewable electric energy by using the wind, sun, and wave energy together with renewable electric energy generated on land. The ship has a battery that stores this energy and is connected to the fuel cell. When the ship is in the harbour, it can connect to the electrical grid to recharge its battery. No emissions come free in this process. However, the weight of the battery should be considered. The battery could become too heavy and too big when it needs to store a lot of energy which is detrimental to the ship.

Renewable electric energy island
Chapter 4.3.3.1 showed that wind energy, solar energy, geothermal energy, and hydrokinetic energy are all possible sources to produce electricity on the private islands of Royal Caribbean. Theoretically, ships can recharge their batteries when they dock in the harbour. However, this research assumes that it is better to use this electricity on the island itself. The ship can use the renewable electric energy generated onboard as in roadmap A.

Roadmap
Which of the above options is the best scenario for retrofit ships and newly built ships of the future? The possibilities of hydrogen and methanol are both discussed in Roadmap A. Table 45 shows which combinations are possible now, in the near future, and in the late future. The decision whether the combination of fuel and engine falls under the near future or the far future is an educated guess. Biodiesel made from algae can be used in a combustion engine as a drop-in fuel. It is theoretically possible to use biodiesel in fuel cells but not in the near future. Dual fuel engines that use biofuel should be possible soon. Biomass, organic waste produced on board, can be converted to syngas. The syngas is first converted into methanol before it becomes dimethyl ether. Dimethyl ether can be used as a drop-in fuel in combustion engines and the syngas can be used to power a fuel cell in the short future. It is not possible to use dimethyl ether in a dual fuel engine in the near future. Biogas can be used in the short future to power fuel cells and dual fuel engines. In the short future, biogas can be used in fuel cells if made through anaerobic digestion. Biogas can also be used

in dual fuel engines. It is not possible to use biogas in a combustion engine in the near future. The renewable energy produced on boards can be directly used to power a fuel cell as mentioned in roadmap A. When the ship uses a dual fuel engine or a combustion engine, the renewable energy can be stored in a battery. The renewable energy produced on the island will not be used on the ships, although this is possible but on the island itself.

Table 45
Overview of possible combinations of fuel and engine in relation to time – Roadmap B.

	Hydrogen	Methanol	Bio-diesel	Dimethyl ether	Biogas	Renewable Energy Ship	Renewable Energy Island
Fuel Cell	-	-					n.a.
Dual Fuel Engine	-	-					n.a.
Combustion Engine	-	-					n.a.
Now	Near future	Late future					

As in Roadmap A, a distinction is made between retrofit ships and newly built ships. It is also assumed that future cruise ships use fuel cells and the older ships use combustion engines and dual fuel engines.

Retrofit
- Combustion engine -> Biodiesel/ Dimethyl ether
- Dual fuel engine -> Biodiesel/ Biogas

According to table 44 biodiesel and dimethyl ether can both be used in combination with a combustion engine. Biodiesel can be made onboard with algae from wastewater. Dimethyl ether can be made through gasification from organic waste. In both cases, emissions come free and an additional production on land is needed. Installing an algae production on retrofit ships is impossible due to the needed sunlight for algae. This is only possible in the future on newly built ships. Retrofit ships should sail on dimethyl ether when a combination of fuel production on land and onboard is desired, see figure 109.

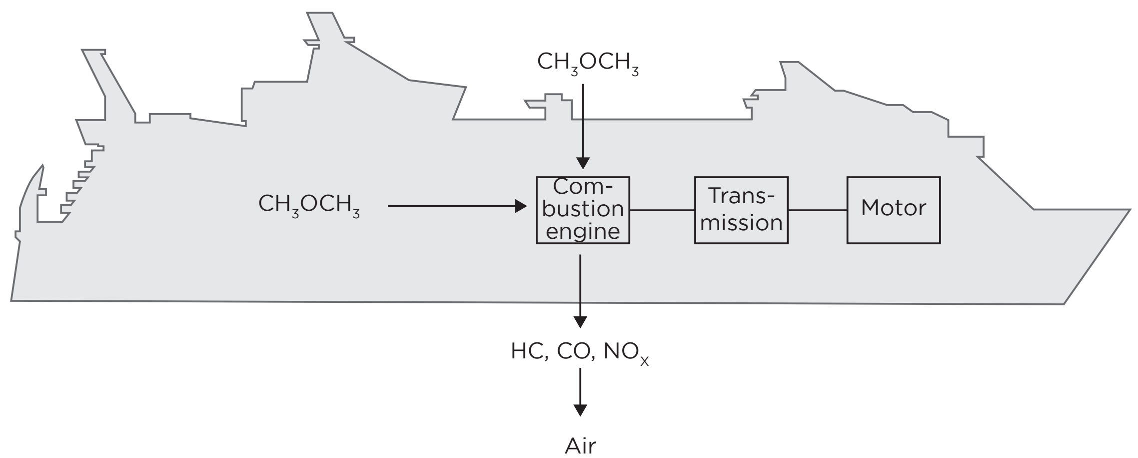

Figure 109: Propulsion system: dimethyl ether as fuel in combustion engine.

Methanol is the preferred option for dual fuel engines however in the short future biodiesel and biogas can also be used. The biogas can be made through anaerobic digestion from organic waste and the biodiesel from wastewater with the use of algae. In both cases, emissions come free. As previously mentioned, installing facilities for algae is impossible on retrofit ships. Dual fuel engines should use biogas when a combination of fuel production on land and onboard is desired, see figure 110.

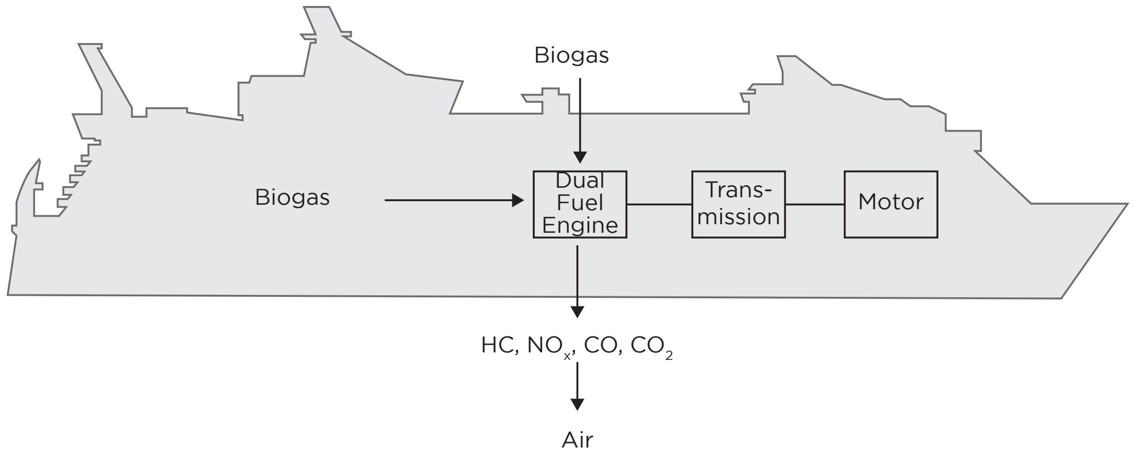

Figure 110: Propulsion system: biogas as fuel in dual-duel engine.

However, in both cases, biodiesel from algae can be used when the fuel is produced on land without a fuel production onboard, see figure 111 and figure 112. The benefit of algae compared to 2nd generation biomass is that algae use CO_2 in the production process of biodiesel. This is a small advantage. However, both options are possible.

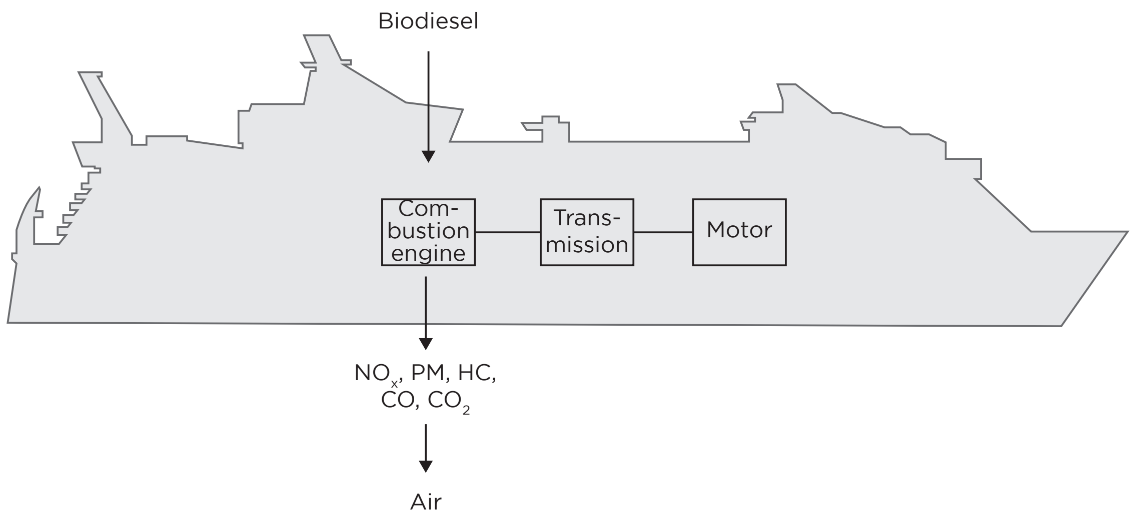

Figure 111: Propulsion system: biodiesel as fuel in combustion engine.

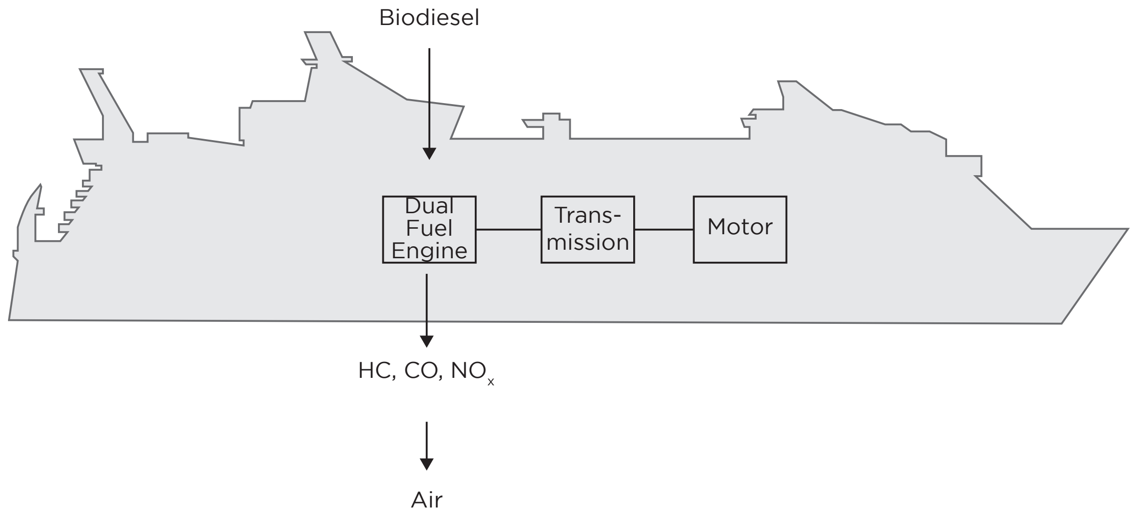

Figure 112: Propulsion system: biodiesel as fuel in dual-duel engine.

Newly built

- Fuel Cell -> Dimethyl ether/ Biogas

The preferred fuel for fuel cells is hydrogen or methanol. However, in the short future dimethyl ether or biogas can also be used, see figure 113 and figure 114. Both options are possible. Which one is preferred depends on the development of both fuels in the near future, the cost, and the amount of released emissions.

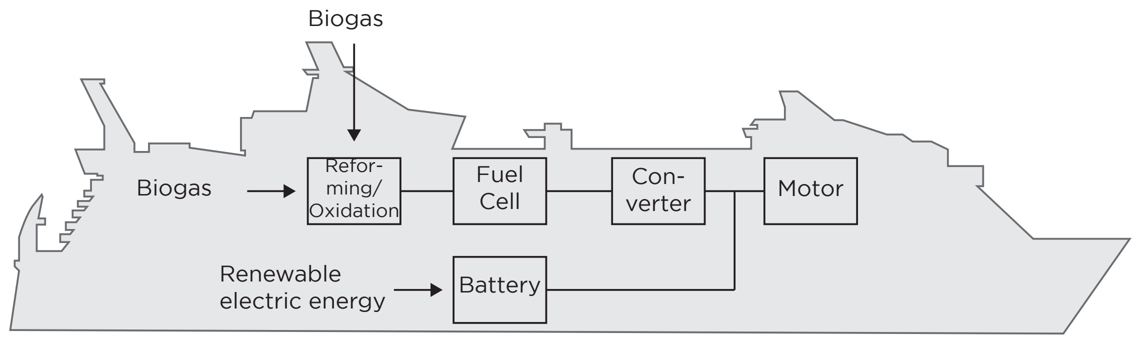

Figure 113: Propulsion system: biogas and renewable electric energy as fuel in fuel cell.

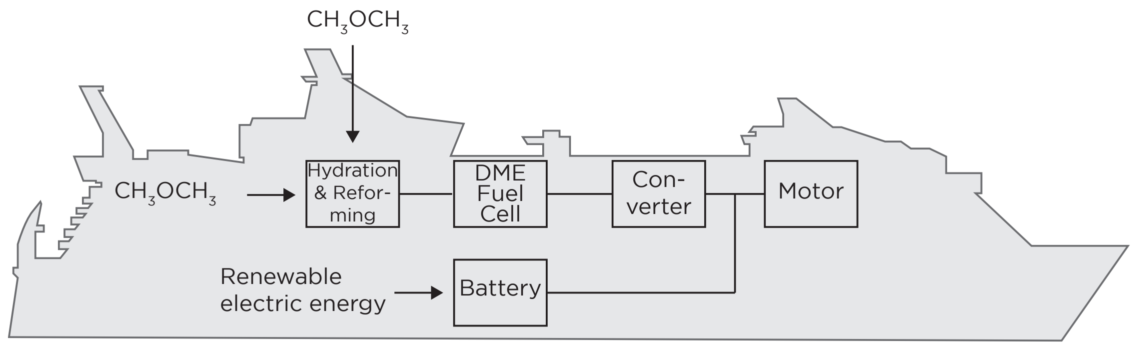

Figure 114: Propulsion system: dimethyl ether and renewable electric energy as fuel in fuel cell.

Reduce, Reuse, Recycle

The same measures which are given in roadmap A applied to roadmap B, see figure 115.

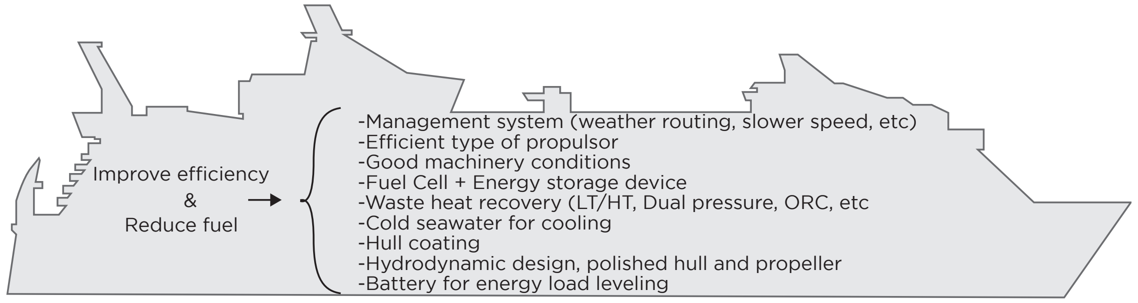

Figure 115: Overview measures to improve efficiency.

4.4.3.3 Roadmap B – Fluid stream

There are four wastewater streams onboard of a cruise ship: black water, greywater, bilge water, and ballast water. Chapter 4.3.2.2 showed that pollutants come back into the environment when the current treatment systems for black and grey water and bilge water is used. A sustainable circular cruise ship only uses seawater to produce freshwater and treats the produced wastewater as good as possible onboard. The remaining sludge and solids streams are disposed to land where this waste is treated in a sustainable way. This roadmap shows which additions and adjustments can be made to reducing the pollutants in the wastewater and how the remaining waste can be treated through a collaboration between the cruise line and the harbour.

Roadmap B – Black and Grey

Black and grey water are treated together with the systems of Evac. By using this system, the discharged wastewater complies with the current legislation set by IMO. However, the wastewater still contains pollutant substances as micropollutants. There is no treatment system found in the literature that can fully treat the wastewater. Research is still being conducted in new treatment systems which can remove or reduce the number of micropollutants, heavy metals, nutrients, phosphorous and nitrogen in the current discharged wastewater (Bentley & Ballard, 2007; Grandclément et al., 2017; Koboevic & Kurtela, 2011; Vicente-Cera et al., 2019; Westhof et al., 2016). The systems from Evac are used as the base and it is assumed that this is the best treatment system on the market.

Adjustments and additions

Heat, nutrients, and harmful substances can be extracted when other systems are implemented. An anaerobic digester can treat the wastewater from food and sludge, and simultaneously create biogas. The biogas can be used onboard as fuel or disposed of to land and used in other industries. The anaerobic digester is coupled to the prime solid removal. Phosphor and nitrogen are important nutrients

for agriculture and are found in wastewater that comes out of the anaerobic digester. Struvite can be recovered after this process and used onboard for agriculture or send to land. It is also possible to use algae to treat the wastewater. Algae use the nutrients in the wastewater to grow. The needed nutrients can be found in the bio sludge, but this substance is not liquid enough. That is why the algae can be implemented between denitrification and DAF. A special design must be made which receives light to make this possible. Biodiesel is made during this process. The biodiesel can be used onboard or disposed of to land and used in other industries.

Thermal energy can also be recovered, next to extracting these nutrients from the wastewater. The heat from the showers is separately recovered because this heat can be immediately used to warm the shower through a heat exchanger. The remaining heat from the black and grey water is recovered after the wastewater is treated to prevent clogging and maintain the efficiency of the wastewater treatment system. The additions can be seen in figure 116. There are two streams left, the biosolids and the sludge. These streams can be recycled on land, see next chapter treatment on land.

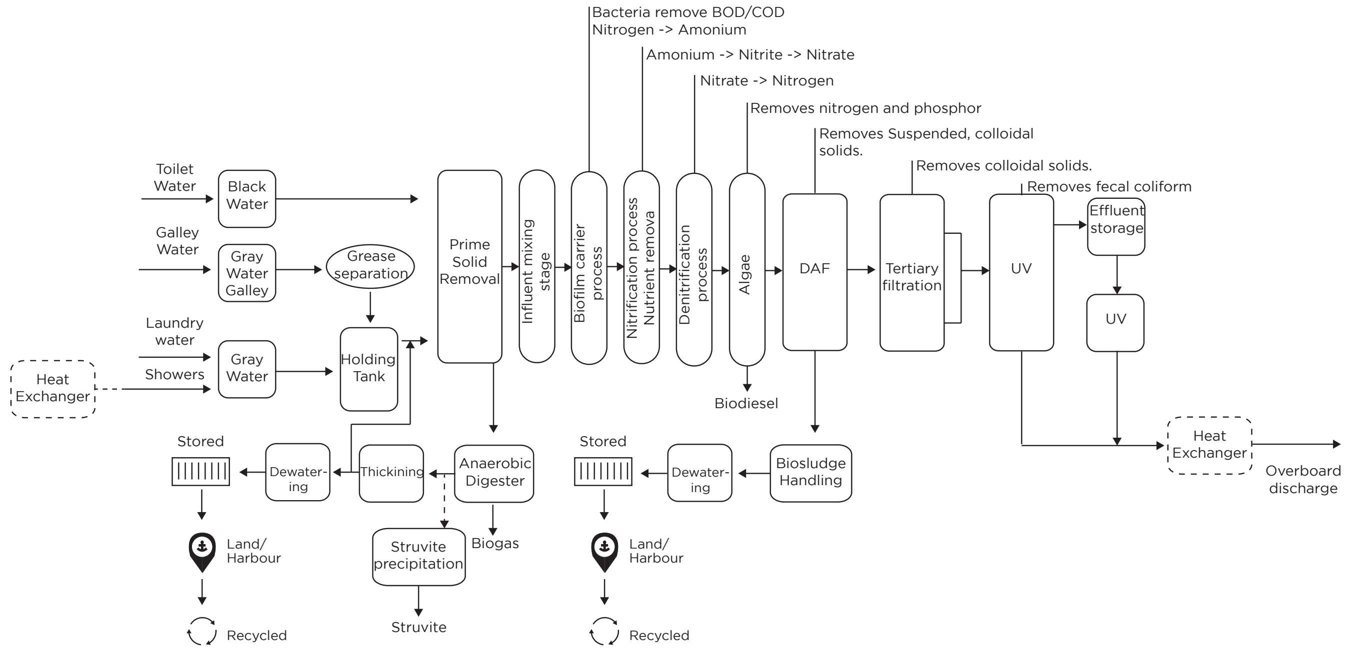

Figure 116: Wastewater treatment system with recycle options.
Note. Adapted from Evac (2019).

Treatment on land

The biosolids and sludge can be stored on board of the cruise ship and disposed to land when there is a collaboration between the cruise line and the harbour. Chapter 4.3.3.2 showed that there are 5 different options to treat the biosolids and sludge: landfilling, land application, bioprocessing, thermal processing, and other applications. When possible the biosolids and sludge should be used for land applications. The biosolids and sludge should be

carefully analyzed before it is used in agriculture to prevent contaminant accumulation in the ground. The biosolids and sludge can also be used for land reclamation or forestry. The sludge can be composted and used as a replacement of inorganic fertilizers. In the designed wastewater treatment, the fertilizer struvite is already recovered. When it is not possible to use the sludge on land, it can be included in other products as mortar and concretes. The dried sludge can be used for bricks and tiles and concrete aggregate. Thermal processing should be the last option due to the emissions that come free in this process. The ash that is left can be used in the construction industry. Landfilling should be prohibited because of the direct CO_2 emissions and leachate production.
It is impossible to store the treated black and grey water on board due to the high quantities, 634,800 per day. A part of the treated black and grey water is stored as ballast water and the remaining water should be discharged into the sea.

Reduce, Reuse, recycle
This chapter gives a short overview of the measures that can be taken to reduce the amount of black and grey water generated and the options to reuse or recycle this stream, see table 46.

The amount of black water is already reduced by using vacuum toilets. It is impossible to reduce this stream even more because the stool of people cannot be controlled. The blackwater is treated by the wastewater treatment system and cannot be reused. The blackwater can be recycled into biogas or biodiesel when anaerobic digestion or algae are used in the wastewater treatment system.
Several greywater streams can be found on board of the cruise ship. The wastewater can come from sinks, showers, galleys, and laundry. The water use of sinks, showers, and galleys can be reduced by creating awareness among passengers and crew and by using water-reducing and efficient equipment. To reduce the water use for laundry some small adjustments can be made. Reuse towels more than once, run full loads, and use efficient washing machines. The greywater is like the black water treated by the wastewater treatment system. The cleaned water can be reused for laundry, watering the plants, and flushing toilets. The sludge can be recycled on and. Preferably for land application and otherwise as material for other products. Thermal processing is the last go-to option due to the emissions that come free.

Table 46
Reduce, reuse, recycle principle – Water streams.

Water stream	Reduce	Reuse	Recycle
Toilet water	-	-	Wastewater treatment system with anaerobic digester and algae can recycle the wastewater into biogas or biodiesel. The heat can be recovered, and the sludge is recycled on land.
Sinks, showers, galleys	Creating awareness by passengers and crew and use efficient equipment.	-	Wastewater treatment system with anaerobic digester and algae can recycle the wastewater into biogas or biodiesel. The heat can be recovered, and the sludge is recycled on land.
Laundry	Reuse towels, run full loads, use efficient equipment.	-	Wastewater treatment system with anaerobic digester and algae can recycle the wastewater into biogas or biodiesel. The heat can be recovered, and the sludge is recycled on land.

It can be seen that there is not yet a solution to fully treat and reuse the wastewater streams. Some additions and adjustments can be applied to optimally use the wastewater stream as recovering energy and nutrition’s. These adjustments and additions are easier to apply on a newly built ship than on a retrofit ship, see figure 117 and figure 118. Especially the algae are difficult to install because of the large pipe system. Special research is needed to find out if this is possible. It is assumed that the general heat recovery can be installed on retrofits because this process takes place after the wastewater treatment and it is just 1 extra system. Through a collaboration with the harbour, the sludge can be stored and recycled on land.

Retrofit
- Heat recovery black and greywater.
- Recycling of biosolids and sludge on land.

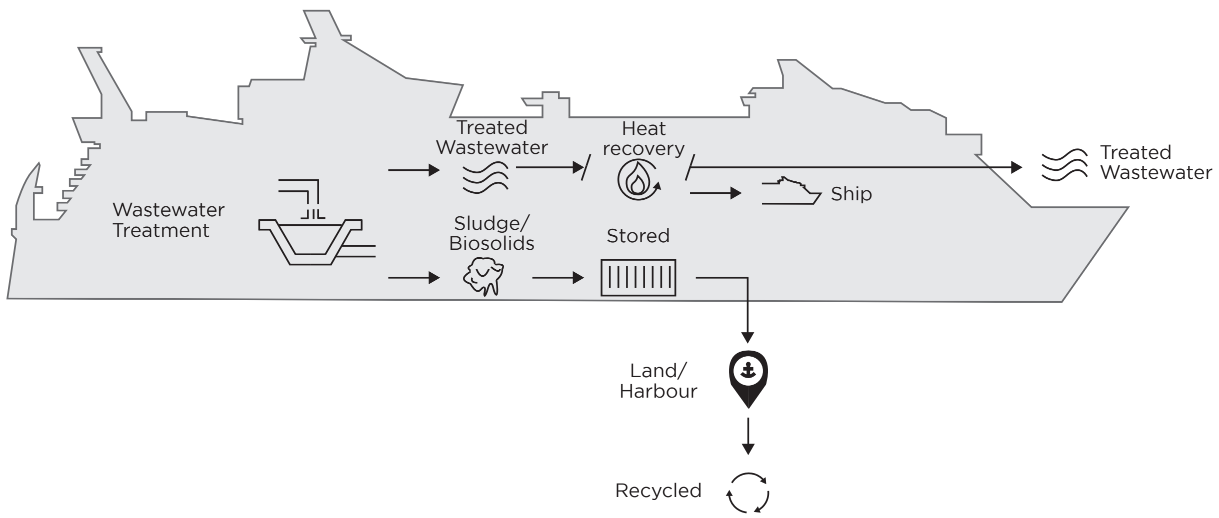

Figure 117: Additions to wastewater treatment system of retrofit ships.

Newly built
- Heat recovery black and greywater.
- Recycling of biosolids and sludge on land.
- Heat exchanger shower.
- Anaerobic digester.
- Struvite recovery.
- Algae system.

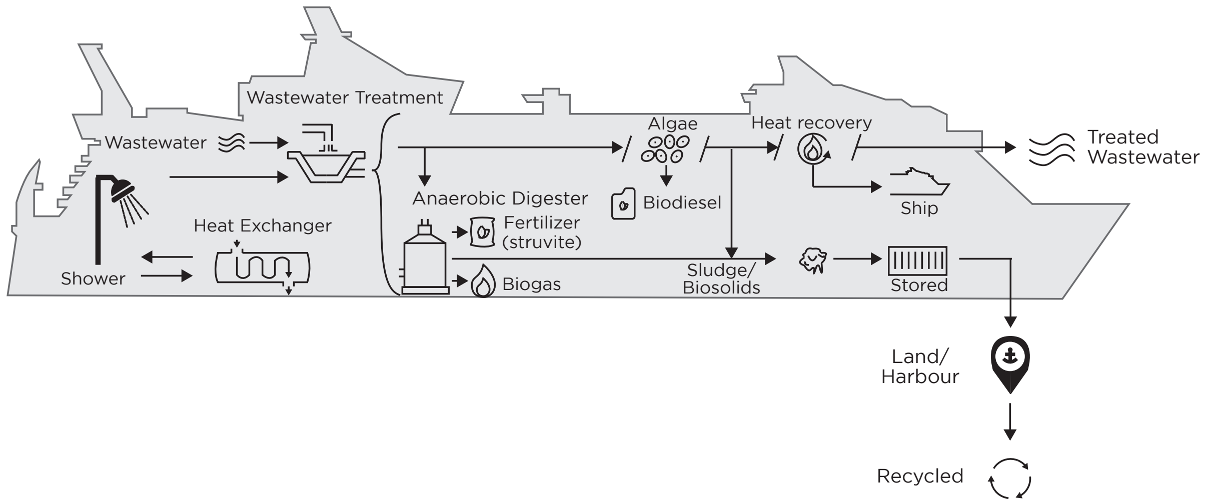

Figure 118: Additions to wastewater treatment system of newly built ships.

Roadmap B – Bilge water

The bilge water is formed by liquids coming together in the bilge. This is not a desired, or manually created and controlled process. Compared to the other wastewater streams it is not created with a purpose. Bilge water can legally be discharged into the sea when it contains less than 15 ppm. Royal Caribbean strives to 5 ppm with their above and beyond compliance. According to chapter 4.3.2.2, Royal Caribbean uses a gravity oil water separator together with coagulation and flocculation, and adsorption with a granular activated carbon filter. The discharged bilge water complies with the current legislation of the IMO, which only focusses on the oil content and not on other harmful particles. This means that the bilge water still contains some hazardous components as emulsified oil and heavy metals which come back into the environment. Chapter 4.3.3.2 showed that electrochemical wastewater treatment can be implemented.

Treatment system

Electrochemical treatment system can remove the harmful particles from the bilge water where IMO is not yet focusing on, as the emulsified oils, heavy metals, grease, and organic matter. In the electrochemical reactor, hydroxides are formed which connect to the emulsified materials, suspended solids, and colloidal materials. The H_2 generated at the electrode can remove flocks and precipitates by floating. The sludge is skimmed off and transferred into the sludge tank. A full description of this process can be seen in

chapter 4.3.2.2.This treatment method is insufficient by itself and needs to be combined with another treatment method as ultrafiltration, see figure 119. However, more research is still needed in optimising this system and removing all the hazardous pollutants from wastewater.

From the existing oily water polishing systems, the membrane technologies as reverse osmosis and nanofiltration are good options to remove heavy metals (Akarsu et al., 2016). Membrane technologies do not need a lot of space and are therefore easier to install on retrofits. A membrane can be added to the current bilge water treatment processes or it can replace one of the polishing treatments, see figure 120. This option should be used on retrofit systems because today electrochemical treatment is not yet possible and by implementing ultrafiltration more harmful substances are removed from the bilge water.

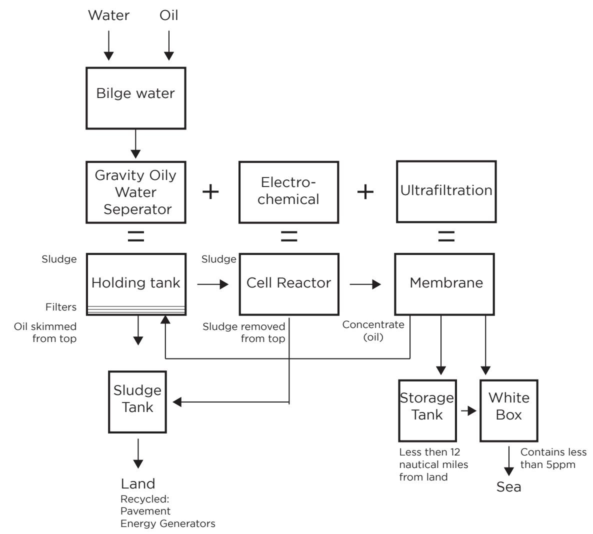

Figure 119: Bilge water process with electrochemical treatment – newly built ships.

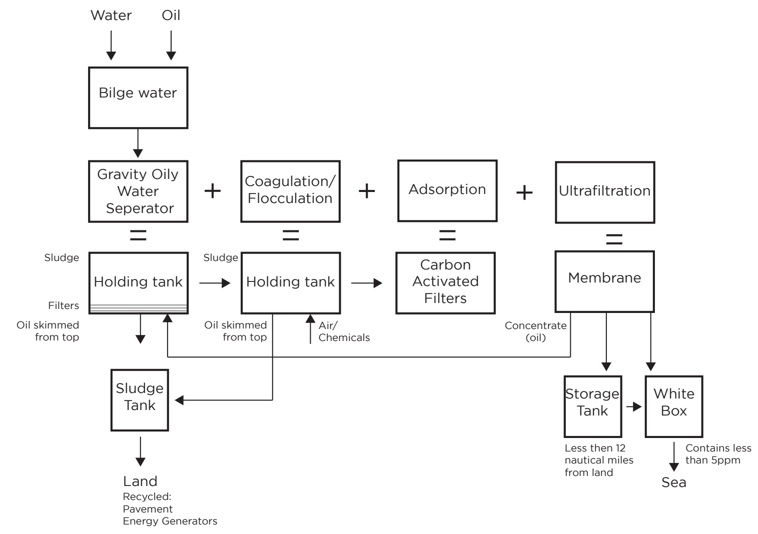

Figure 120: Current bilge water process with ultrafiltration treatment – retrofit ships.

Treatment on land

The oily sludge is stored in a tank and disposed to land when possible. The disposed sludge can be recycled as asphalt extender, binder for paved and unpaved road mixes, material for the composition of asphalt concretes, and as roadbed material. By doing this an alternative purpose is found with economic and environmental benefits. In figure 32 can be seen that Royal Caribbean already recycles the sludge for pavement but also for energy recovery. Biosludge for energy recovery should be prevented as much as possible due to the emissions that come free during incineration.

It is impossible to store the treated bilge water due to the high quantities generated per week, 35-140m³ (35,000-140,000 litres). The treated bilge water should be discharged into the sea.

Reduce, reuse recycle
Measures that can be taken to reduce the formation of bilge water are manual actions from the crew such as preventing leakages and spills and carefully handle liquids for cleaning and maintenance. The oil and the oily sludge recycled from the bilge water can be reused, incinerated, or offloaded to shore. Newly built ships in the future do not use marine fuels that contain oil but use clean fuels like hydrogen and renewable energy. This will reduce the number of harmful substances in the bilge water. The biggest problems are leakages of other processes that take place in the bilge and crew spilling cleaning and maintenance liquids. Figure 121 shows the treatment system for bilge water on retrofit ships, and figure 122 shows the treatment system for bilge water on newly built ships.

Retrofit
- Membrane treatment (Nanofiltration/ Reverse osmosis).
- Recycling of oily sludge on land.

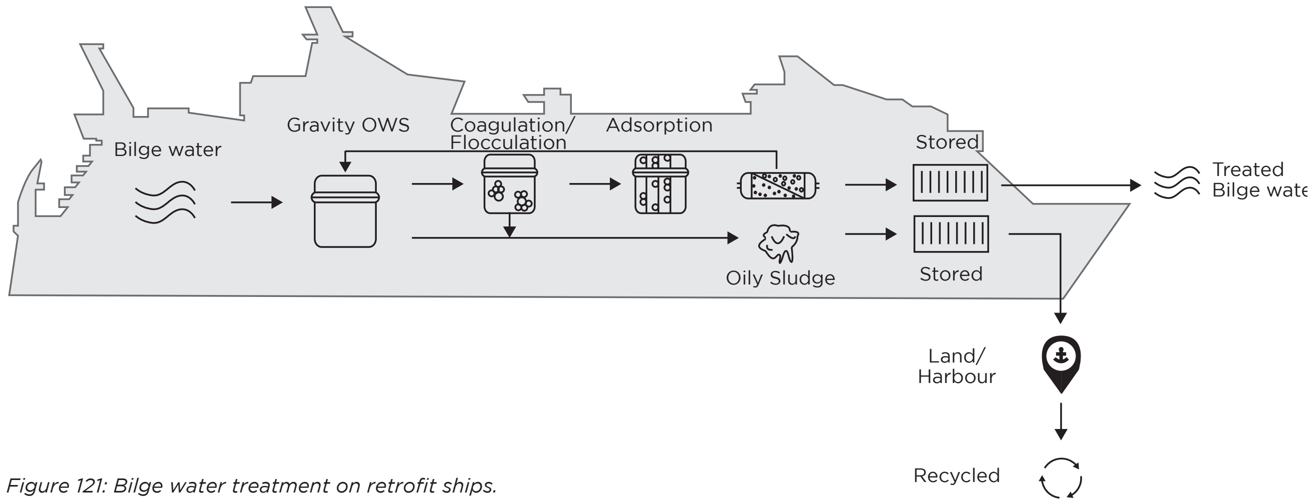

Figure 121: Bilge water treatment on retrofit ships.

Newly built
- Electrochemical treatment.
- Recycling of oily sludge on land.

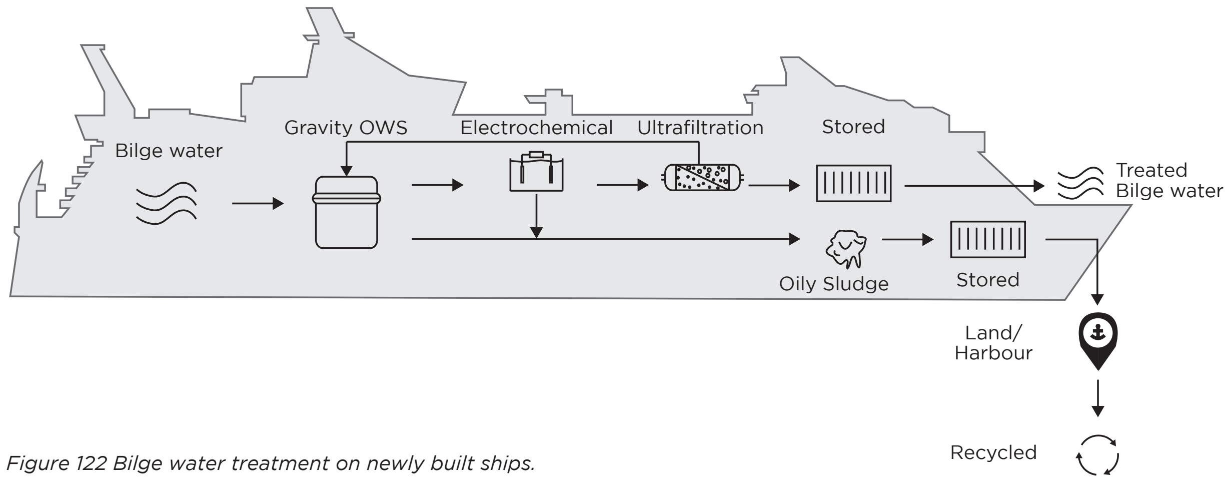

Figure 122 Bilge water treatment on newly built ships.

Roadmap B – Ballast water
As in Roadmap A treated black and grey water is used as ballast water, see figure 123. The storage of reusable water is expanded, and seawater is not needed as ballast.

Retrofit
- Treated black and grey water as ballast water.

Newly built
- Treated black and grey water as ballast water.

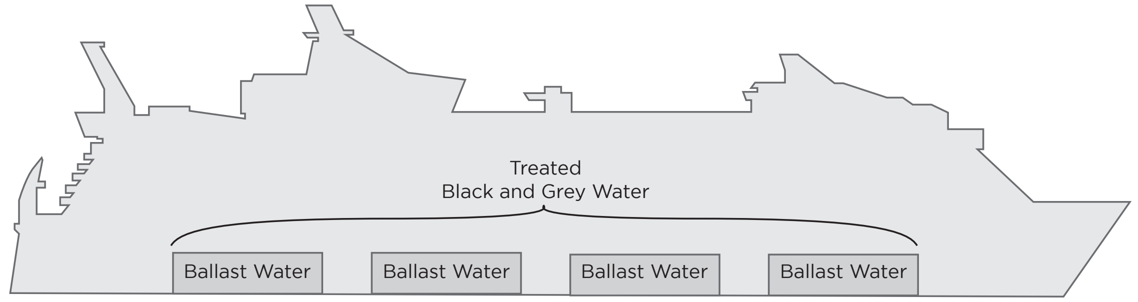

Figure 123: Treated black and grey water as ballast water.

4.4.3.4 Roadmap B – Solid stream
The solid waste stream is divided into non-hazardous solid waste and hazardous solid waste. Chapter 4.3.1.3 showed that it is impossible to make a cruise ship fully circular concerning the solid waste streams. A sustainable cruise ship reduces the amount of waste generated onboard, reuse the waste when possible onboard, and disposed the waste to land where it can be sustainably recycled. This is possible due to the collaboration between the cruise line and the harbour. This roadmap shows how solid waste can be reduced, reused, and recycled.

Roadmap B – non-hazardous solid waste
Chapter 4.3.3.3 showed that there are possibilities to reduce, reuse, and recycle the products used onboard. The food waste stream is already discussed in roadmap A. The glass bottles, plastic bottles and aluminium cans can be reduced by using liquid storage tanks instead of only using individual bottles and cans. The bottles and cans that are used can be recycled on land into new products. The use of plastic bottles can also be reduced by giving every passenger one reusable plastic bottle at the beginning of the vacation, which they can use and hand in at the end.
The cruise line should collaborate with the suppliers of their products. By doing this they can reuse the paper and cardboard packaging and the pallets their products arrive on. The softwood pooled pallets can be reused multiple times. The pallets and used packaging are taken back to the supplier which reuses the materials. The paper and cardboard can be recycled into recycled paper and cardboard and the broken pallets are recycled into new

pallets. The use of paper programs and leaflet can also be eliminated because the information is shown on screens and in the app. The last waste stream onboard is the incinerator ash. This waste stream can be reduced or even eliminated when the products are recycled as mentioned above. The ash that is still generated should be disposed to land where it can be recycled in cement production, ceramic and glass production, brick production, and road construction. These measures can be seen in table 47. Figure 124 shows the measures taken for the non-hazardous solid waste stream on retrofit ships and figure 125 shows the measures taken for the non-hazardous solid waste stream on newly built ships.

Table 47
Reduce, reuse, recycle principle – Non-hazardous solid waste.

Non-hazardous Solid Waste	Reduce	Reuse	Recycle
Glass	Receive as much as possible in liquid form + big storage tanks.	Clean and reuse the glass bottles again	Dispose to land when the glass reached their end-of-life. The glass can be recycled into other products.
Plastic	Eliminated single-use plastic bottles and garbage bags. Use reusable plastic bottles.	Give every passenger a reusable bottle, which they must hand in at the end of the vacation.	Dispose to land when the plastic reached their end-of-life. The plastic can be recycled into other products.
Aluminium & Metal Cans	Receive as much as possible in liquid form + big storage tanks.	-	Dispose to land when the cans reached their end-of-life. The cans can be recycled into new cans.
(news)Paper & Cardboard	Eliminated single used paper as day programs and leaflets.	Reuse the packing and dunnage of the products by a collaboration with the supplier.	Dispose to land when the paper & cardboard reached their end-of-life. The paper and cardboard can be recycled into recycled paper and cardboard.
Wood	Establish a collaboration with the supplier and use pooled softwood pallets.	Send the panels back to the supplier and reuse the panels for the next cargo.	Dispose to land where parts can be recycled to repair other pallets.
Incinerator ash	Recycle the products instead of incinerating them.		Dispose to land where the ash can be recycled in cement production, ceramic and glass production, brick production and road construction

Retrofit

- Eliminate single use plastic.
- Give a reusable plastic bottle to every passenger onboard which they must hand in at the end of their vacation.
- Eliminated all the paper information, show everything on screens.
- Reuse packaging and pallets multiple times.
- Recycle the products instead of incineration.
- Dispose of glass, plastic, aluminium, newspaper & cardboard, wood and incinerator ash to land where it can be recycled.

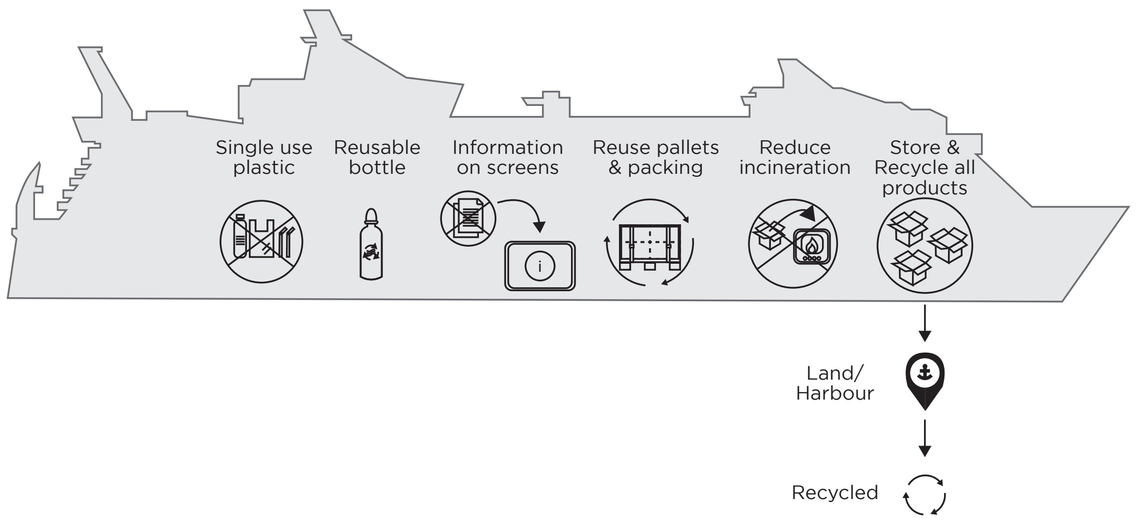

Figure 124: Measures for the non-hazardous solid waste stream on retrofit ships.

Newly built

- Receive all the drinks in liquid form and store it in tanks. This eliminates the need for single used glass, plastic and aluminium bottles.
- Eliminate single use plastic.
- Give a reusable plastic bottle to every passenger onboardd which they must hand in at the end of their vacation.
- Eliminated all the paper information, show everything on screens.
- Reuse packaging and pallets multiple times.
- Recycle the products instead of incineration.
- Dispose of glass, plastic, aluminium, newspaper & cardboard, wood and incinerator ash to land where it can be recycled.

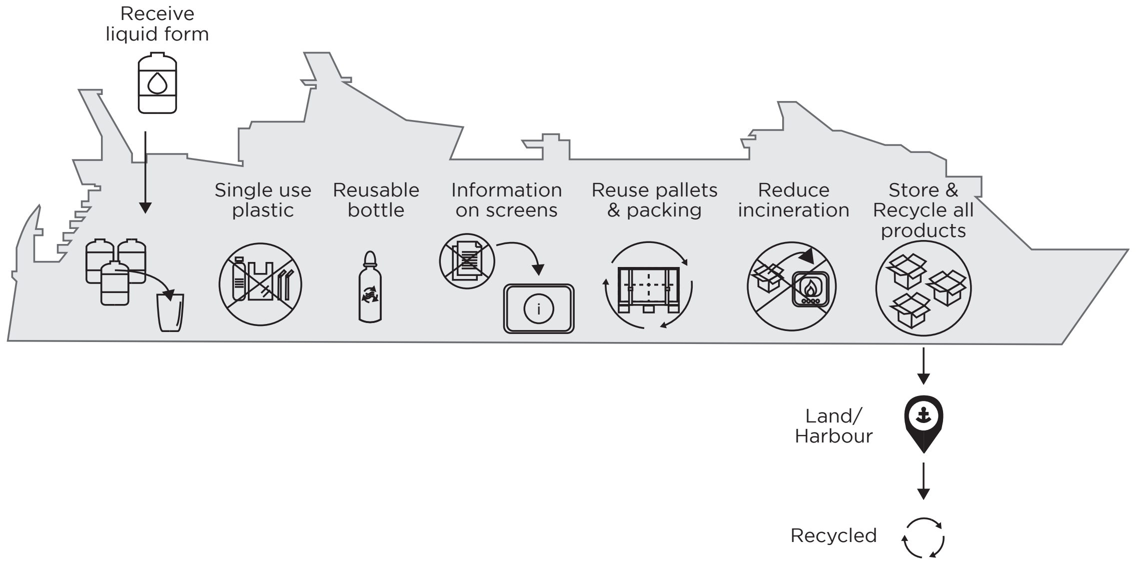

Figure 125: Measures for the non-hazardous solid waste stream on newly built ships.

Table 48
List of hazardous solid waste.

Hazardous waste
Paints waste
Fluorescent and mercury vapour light bulbs
Batteries
Medical waste
Photo waste
*Explosives
*Chemical
*Incinerator ash

*Discussed in roadmap A
Note. Data retrieved from: United States Environmental Protection Agency (2008).

Roadmap B – Hazardous solid waste

Chapter 4.3.3.3 showed the possibilities to reduce, reuse, and recycle the hazardous solid waste produced on board. It is impossible to eliminate this waste stream due to the needed products. Roadmap A showed that the explosive, incinerator ash and chemical stream can be taken care of on a circular cruise ship. The other hazardous waste should be disposed of, and recycled on land. Table 48 shows the hazardous waste found on board.

The conventional paints must be replaced with electrochemical active coating for the outside and sustainable non-fossil-based paints for the inside. The paint should be carefully handled to make optimal use of the paint. There are no companies which recycle used paints. For now, it should be thrown away until such a company is established. LED lights should be used instead of incandescent bulbs and fluorescent light because it consumes less energy, eliminates the use of mercury, and is long-lasting. When the lights reached the end of their life, they are disposed to land where the components of the lights are recycled. More research should be done into designing lights with principles as design for disassembly, replaceable parts, minimal material types, and a proper take-back system. Battery use cannot be eliminated on board of the ship. However, lithium batteries should be replaced by batteries which do not use scare materials as magnesium. More research should be done into developing sustainable batteries. The cruise industry should follow these developments and use sustainable batteries as replacements. The batteries are disposed to land where the metals can be recovered and recycled. Pharmaceuticals are on board in case people get sick. They become waste when its off-specification or exceeded the shelf life. A special registration system should minimize the number of pharmaceuticals that exceeded their shelf life. For now, medical waste should go to the incinerator on board or on land as long as there are no other reuse or recycle options. The medicines should be disposed to land when it is no longer unethical to reuse or recycle the medicines. The amount of photo and printing waste can be reduced by only printing the photos passengers bought and only print when a hardcopy is needed. As with reducing the paper waste stream, all the information can be seen on screens and on apps. The cruise line should collect the used cartridges and toners and dispose them to land. There are cartridge remanufacture companies that take back cartridges and reuse and sell them. These measures can be seen in table 49. Figure 126 shows the measures taken for the hazardous solid waste stream on retrofit ships and figure 127 shows the measures taken for the non-hazardous solid waste stream on newly built ships.

Table 49
Reduce, reuse, recycle principle – Hazardous solid waste.

hazardous Solid Waste	Reduce	Reuse (onboard)	Recycle
Paints waste	Reduce/ eliminate the conventional type of paint and use electrochemically active coatings as anti-fouling paint and sustainable paints for inside.	The paint should be carefully handled and reused until there is nothing more left.	No recycle companies are found. Paint is thrown away with general waste.
Fluorescent and mercury vapour light bulbs	Reduce/ eliminate the incandescent bulbs and fluorescent light and use LED lights.	The lights are used until they reached the end of their life.	Dispose to land where the components in the LED light can be recycled.
Batteries	Reduce the use of lithium batteries. (More research needed in which batteries are most sustainable).	The batteries are used until they reached the end of their life.	Dispose to land where the metals can be recovered and recycled.
Medical waste	Use a registration system to find out the needed amount of medicines.	It is (for now) not allowed to reuse medicines.	Medicines cannot be recycled and go into the incinerator on land or onboard.
1.Photo waste **2.Print waste**	Only print the pictures which are bought. Only print when a hardcopy is needed. All the other information can be seen on screens and in the app.	The cartridges, ink, and toners are used until they reached the end of their life.	Dispose to cartridge remanufacture companies on land which take back cartridges and reuse them.

Retrofit

- Replace the paints, lights, and batteries with sustainable alternatives.
- Only buy the needed amount of pharmaceuticals.
- Only print when a hardcopy is needed and pictures are bought.
- Dispose of paint waste, lights, batteries and photo, and printing waste to land where it can be recycled.

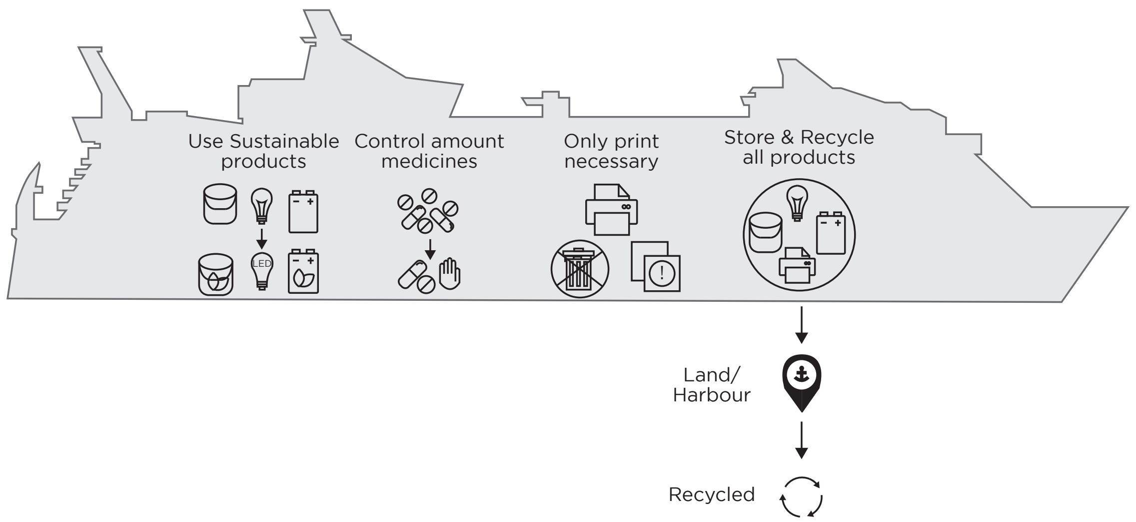

Figure 126: Measures for the hazardous solid waste stream on retrofit ships.

Newly built

- Replace the paints, lights, and batteries with sustainable alternatives.
- Only buy the needed amount of pharmaceuticals.
- Only print when a hardcopy is needed and pictures are
- bought.
- Dispose paint waste, lights, batteries, photo, and printing waste, and medical waste (if allowed) to land where it can be recycled.

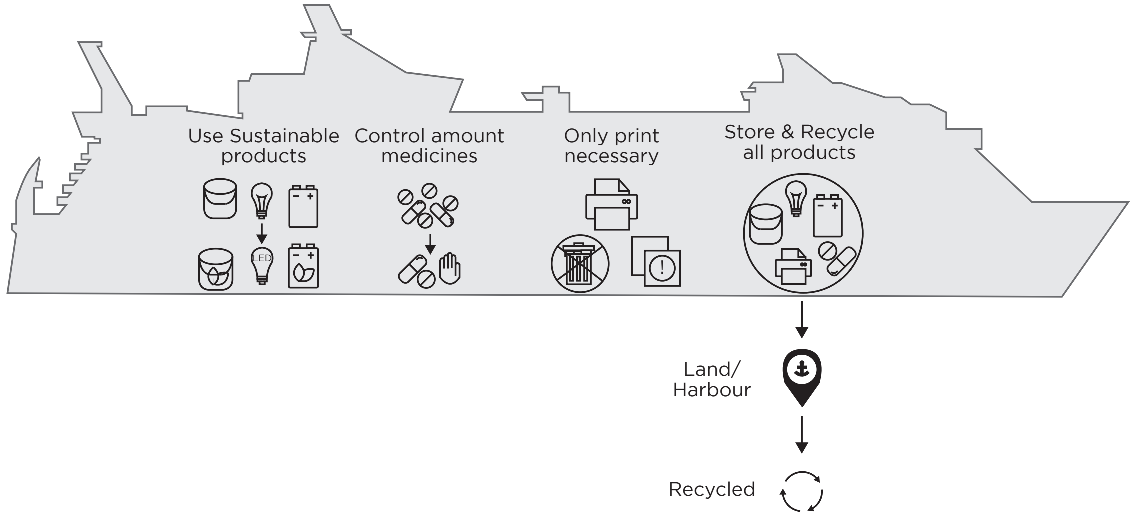

Figure 127: Measures for the hazardous solid waste stream on newly built ships.

Roadmap B – Conclusion

A sustainable cruise ship from scenario B collaborates with the harbour or companies on land to get rid of unavoidable and untreatable waste, provided this is done in a sustainable manner. The ship can also receive the needed supplies from land which they cannot generate themselves. In this roadmap cruise ships do not strive to become circular which means some waste streams will leave the ship. However, these waste streams should be taken care of on land and are still not allowed to enter the environment.

It is impossible for retrofit ships to fully eliminate the emissions into the air when a combination of fuel produced on land and onboard is used. However, when dimethyl ether is used in a combustion engine and biogas in a dual fuel engine the emissions are reduced compared to the current combinations of fuel and engine. Biodiesel can also be used in a combustion engine and dual fuel engine when it is produced on land. It is not possible to install a biodiesel production facility on a retrofit ship. As in roadmap A, the cruise ship produces its own fresh water from seawater and does not buffer freshwater from land. This water is treated and used as drinking water. A heat recovery system is integrated to recover the heat from black and grey water and use it on board. Next to this, the generated biosolids and sludge are disposed to land where they can be recycled, preferably for land application or land reclamation and

forestry. Otherwise, it can be recycled into other products as mortar and concretes. The sludge should not end up as landfilling or in the incinerator. Membrane treatment is added to the treatment system of bilge water to reduce the number of heavy metals. The sludge is sent to land where it is recycled as asphalt extender, binder for paved and unpaved road mixes, etc. However, the treated black and greywater and the treated bilge water still contain some pollutants which end up in the sea. The treated black and grey water is used as ballast water as in roadmap A. To reduce the amount of non-hazardous solid waste, single used plastic should be eliminated together with paper information. Instead, reusable bottles should be used, and the information can be seen on screens and apps. The packaging and pallets are reused through a collaboration with the supplier. The products that reach the end of their life are not sent to the incinerator but disposed to land where they can be recycled into new products. The cruise industry should strive to use sustainable products. This means for the non-hazardous solid waste that non-fossil-based paints should be used together with electrochemically active coatings, LED lights should replace incandescent bulbs and fluorescent light and lithium batteries should be replaced by more sustainable batteries. A registration system is used to find the needed number of pharmaceuticals and pictures and information is only printed when needed to reduce the amount of waste. The waste that is generated is sent to land where it can be recycled. This can be seen in figure 128.

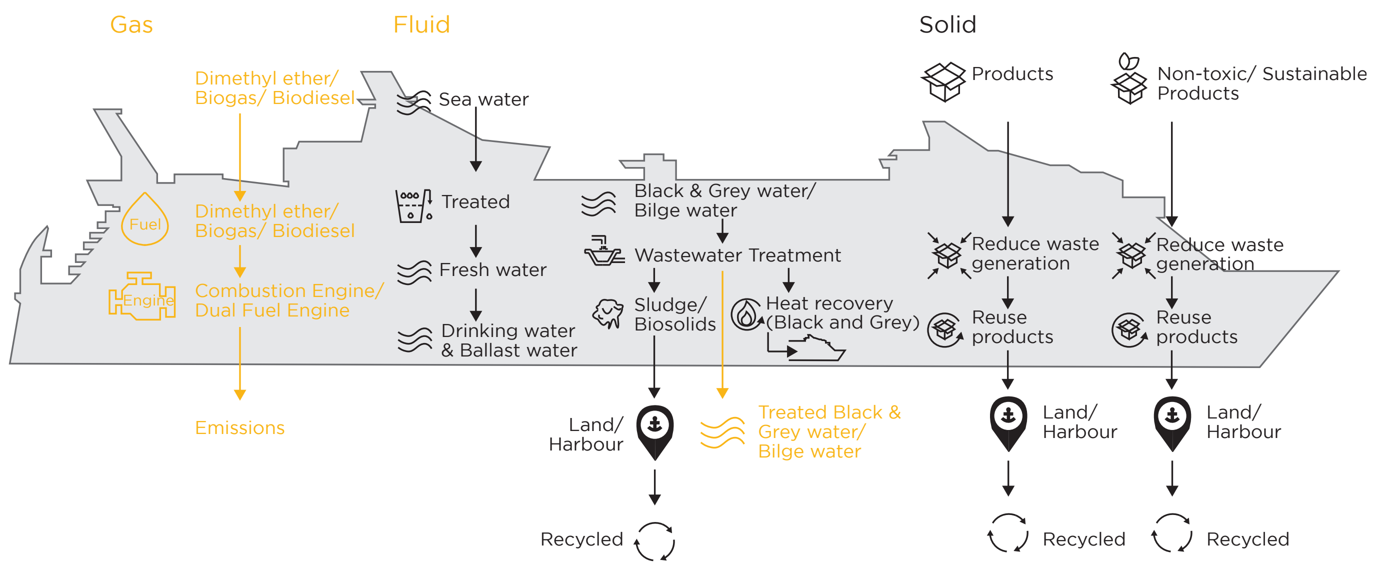

Figure 128: Conclusion drawing waste streams roadmap B, retrofit.

It is also for newly built cruise ships impossible to eliminate emissions from coming into the air when a combination of fuel produced on land and onboard is used. In this scenario, dimethyl ether and biogas are the preferred fuel for fuel cells in combination with a battery. During the production of these fuels, CO_2 comes free. Newly built cruise ships only use seawater to produce freshwater, as with the retrofit ships. Both ships recover the heat from black and grey water and recycle to sludge and biosolids on land into new products. However, newly built ships can implement heat exchangers for showers to directly recover the heat, install anaerobic digester to produce biogas, recover the fertilizer struvite, and use algae to produce biodiesel. This is not possible for retrofit ships due to the large impact on the current systems. Biogas can be used as fuel onboard of the ship. When the ship uses another type of fuel, the biogas and biodiesel can be disposed of to land and used in another industry. The struvite can also be used onboard for the greenery and food production or disposed of to land. Future cruise ships will use electrochemical treatment to reduce the amount of emulsified oils, heavy metals, grease, and organic matter. The sludge is sent to land where it is recycled as asphalt extender, binder for paved and unpaved road mixes, etc. Treated black and grey water is used as ballast water as with the retrofit ships. However, the treated black and grey water and bilge water still contains some pollutants that are discharged into the sea. The only difference in the non-hazardous solid waste stream is that the drinks which are used often come onboard in their liquid state and stored in big tanks. This eliminates the need for single used glass, plastic and aluminium bottles. Pharmaceuticals should be sent to land and recycled when this is legal in the future. As with the retrofit ships, sustainable products should be used, the number of pharmaceuticals and prints onboard should be reduced, and the waste should be recycled on land. This can be seen in figure 129.

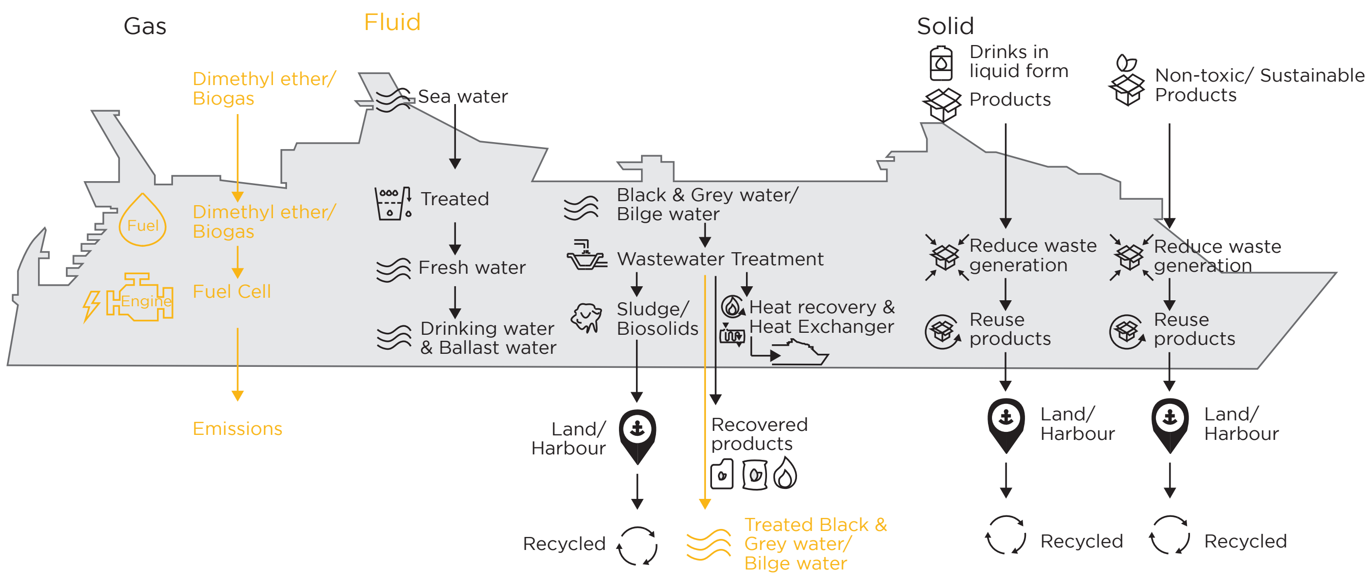

Figure 129: Conclusion drawing waste streams roadmap B, newly built.

4.4.4 Roadmap C – Positive Effect on the Environment

4.4.4.1 Introduction

Roadmap A and roadmap B looked at the current waste streams of the cruise ship and tries to improve this stream by implementing new techniques and using the reduce, reuse, and recycle method. Roadmap C does not focus on the waste streams from the ship but on the polluted environment. In the scenario of roadmap C the cruise ships contribute to the environment they sail in by doing research into the environment and cleaning the environment. This roadmap points out the future possibilities, but more research and technological development are needed. Figure 130 shows the vision of roadmap B and figure 131 shows the vision of roadmap C.

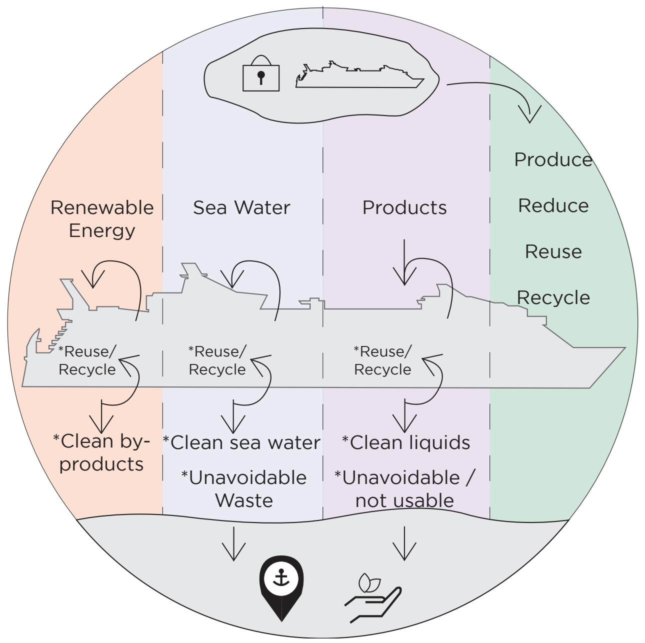

Figure 130: Vision of Roadmap B.

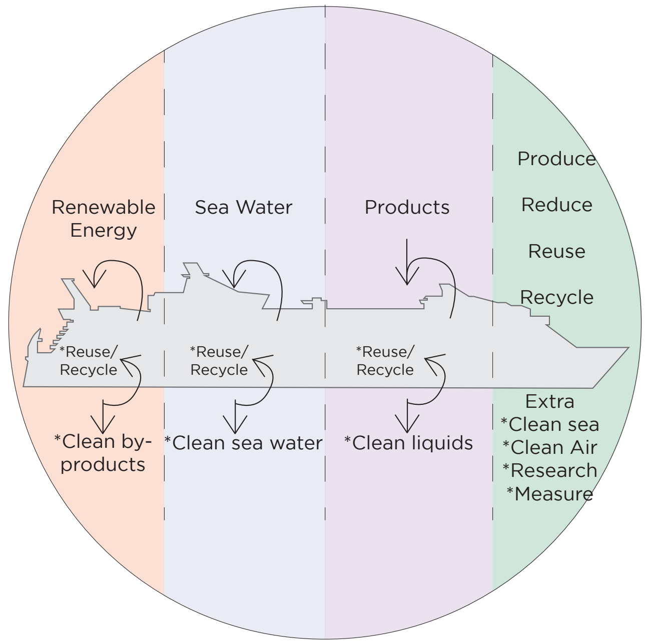

Figure 131: Vision of Roadmap c.

4.4.4.2 Research

A cruise ship is the ultimate place to do research into the environment. Cruise ships sail all around the world. This allows them to perceive changes. A cruise ship is also able to get to remote places. The Royal Caribbean already installed oceanographic and metrological instruments on 5 ships of their fleet to measure atmospheric and ocean conditions which are important for climate change research. This equipment should be extended to all the ships and the research itself should be elaborated. A cruise ship should do research into the following aspects:

- Temperature change - air
- Air quality
- Temperature change – sea
- Tidal change sea
- Sealife/ marine life
- Water quality
- Scanning seabed (lost objects)

A ship could monitor the temperature and air quality. From these measurements can be seen whether the measures taken worldwide have a positive effect on climate change or not. The ship can also track the temperature and tidal changes in the sea. Simultaneously the ship can do research into the marine life and track changes into plants, animals, and other organisms living in the sea. It can help with tracking the development of coral reefs and detect whether species are threatened with extinction. When necessary, the ship can intervene and help by placing cultures and seeds. The ship also monitors the water quality and detects spills or deterioration. Besides contributing to the environment, the ship could also scan the seabed during their voyage and detect lost objects as sunken planes and ships or lost cultural heritage. The technology still needs further development for these applications. However, this would be possible in the future.

4.4.4.3 Cleaning

The cruise ships could also clean the environment they sail in. Special equipment could be installed in the future to absorb pollutants from the air. These pollutants can be recycled or captured to prevent environmental pollution. The cruise ships can also install equipment to clean the sea they sail in. Perhaps they have special arms that collect plastic and other debris from the sea. This plastic and debris can be stored onboard and recycled on land. As with the research applications, the technology needs to be further developed before these cleaning applications can be installed. This roadmap points out the future possibilities, but more research is needed. Figure 132 shows the future possibilities of how a cruise ship can contribute to the environment.

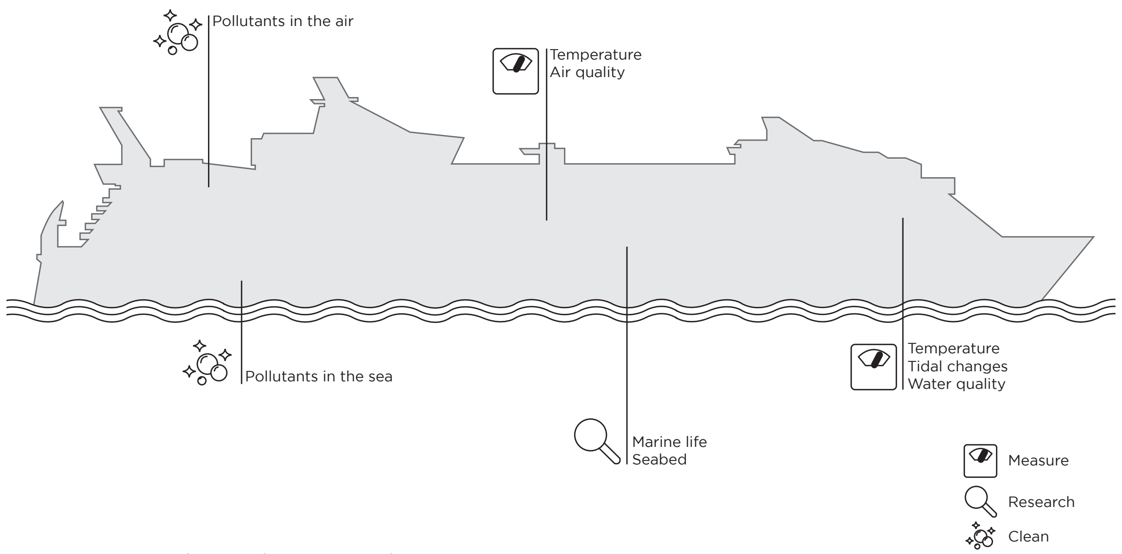

Figure 1312 Conclusion drawing roadmap C.

4.5 The optimal combination

4.5.1 Introduction

Roadmap A and roadmap B focus both on the optimal scenario under the conditions made for that roadmap. However, in reality, a combination of both is possible. To design the most sustainable cruise ship, a combination of roadmap A and B is needed.

4.5.2 Combination roadmap A and roadmap B

Retrofits

It can be seen that there will always be emissions coming into the air on retrofit ships regardless of the fuel. Roadmap A favours methanol and hydrogen and roadmap B dimethyl ether, biogas, and biodiesel. Methanol can be used in dual-fuel engine and biodiesel or dimethyl ether in a combustion engine. Algae uses CO_2 in the production process of biodiesel, this is a small advantage compared to the production process of dimethyl ether. These fuels should be used today in retrofit ships. The next step is to use methanol in a combustion engine in the short future when the cruise industry prefers to produce its own fuel. Hydrogen can be used in a dual fuel cell in the short future.

In the case of the fluid and solid waste streams, it is clear that a collaboration between the cruise line and land is necessary. The cruise ship cannot take care of the waste products onboard in a sustainable matter. However, with a collaboration, it is possible to recycle waste on land. A heat recovery system is added to the wastewater treatment system to recover and reuse the heat. The generated waste during the wastewater treatment, the biosolids and sludge, are recycled on land as asphalt extender, binder for paved and unpaved road mixes and material for the composition of asphalt concretes. The treated black and grey water is also used as ballast water to eliminate the need of seawater and the ship produces its own drinking water through reverse osmosis. To remove the heavy metals from the bilge water, nanofiltration is added and the sludge is recycled on land. The same applies to the solid waste stream. Throughout the collaboration, the products that reach the end of their life can be recycled on land. Next to this, cruise ships eliminate the use of single plastic, use recycle bottles, reduce paper waste and reuse packaging and pallets to minimize waste production. Cruise ships use sustainable, non-toxic alternative products when these are on the market to reduce hazardous waste. Next to this, the generated hazardous waste is also recycled on land. Figure 133 shows these combinations of measures for retrofit ships.

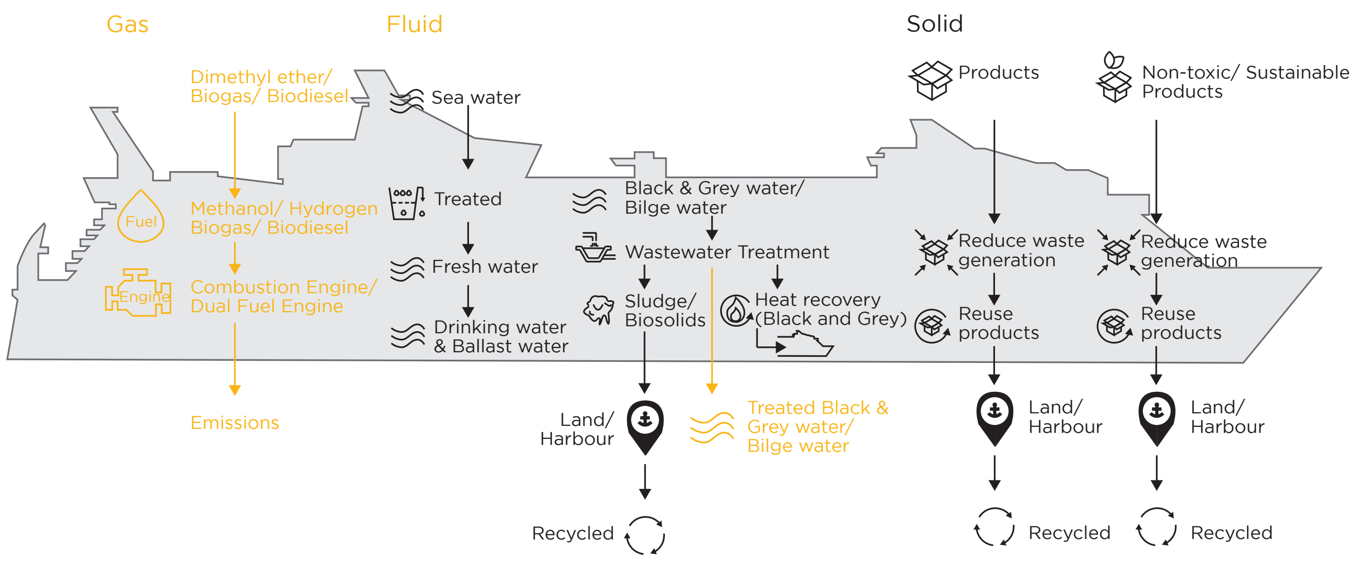

Figure 133: Conclusion drawing waste streams combination roadmap A and B, retrofit.

Newly built

It is clear that newly built ships should sail on hydrogen with renewable energy to power a fuel cell. No emissions come free during the production of the fuel and when the fuel is used in the engine. As with the retrofit ships, a collaboration is needed to optimal handle the fluid and solid waste streams. Next to the heat recovery system a heat exchanger for the shower, anaerobic digester, and algae system are added to the wastewater treatment system. These systems clean the wastewater and produce biogas, biodiesel and struvite. The biogas and biodiesel can be used on land in other industries and the struvite can be used onboard for the greenery and food production. The biosolids and sludge are recycled on land as with the retrofit ships. Next to this the treated black and grey water is used for ballast water and the ship makes its own drinking water from seawater. The bilge water is treated by an electrochemical treatment system which also removes emulsified oils, heavy metals, grease and organic matter. The oily sludge is recycled on land. Handling the solid waste is on the newly built ship the same as on the retrofit ship with a few additions. The non-hazardous and hazardous waste is reduced and reused onboard as much as possible. When the products cannot be used anymore, they are disposed of to land and recycled. Next to these measures, the often-used drinks come on board in liquid form on newly built ships and stored in tanks to reduce single-use cans and bottles. Also, the food is produced and recycled onboard. There is no need for help from land. Figure 134 shows the optimal combination of roadmap A and roadmap B for newly built ships.

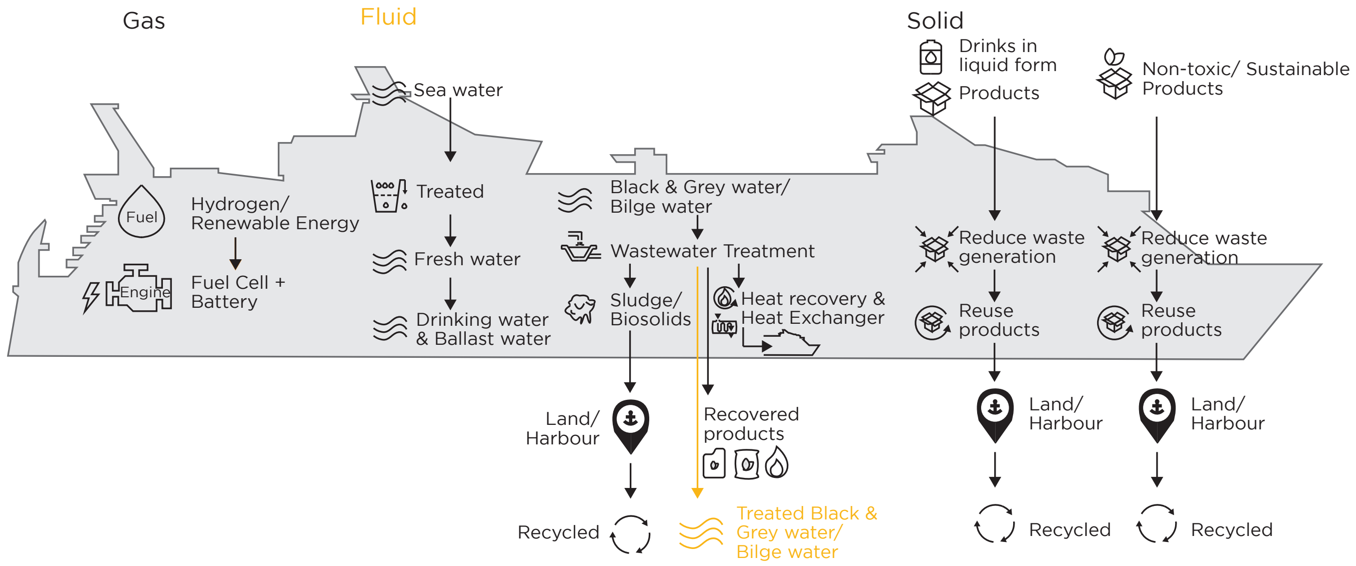

Figure 134: Conclusion drawing waste streams combination roadmap A and B, newly built.

In short, it can be seen that the treated black and grey water and bilge water still contain pollutants that come back into the sea. Also, the techniques to recycle the generated waste on land should improve. Some products cannot yet be fully recycled. While designing any kind of product, techniques as design for disassembly, replaceable parts, minimal material types, and a proper take-back system must be considered and incorporated. Recycling of waste should be the standard and incineration should be the exception. This final design for newly built cruise ships is not fully circular. However, the emissions from the gas stream are eliminated, more pollutants are removed from the black, grey and bilge water, pollutant by-products are recycled on land, heat is recovered and reused, clean products as biogas, biodiesel and struvite are produced, seawater as ballast water is not needed, and non-hazardous and hazardous waste is reduced, reused and recycled.

4.6 Designing a ship as a City

4.6.1 Introduction

As mentioned in the background information, a cruise ship can be seen as a city or a building complex. This master thesis focusses on the waste streams of a cruise ship. These gas, fluid, and solid waste streams can also be found in a city or building complex. However, this is not the only comparison that can be made. The same design principles and interventions used in cities and building complexes can also be implemented on cruise ships. This includes the reduce, reuse, and recycle principle that is already used in this research, but also reducing, producing and exchanging the energy demand, improving the (building)envelope and the interior conditions. This chapter shows that design interventions taken in the built environment can also be applied to the envelope (hull) and interior of the ship.

4.6.2 Design interventions – Interior

New Stepped Strategy

Around the 1980s, designers used the Trias Energetica guidelines as an approach to design sustainable buildings. This is a three-stepped strategy; 1. Reduce the demand, 2. Use renewable Energy, and 3. Supply the remaining demand cleanly and efficiently. However, these guidelines did not lead to the desired progress because step 2 was often skipped - after some limited efforts of step 1 - and with the main focus on step 3 (Tillie et al., 2009). Van den Dobbelsteen (2008) made the New Stepped Strategy (NSS) as a substitute for the Trias Energetica which is inspired by the Cradle-to-Cradle philosophy. The first step of the NSS is to reduce the demand by passive, smart & bioclimatic design, the second step is to reuse the residual streams (waste heat, wastewater, waste material) and the last step is to solve the remaining demand sustainably and use the remaining non-toxic waste as food for the environment, see figure 135. It is useful to apply the NSS in a single building, however, in an urban context, the surroundings should be included as well. Energy exchange between buildings with a different energy pattern should be applied to solve the remaining heating and cooling demand. This is implemented in the REAP methodology which exchanges, storage or cascade the energy (Tillie et al., 2009). The New Stepped Strategy can also be applied to cruise ships, see figure 136.

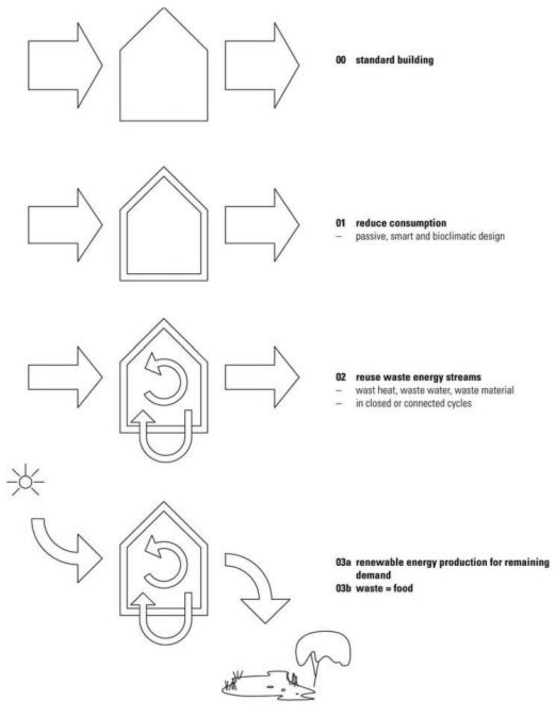

Figure 135: The New Stepped Strategy
Note. Reprinted from Tillie et al. (2009).

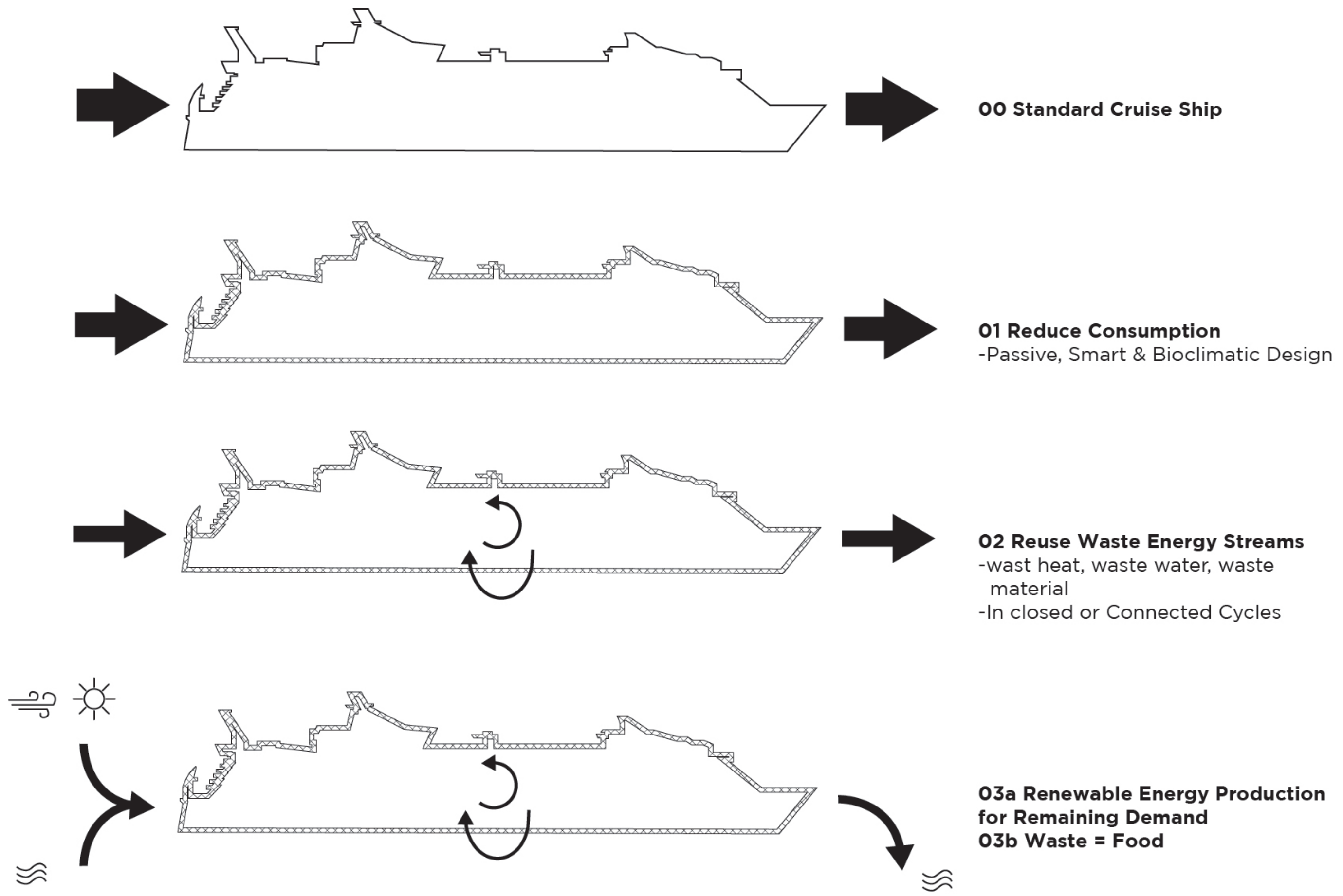

Figure 136: The New Stepped Strategy on Cruise ships
Note. Adapted from Tillie et al. (2009).

According to the NSS, the first step is to reduce the demand for energy by passive, smart & bioclimatic design (van den Dobbelsteen et al., 2018). For buildings and neighbourhood's, the context is taken into account and local conditions as climate, land and environment are smartly used (Tillie et al., 2009). Cruise ships sail all over the world which means that both extremes, warm conditions and cold conditions should be considered when designing the ships envelope and heating and cooling system (Hart, 2004). The ships envelope will be discussed in the Design interventions – Hull chapter. The energy demand for buildings can be reduced through good insulation. The ship can also reduce the general energy demand through insulation because a big part of the ship's energy is used by the HVAC. The insulations reduce the energy demand, influences the thermal environment, prevents problems as condensations, damp spots, corrosion and thermal bridges as with buildings (Hart, 2004). Not only the ship's hull should be insulated also smaller facilities and rooms inside the ships as the individual cabins, cool and freezing areas, the ice rink, and the restaurants should be insulated together with the ducks and piping. Other measures that can be added to improve the energy efficiency of buildings can also be applied on cruise ships as; triple glazing, heat recovery unit, and sealing (van den Dobbelsteen et al., 2011). The difference with buildings is that a part of the hull is below water and a part of the hull is above water. The part of the hull that is below water needs insulation that limits heat loss to the water and prevents moisture on the cold steel surface due to the low water temperature and higher heat transfer coefficient from water than air (Hart, 2004).

The second step is to reuse the waste flows from the cruise ship (van den Dobbelsteen et al., 2018). This research paper already focused on reusing the gas, fluid, and solid waste flows. The REAP methodology showed that the remaining energy from a building can also be exchanged, stored or cascaded. Before this methodology can be applied on a cruise ship it is important to know which systems the ships of Royal Caribbean use. The ships of Royal Caribbean use computer-operated demand systems which measure the CO_2 levels in the room. By measuring the CO_2, the system can calculate how many people are in the room and conditions the air for their comfort. The Royal Caribbean wants to recirculate the air inside the ship. Warm air is extracted from a room and send to a heat exchanger. The heat is caught, and the cool air is used as fresh air intake. The bulk air from outside is sent into closed loop chillers filled with water before it is sent to the staterooms, common areas, etcetera. Fan coils recirculate the air inside the ship once it is already cooled (Royal Caribbean Cruises Ltd., 2016b).

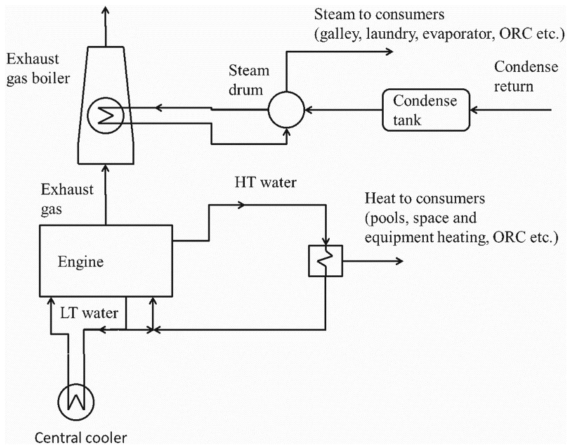

Figure 137: Basic energy system
Note. Reprinted from El geneidy et al (2017).

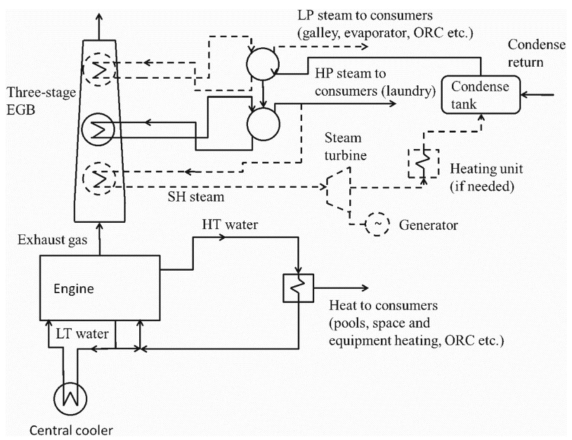

Figure 138: Schematics of the dual-pressure steam system
Note. Reprinted from El geneidy et al (2017).

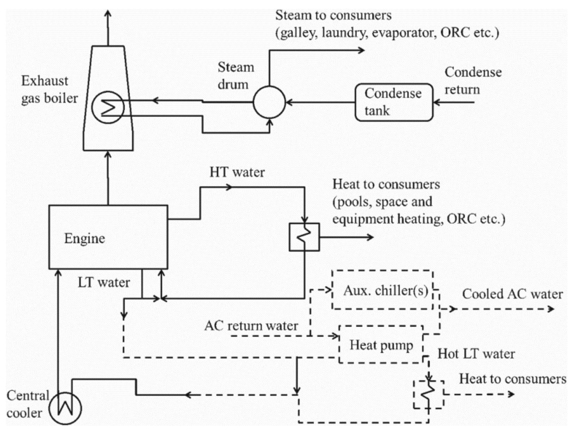

Figure 139: Schematics of the energy system with LT water used on the hot side of the heat pump.
Note. Reprinted from El geneidy et al (2017).

El geneidy et al. (2017) did research into improving the energy efficiency of passenger ships. Cruise ships need to provide energy for the navigation and transportation systems but also for the hotel load which includes pools, laundries, and entertainment. The energy for the latter can also come from onboard steam or hot water. The diesel-electric engines onboard of the cruise ship can be seen as a power plant which can be compared to a conventional land-based power plant. Around 46% of the energy is used for the propulsion system, 27% for the heat, and 27% for electric power generation. Most cruise ships produce heat and steam from the waste heat of the main and auxiliary engines or use boilers (Baldi, Ahlgren, Nguyen, Thern, & Andersson, 2018). Chillers are often used for cooling together with cold seawater, this is also the case for the Royal Caribbean ships. The heat and cooling demands differ during the trip, this depends on the ambient temperature and scheduling of different hotel systems and events. The boilers are used when there is not enough heat recovered from the waste heat. The diesel engines are cooled by low-temperature water (LT-water), around 40-60 °C, and high-temperature water (HT-water) around 70-90 °C (Baldi et al., 2018; El geneidy et al., 2017). The waste heat is recovered from both water streams. The exhaust gas boilers and heat recovery fulfil 75% of the heat demand, the remaining demand can be provided by the boilers (Baldi et al., 2018). This basic energy system can be seen in figure 137. Baldi et al. (2018) state that the remaining heat that is needed and not already recovered from the waste heat can come from a heat-to-power WHR installation. El geneidy et al. (2017) looked into the following installations: dual-pressure gas boilers with a micro steam turbine, Low-temperature (LT) engine cooling water utilization with heat pumps, Low-temperature (LT) engine cooling water utilization for potable water preheating, and ORC powered by steam or hot water. The dual pressure steam concept uses an exhaust gas boiler to produce electricity from the excess steam, see figure 138. The low-pressure and high-pressure steam are then distributed to the consumers. Low-temperature water can be used on the hot side of the heat pumps, on the cold side of the heat pump, and to preheat potable water. The energy efficiency of the ship can be improved when the low-temperature water is used on the hot side of the heat pump. The LT water acts as the hot side of the heat pump and the water for the air conditioning on the cold side. The LT water from the engine is further heated by the heat pump, the heat goes to the consumers. The cold side is used for the cooling demand. When this is not enough the water goes through the chillers, see figure 139. ORC uses the traditional Rankine cycle to generate electricity from low-grade heat sources. The research showed that the dual pressure system with an exhaust gas boiler works well in combination with the ORC and improves the overall energy efficiency. Also, the low-temperature water heat pump system with low-temperature water utilized on the hot side of the heat pump works well in combination with an ORC. The heat pump should not be used alone because then it only consumes electricity (El geneidy et al., 2017).

The REAP methodology showed three options of tuning heat and cold: individual self-provision, exchanging and cascading (van den Dobbelsteen et al., 2018). The energy exchange principle can also be applied on board of a cruise ship, next to reusing the energy in the energy system itself. The facilities onboard the ship have different energy demands. The general heating and cooling demand depend on the location of the ship. Cooling is often needed when the ship sails around the equator and heating is needed when the ship sails in colder regions. Some facilities require a higher heating or cooling demand, as a swimming pool or an ice rink. An educated guess is made from some functions onboard to find out the required heating, cooling and electricity need. A distinction is made between a cruise ship sailing in a warm climate and a cold climate.

The cruise ship that sails in a warm climate has a higher cooling demand. The restaurant and theatre have a similar cooling demand because they're both used during the evening and can host around the same amount of people, see figure 140. This also applies to the public places as the bars, casino, arcade, shops, and children rooms. These facilities have a slightly higher cooling demand because they are used for the whole day. The Ice rink has a higher cooling demand to keep the ice on temperature. The pools require a higher heating demand to warm the water. The solarium is a special kind of indoor pool with a glass roof. The indoor temperature is always high, and it is more humid. This space can be compared with a greenhouse, both capture passive solar energy. This heat can be captured and used to heat other facilities with a heat exchanger (Tillie et al., 2009). The gym requires more cooling than the general public space due to the heat released by the people and the spa requires more heating due to the needed warm environment. There are multiple food storages onboard which have a high cooling demand to store the food.

Warm Climate

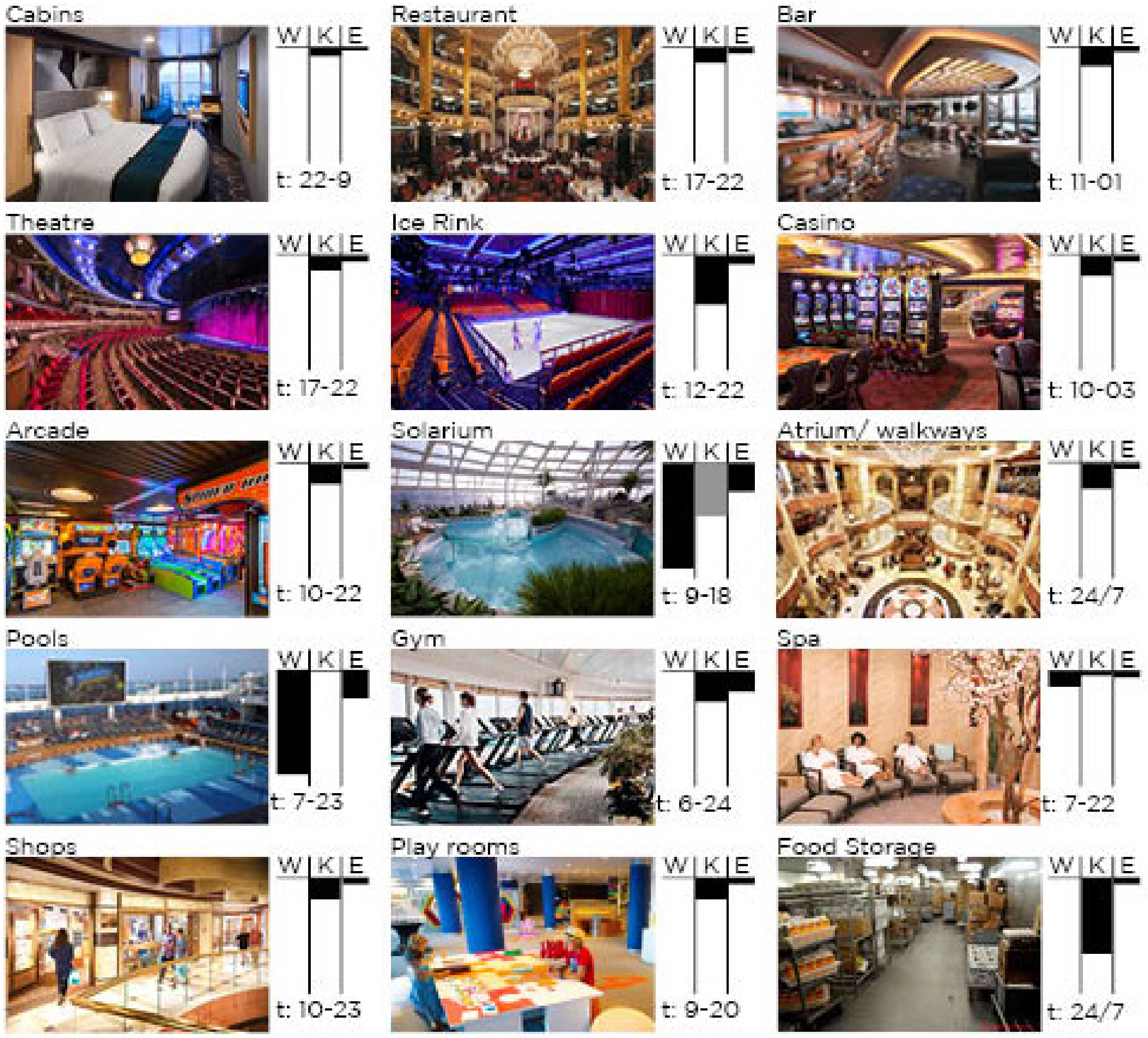

Figure 140: Energy demand facilities – Warm Climate
Note. Adapted from Royal Caribbean International (n.d.-a), Dreamlines (n.d.-b), CruiseReizen (n.d.), Cruisebe (n.d.-b), Cruisebe (n.d.-a), Grant (2019), Cruise Critic (n.d.-b), Hochberg (2015), Katzman (2018), Zimmerlin (n.d.), Dreamlines (n.d.-a), Royal Caribbean (2018), Princess (n.d.), Family vacation critic (2020), LBcruiseshipblogger (2016).

Functions with high cooling demand can exchange their heat with a function that has a higher heating demand and the other way around. The solarium is a special case. Due to the heating demand, it can be coupled to a space which has a cooling demand but because of the greenhouse effect, it can also be coupled to a space with a heating demand. It can be seen that most functions on a cruise ship sailing in a warm environment have a cooling demand, only the solarium and the outdoor swimming pools with the whirlpools have a heating demand. A cruise ship has often 1 or 2 outdoor pools with a minimum of 3 whirlpools. These pools can be coupled to facilities with a cooling demand as the general public places or the ice rink and food storage, see figure 141 and figure 142..

Warm Climate

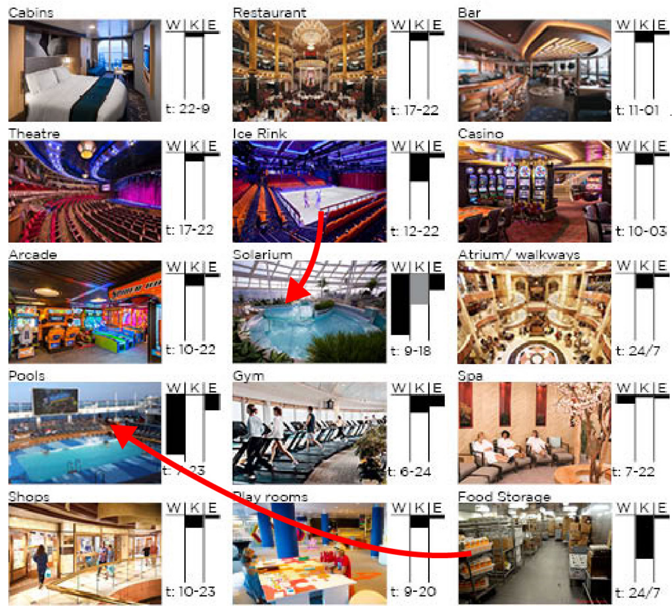

Figure 141: Exchange energy demand example 1 – Warm climate
Note. Adapted from Royal Caribbean International (n.d.-a), Dreamlines (n.d.-b), CruiseReizen (n.d.), Cruisebe (n.d.-b), Cruisebe (n.d.-a), Grant (2019), Cruise Critic (n.d.-b), Hochberg (2015), Katzman (2018), Zimmerlin (n.d.), Dreamlines (n.d.-a), Royal Caribbean (2018), Princess (n.d.), Family vacation critic (2020), LBcruiseshipblogger (2016).

Warm Climate

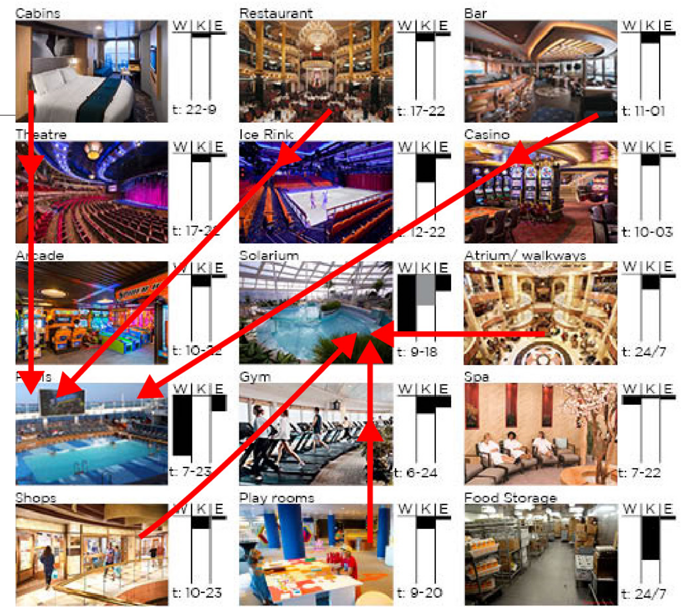

Figure 142:Exchange energy demand example 2 – Warm climate
Note. Adapted from Royal Caribbean International (n.d.-a), Dreamlines (n.d.-b), CruiseReizen (n.d.), Cruisebe (n.d.-b), Cruisebe (n.d.-a), Grant (2019), Cruise Critic (n.d.-b), Hochberg (2015), Katzman (2018), Zimmerlin (n.d.), Dreamlines (n.d.-a), Royal Caribbean (2018), Princess (n.d.), Family vacation critic (2020), LBcruiseshipblogger (2016).

Cruise ships that sail in colder climates have a higher heating demand. The heating demand of the restaurant and the theatre and the heating demand of the bar, casino, arcade, shops and children rooms are again similar to each other, see figure 143. The solarium and the pools have a slightly higher heating demand compared to ships that sail in a warm climate. In this case, the heat that comes free from the ice rink, the food storage and the solarium.

Cold Climate

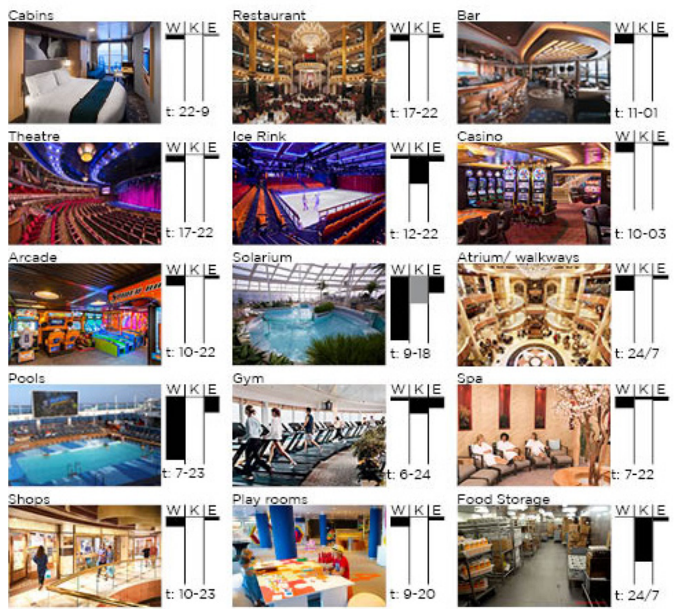

Figure 143: Energy demand facilities – Cold Climate
Note. Adapted from Royal Caribbean International (n.d.-a), Dreamlines (n.d.-b), CruiseReizen (n.d.), Cruisebe (n.d.-b), Cruisebe (n.d.-a), Grant (2019), Cruise Critic (n.d.-b), Hochberg (2015), Katzman (2018), Zimmerlin (n.d.), Dreamlines (n.d.-a), Royal Caribbean (2018), Princess (n.d.), Family vacation critic (2020), LBcruiseshipblogger (2016).

Cold Climate

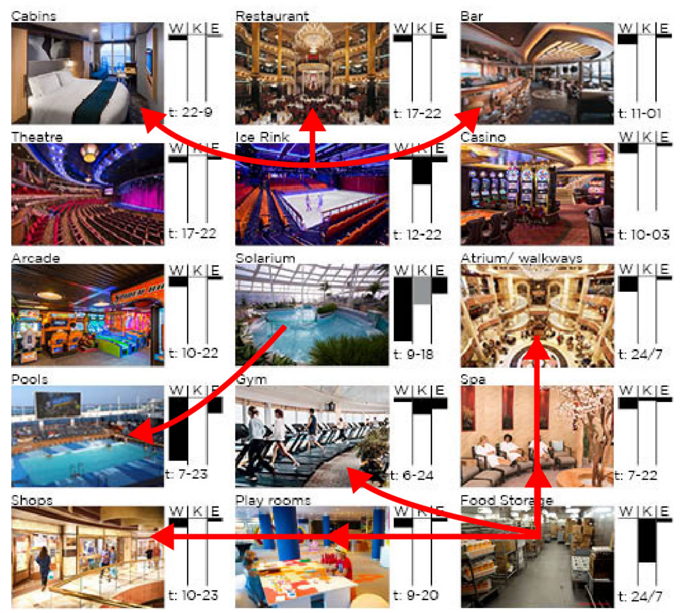

Figure 144: Exchange energy demand example – Cold climate
Note. Adapted from Royal Caribbean International (n.d.-a), Dreamlines (n.d.-b), CruiseReizen (n.d.), Cruisebe (n.d.-b), Cruisebe (n.d.-a), Grant (2019), Cruise Critic (n.d.-b), Hochberg (2015), Katzman (2018), Zimmerlin (n.d.), Dreamlines (n.d.-a), Royal Caribbean (2018), Princess (n.d.), Family vacation critic (2020), LBcruiseshipblogger (2016).

The REAP method also shows that energy-specific functions can be added when the energy is in disbalance. An extra pool can be added which requires heat or an ice rink that requires cold (van den Dobbelsteen et al., 2018). It is also possible to add a greenhouse in combination with a heat exchanger to use the waste heat to heat other facilities. This principle should be used when a cruise ship is designed. The cruise industry could consider designing ships for specific climates. By doing this they can optimize the energy streams but lose a bit of flexibility.

The last step of the NSS is to use renewable energy sources for the remaining demand and use the waste as food. The remaining energy demand can come from PV panels and wind turbines installed on the deck of the ship or from bio-fermentation installations which use a power-heat coupling to produce heat or electricity (Tillie et al., 2009). The PV panels and fixed sails and wind turbines will be discussed in the design interventions – Hull.

Besides optimizing the energy flow of a building or between buildings there are also other techniques and methods used to design a sustainable building. Currently, a well-known term in the built environment is circularity. There are multiple methods which strive to a circular build environment. Next to the New Stepped strategy, methods as material matters and Cradle to Cradle work towards this goal.

Material Matters

The book material matters is written by Thomas Rau and Sabine Oberhuber. They state that we live in a linear economy and we use the take make and waste strategy. One of the biggest problems in this economy is that power and responsibility are not in the same place. The decisions of the manufacturer and its consequences are at the expense of consumers. However, the consumer does not know what is exactly in the product and the product will end up in landfills (Rau & Oberhuber, 2017). The world is a closed system where everything is equally important and with finite resources. Wubbo Okkels called our planet because of this ''spaceship earth'' (Rau & Oberhuber, 2017). Rau & Oberhuber (2017) developed the Turntoo-model where products and even materials can be seen as a service. This means that the responsibility stays with the manufacturer, the consumer only pays for the use of the product. When the product is not needed anymore the manufacturer takes the product back. He can give the product on loan again, partially repurpose it into another product, or reuse the material. There is no loss of value through the use of the material passport. The material passport states exactly which materials the product consists of. The passport includes the Universal Declaration of Material Rights so that the products and materials cannot end up in anonymity. The Turntoo model consists of two parts: the value sustain chain and the value creation chain, which together form a perpetual chain. Three current business models need to change, to make this change possible. Nowadays products are made according to the following 3 conditions: design to fail, design to be outdated, and design to be out fashioned. These conditions are made to make sure consumers need to buy a new product in a relatively short time. These conditions should change into: design to perform, design to be updated, and design for passion, see figure 145. As a result, the products and the materials in the products last longer which lead to lower cost for the consumer and remanufacturer. Through the Turntoo model, the products and materials are not lost and stay in the perpetual chain (Rau & Oberhuber, 2017). This model is - together with the material passport - already applied in the building industry. BAMB (Building as Material Banks) develops the electronic material passports to give the materials the value to recover them, see figure 146. It aims to keep the value of the product, support developers to choose sustainable and circular products, and make sure that the materials can be taken back (BAMB, 2019). Buildings and products are seen as a material bank. As previously mentioned, a cruise ship can be seen as a building or building complex. Both have an outer envelope and similar facilities on the inside as a place to sleep, eat, shower, etcetera. This means a cruise ship can also be seen as a material bank, CAMB (Cruise ship as Material Bank), see figure 147. The Turntoo-model should be applied in all sectors to create a circular economy and to make sure spaceship earth persist.

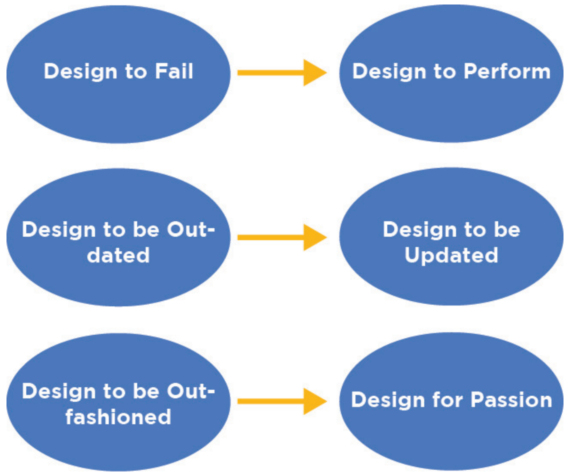

Figure 145: Change of business models. Adapted from Rau & Oberhuber (2017).

Figure 146: Change of business models. Adapted from Rau & Oberhuber (2017).

Cradle to Cradle

The NSS is based upon the Cradle to Cradle method. The Cradle to Cradle method is developed by William McDonough and Michael Braungart which integrates attributes as safe materials, continuous reclamation and re-use of materials, clean water, renewable energy, and social fairness (MBDC & EPEA, 2016). This method exists of three principles: eliminate the concept of waste, use renewable energy, and celebrate diversity. Materials are seen as nutrients in one of the two cycles, the technical cycle or the biological cycle, see figure 147.

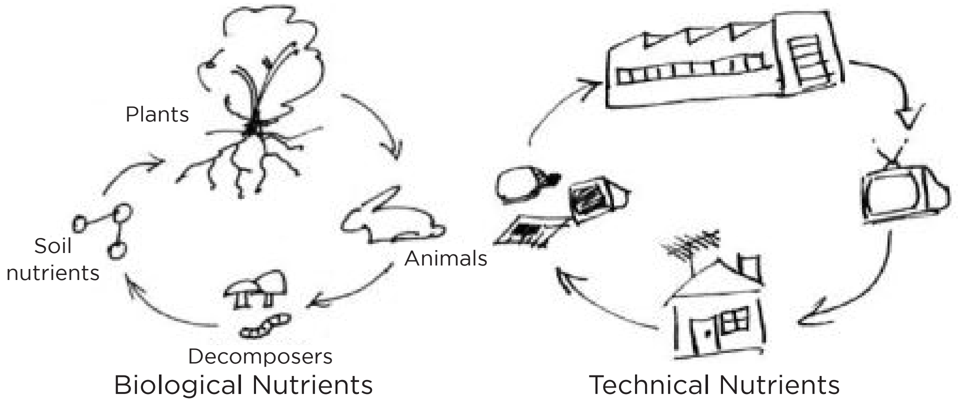

Figure 147: Biological and Technical nutrients cycle
Note. Reprinted from MBDC & EPEA (2016).

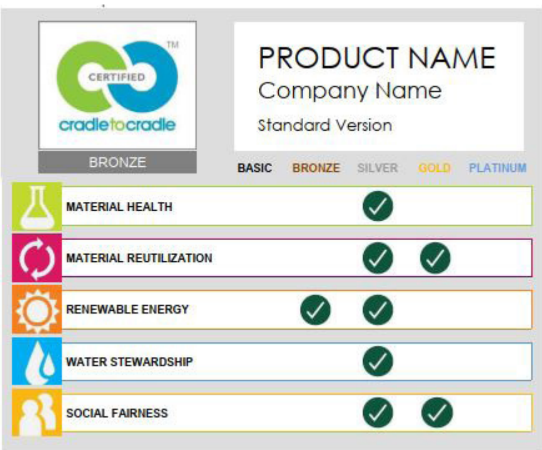

Figure 148: Cradle to Cradle Scorecard
Note. Reprinted from MBDC & EPEA (2016).

A distinction is made between products of consumption, which consist of biological nutrient materials that can be absorbed into the biological system and products of service that are a service to the user who does not own the material. These materials are part of the technical cycle and cannot be returned into the air, soil or water but are deconstructed. A Cradle to Cradle CertifiedTM products program is developed to evaluate products according to five categories: Material Health, Material Reutilization, Renewable Energy and Carbon Management, Water Stewardship, and Social Fairness. Products can be certificated with a certain achievement level: Basic, Bronze, Silver, Gold and Platinum for each of the five categories, see figure 148. This certificate can be used to educate the consumers about the level of achievement of the product. A list is made on the Cradle to Cradle website where the products and their certification level can be seen (MBDC & EPEA, 2016). This list can be used to make an informed and sustainable choice for a certain product made for the circular economy. The list consists of several categories: Auto & Tires, Building Supply & Materials, Fashion + Textiles, Interior Design & Furniture, Packaging & Paper, etcetera. The cruise industry can also use this list during the design phase of a cruise ship. Under the category of Interior Design & Furniture, products as carpets, floor covering, ceilings, wall coverings and seating's can be found. These products are found on a cruise ship. Carpets that are designed with disassembly and recycling in mind and carpets that are lighter in weight and low in VOC emissions can be found in the list. Together with hardwood flooring and acoustic wooden ceiling panels. Next to this natural and synthetic fibres can be used for furniture and recycled glass for countertops, flooring, and reception and furniture tops. Under the category of Building Supply & Materials, products as architectural glass, floors, partition walls, paint, finishes & coatings, and insulation can be found. Insulation made of seaweed has a gold certification and can be used to replace standard non-organic materials like mineral wool. Also, inorganic paints and partition walls made from cellulosic waste and non-VOC emitting, fire retardant, moisture resistant and thermal insulating can be found in the list (Cradle to Cradle, n.d.). The cruise industry should use this list to make sure sustainable products are used on board of the ship which has a positive impact on the planet. Figure 149 shows an example of a bar which can implement Cradle to Cradle products as the above-mentioned ceiling panels, flooring, countertops, seaweed insulation, and natural and synthetic fibres for the furniture.

Figure 149: Cradle to Cradle Certified Products
Note. Adapted from Royal Caribbean International (2019).

Plants

The indoor environment is very important for the health of humans because they spend around 80-90% of their time inside (Deng & Deng, 2018). A lot of research is done into the effect of plants on the indoor environment. People are exposed to indoor air pollutants as particular matter, bioaerosols and gaseous contaminants which come from building product emission, human activity, and outdoor air infiltration which lead to poor indoor air quality (IAQ). The removal of pollutants by plants is called Phytoremediation (Deng & Deng, 2018). Through photosynthesis, plants can remove a part of the indoor CO_2 and release O_2. The amount of CO_2 removed depends on the leaf area and the type of plant. A research estimated that 400 plants are needed to remove the exhaled CO_2 of one person. It can be concluded that a large amount of plants is needed to see the effect. During the photosynthesis, negative air ions (NAIs) are produced which can absorb dust and clean the air (Deng & Deng, 2018). Volatile organic chemicals (VOCs) and other pollutants are released from furniture and household products. Some of these pollutants are toxic and cause skin irritation, dry throat and are carcinogenic at high concentrations. Using plants is a cost-effective way to lower the VOC concentrations in the indoor environment. Not only the leaves of the plant remove the VOCs also the roots and the microorganisms in the soil. The amount of reduced VOCs in the indoor environment depends on several factors: the plant species, light intensity, growing media, temperature, VOC concentration, VOC identity, VOC in mixtures and genetic transformation of the plant (Dela Cruz, Christensen, Thomsen, & Müller, 2014; Deng & Deng, 2018).

Research is also done into the psychological effect of plants. These researches focus on psychological wellbeing, physical health, and job satisfaction. Multiple studies found out that plants can reduce nervousness and anxiety, reduce stress, and increased performance and comfort. However, the exact effects of plants on psychological performances is still unclear but the general idea that plants play a role in mental health is settled (Deng & Deng, 2018).

It can be seen that plants can improve the indoor air quality by removing VOCs from the air and converting CO_2 in O_2. Plants also have a positive effect on the mental health of people. The cruise industry should apply plants into their interior design to improve the IAQ and stimulate the mental health of their passengers and crew members. A design feature that can be implemented is the green wall. These walls consist of multiple plant species and due to the number of plants and their leave area, the effect will be greater than that of a single plant. These walls can easily be implemented into the public areas due to their aesthetic value. Some disadvantages of plants are the needed maintenance and their need for water and nutrients. The bigger ships of the Royal Caribbean have a central park with 12,000 living plants and a green wall, see figure 150 (Good Earth Plants, 2014).

Figure 150: Central Park and Green wall on Royal Caribbean Cruise ship.
Note. Adapted from Cruise Critic (n.d.-a).

4.6.3 Design interventions – Hull

In the previous chapter, the NSS is applied to the interior of the ship, specifically to the energy balance. However, this strategy can also be applied on the envelope, the hull of the ship. This chapter applies the NSS and looks into passive, smart & bioclimatic design for cruise ships, solving the remaining energy demand sustainably, using the Cradle to Cradle method, using plants and heat pumps, and shows the carbon accounting method.

New Stepped Strategy

The first step of the NSS is to reduce the demand by passive, smart & bioclimatic design. McCartan & Kvilums (2013) looked into the possibility of making a passive design for eco-luxury cruise ships for the Mediterranean. McCartan & Kvilums noticed the bioclimatic design trend in the building industry and tried to apply this on luxury cruise ships. Most of the energy is needed for the propulsion of the ship, but also for the hotel load, with the HVAC as the highest energy-consuming application. A catamaran design is proposed in this research to reduce the energy demand for the propulsion system. A negative side effect of the catamaran shape is the loss of space which has a big impact on the cruise ship. Besides the general design of the ship, McCartan & Kvilums focussed on the passive design of the cabins due to their large area and because the cabins are susceptible to solar gain and have the highest window to wall area. Passive solar systems are often used in the building industry to maximise the natural light and minimise direct solar flux. They found out that an occupant responsive louvre control system is beneficial over a static or solar radiation-based louvre control system. In the occupant responsive louvre system, the louvres will close when the passenger is not in the room and opens when the passenger enters the room. The louvres also help with funnelling the wind to induce a flow of air to maximise ventilation. The solar gain can also be reduced by increasing the balcony depth. The most effective reduction is found with a balcony depth of 1.5m. Increasing the balcony depth further does not have that much effect. The combination of the occupant louvre control system and a balcony depth of 1.5m led to a reduction of 59% and 83% for the south and north orientation (McCartan & Kvilums, 2013).

The last step of the NSS is to solve the remaining demand sustainably. As previously mentioned in this research the cruise industry could apply PV-panels or use wind energy by applying soft sails, fixed sails, Flettner rotors, kite sails or wind turbines. The efficiency of the PV-cells depends on the solar radiation which depends on the location of the ship, the time of day and year, and on the surface area. The location and time of day cannot be controlled by

Figure 151: Solar Boat Team TU Delft 2018
Note. Reprinted from Rubal (2018).

Figure 152: Largest solar ship
Note. Reprinted from Butler (2019).

Figure 153: Glow in the dark Deck by Bolidt - Inside
Note. Retrieved from Bolidt.

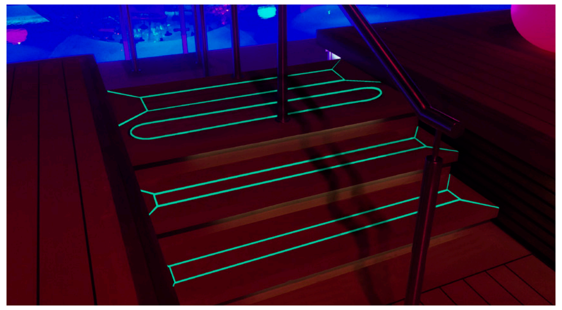

Figure 154: Glow in the dark Deck by Bolidt - Outside
Note. Retrieved from Bolidt.

Figure 157: Ecoship
Note. Reprinted from Ship Technology (n.d.).

the design, however, the area can. PV-cells can be placed horizontally or vertically depending on the design of the ship and usable space. The most efficient way to use solar energy on a boat can be found in the design of the teams competing on the solar & energy boat challenge, see figure 151 (Rubal, 2018). It can be seen that the most efficient way is a horizontal surface of PV-panels. This can also be applied to catamarans, see figure 152 (Butler, 2019). However, the horizontal surface on the outside of the cruise ship is the best place for passengers to be. This is the place where most of the activities are hosted and facilities are found as the pool, sun deck, sports court, bars, etcetera. It is not (yet) possible to install PV-cells in the flooring. However, Bolidt, the main supplier of indoor and outdoor floors for cruise ships, did launch a glow in the dark deck for Royal Caribbean Cruises. The deck stores solar energy during the day and converts it into lighting at night, see figure 153 and 154. The energy demand for lighting will be reduced by installing this luminous decking material (Bolidt, n.d.). The vertical surface of the ship is also a great place for PV panels. These panels generate energy in the morning or afternoon. The panels facing south can even generate more energy in the winter when the sun is low. Horizontal panels have an energy peak in the middle of the day and on sunny days which lead to problems with the grid. Vertical panels can help with a constant energy generation. Companies as KamelonSolar developed vertical solar façade panels that can come in different designs (KameleonSolar, n.d.). In the future special panels can be designed for the hull of a ship. These panels must be able to withstand the sea conditions as hard wind and saltwater. However, it is most likely better to apply a film into the material of the hull. The PV-cells that are placed on the lower part of the hull are pointed a bit downwards instead of vertical. The sunlight is reflected by the seawater and can be captured by the PV-cell. Julajaturasirarath, Jonburom, & Pornsuwancharoen (2012) state that the amount of generated solar energy is doubled when solar cells are combined with mirrors that reflect the solar light. The same principle will occur with the downwards facing PV cells that capture the reflected light from the seawater. These panels will not perform much less than the vertical panels.

NCE Maritime CleanTech designed a ship that imbeds PV-cells in 5,000 square meters of sails together with solar-filmed glass covering the balconies, see figure 155 (Stoichevski, 2019). Peace Boat used similar principles; the Ecoship has 10 retractable solar-panel coated sails and a solar farm on the deck, see figure 156 (Energy Matters, 2015). The Eoseas designed by STX Europe and Stirling Design International has PV-panels on the deck and upper deck and a double skin on the sides that function as a natural air conditioning system, see figure 157 (Ship Technology, n.d.).

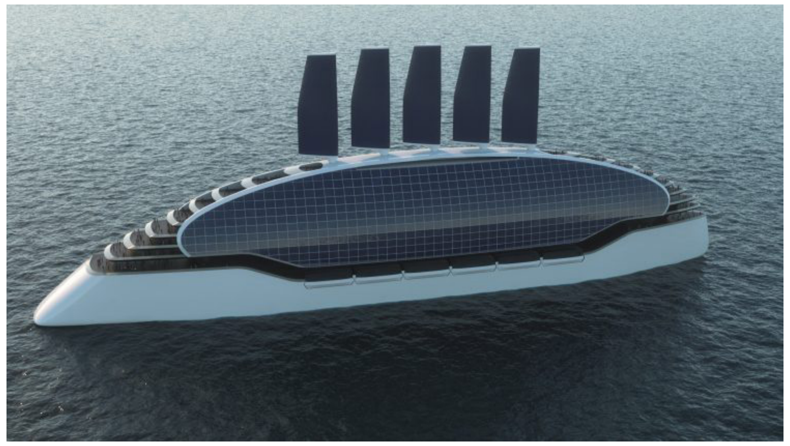

Figure 155: Zero-emission fjord cruises
Note. Reprinted from NCE Maritime CleanTech (n.d.)

Figure 156: Peace Boat
Note. Reprinted from Energy Matters (2015).

Wind turbines can also be added in the future on cruise ships besides the fixed sails. Some buildings are now implementing turbines in the design of their building, see figure 158 and figure 159. The next step could be on cruise ships

Figure 158: Wind turbines in building design -1
Note. Reprinted from De Groene Energie Maatschappij (n.d.).

Figure 158: Wind turbines in building design -2
Note. Reprinted from De Groene Energie Maatschappij (n.d.).

Cradle to Cradle

The Cradle to Cradle method and the Cradle to Cradle CertifiedTM products program is already explained in the interior chapter. One of the categories is Building Supply & Materials. Under this category, products as architectural glass, daylighting & shading, and specialties and miscellaneous applications can be found. The cruise industry should use this list and make sure sustainable products are used on board of the ship which has a positive impact on the planet. Examples of products that can be considered are silver classified fire-resistant glass, sun shading made from biopolymer, and signs which can be mounted through a magnetic key (Cradle to Cradle, n.d.). Ships can set the next step to a sustainable cruise ship by using this certifiedTM products program.

Plants
Plants are added in the interior of the ship to improve the air quality and because of the positive effect they have on the mental health of people. Plants could also be added on the outside of the ship regarding the latter benefit. It is doubtful that plants on the outside of the ship will increase biodiversity. Insects and birds are not found on the open sea. A negative effect of adding greenery is that their current migration pattern could change. Perhaps in the future special plants can be added that can withstand the sea conditions as hard wind and saltwater. However, a more in-depth research is needed into which type of plants and their effect on the environment, the passengers and the animals.

Heat Pumps
Heat pumps can recover heat from multiple sources and can be used in industrial, commercial and residential applications (Chua, Chou, & Yang, 2010). There are for example air to air heat pumps, air to water heat pumps, water to water heat pumps, and water to air heat pumps (Çakır, Çomaklı, Çomaklı, & Karslı, 2013). Heat pumps can recirculate the waste heat, as previously mentioned in the HVAC system, but also environmental heat into a heat production process for the heating and cooling of buildings (Chua, Chou, & Yang, 2010). Besides the waste heat recovery, no papers are found on environmental heat recovery on (cruise) ships. Cakir et al. (2013) state that ambient air, exhaust air, river water, lake water, groundwater, wastewater and effluent are often used as the heat source. Ambient air is everywhere available and could be used by the cruise industry. In the heating season or in warm climates, the heat pump performances decrease when the air temperature decreases. In the winter season or in cold climates, the performances decrease when the air temperature increases. A water heat pump has some small advantages over an air heat pump because of the heat transfer properties of the water (Çakır et al., 2013). However, when a water heat pump is used in a building, pipes go into the ground. It is not possible to apply this exact system on cruise ships. The heat pump should be embedded into the hull of the ship. This could be a pipe structure that is connected to the hull . The insulation is placed behind the hull and the pipes of the heat pump to prevent a thermal bridge from forming. It is also possible to add an air to air or air to water heat pump to recover the heat from the ambient

air and use it in the ship. Figure 160 shows the heat pump that is already placed onboard to recover waste heat and the two possible new heat pumps that use environmental heat. It should be taken into account that a heat pump by itself consumes energy. More research is needed to find out how these systems can be incorporated in the design of the cruise ship and which system has the highest efficiency.

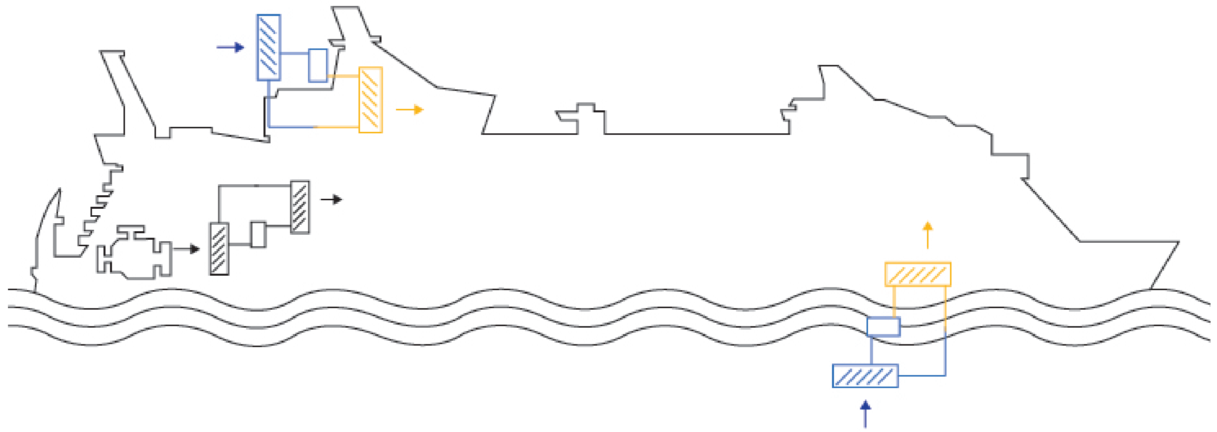

Figure 160: Air to Air and Water to Water heat pump.

Carbon Accounting
Another method used in the building industry is the Carbon Accounting Framework. This framework is developed during the City-zen project which is used as a guideline throughout this study. This framework assesses the Greenhouse Gas emissions of urban environments and used the framework to inform policies. The framework estimates the carbon footprint of a single household (6.93 t CO_2-eq/yr) and use this as average for the neighbourhood. The framework shows interventions for urban retrofitting for energy use, mobility systems, waste and water management. To visualize the intensity and impact of the annually released greenhouse gases into the air, a virtual forestland is made to show how much forest is needed to absorb the equivalent amount of CO_2. This study states that a young forest can absorb an average of 1.35kg CO_2 $m^{-2}yr^{-1}$. This means a single European household needs 0.51 ha forestland to absorb their released carbon emissions (Pulselli, Marchi, Neri, Marchettini, & Bastianoni, 2019). This effective visualisation method can also be applied in the cruise industry to create awareness. Instead of using the carbon uptake from forestland, this research looked into marine life possibilities. The carbon that is captured by marine organisms is called blue carbon. This is often captured in the form of sediments from mangroves, salt marshes and seagrasses, where the carbon can be stored for millennia, see figure 161 (Nellemann & Corcoran, 2009). The carbon sequestration of saltmarshes is around ~242 g C m^{-2} yr^{-1}, of mangroves is ~168 g C m^{-2} yr^{-1}, and of seagrass is ~83 g C $m^{-2}yr^{-1}$ (Taillardat, Friess, & Lupascu, 2018). Royal Caribbean Cruises Ltd. (2018) states that their

Figure 161: Salt Marshes
Note. Reprinted from Scottish Natural Heritage (n.d.).

ships emitted 4,369,021 tonnes CO_2e in 2018. Their fleet consists of 28 ships - assuming each ship emits the same amount of carbon - the total amount per ship is 156,036 ton CO_2e. To absorb the carbon of one ship, 6.4 * 108 m^2 of saltmarsh or 64,477 ha of saltmarsh is needed. This is equal to 87132 soccer fields or 3 times the city of Amsterdam. Figure 162 shows the needed amount of saltmarsh (64,477 ha) to absorb the emissions of one cruise ship. Every square represents an area of 100 ha. It is important to notice that the scale of the cruise ship is 10 times bigger than the scale of the squares, to maintain visibility. A next step is to calculate the reduction of emitted CO_2e. The impact of the taken measures and added techniques can then be visualised by the reduction of squares in the virtual saltmarsh land.

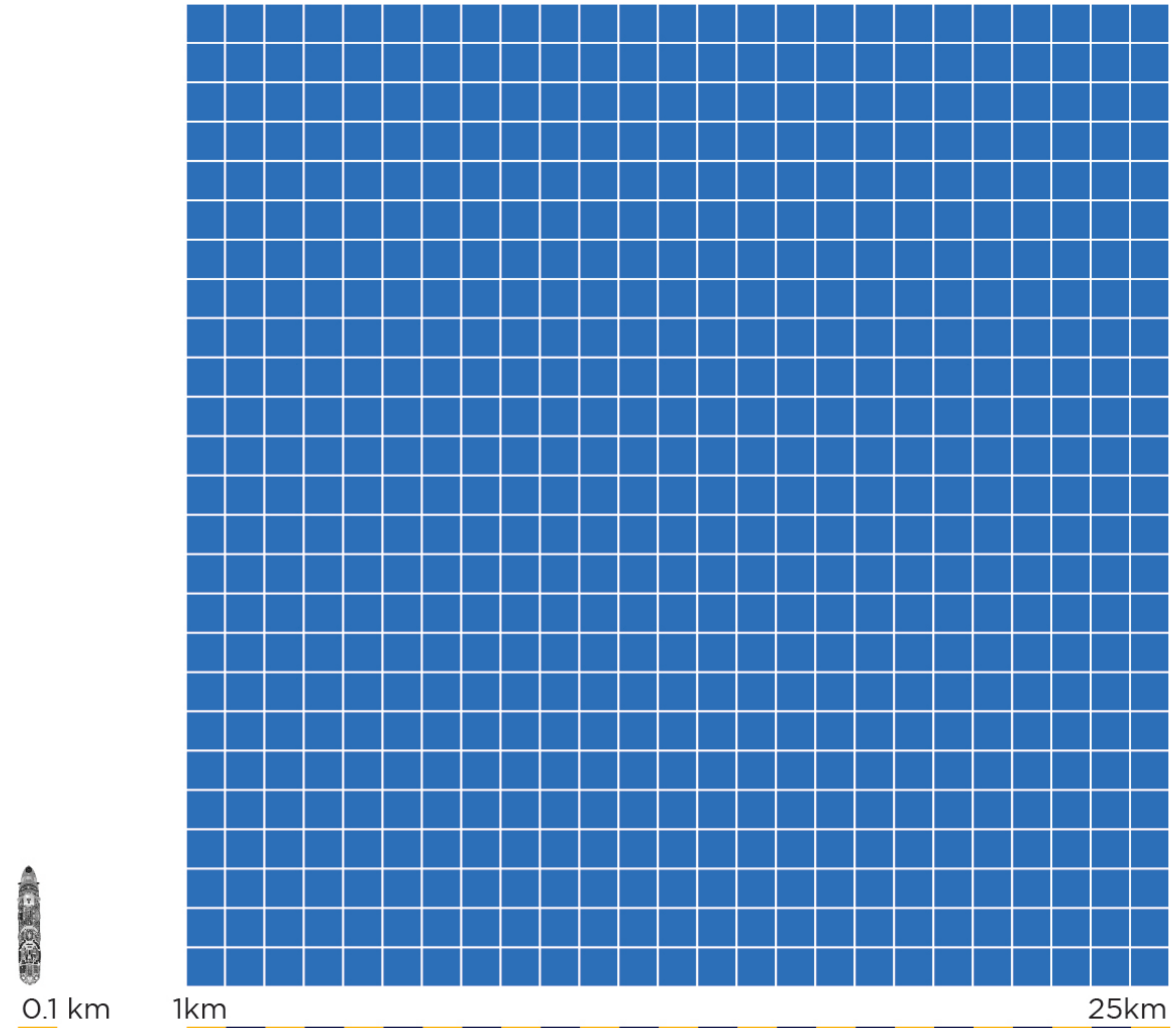

Figure 162: Carbon footprint offset, virtual salt marshland (64478 ha) for 1 cruise ship.

Conclusion

This chapter shows that the same design principles and interventions used in cities and building complexes can also be implemented on cruise ships. The three steps of the New Stepped Strategy can be used to design a sustainable cruise ship. The first step of the New Stepped Strategy is to reduce the demand for energy by passive, smart & bioclimatic design. The energy demand for the cruise ship can be reduced through good insulation. Next to this, measures as triple glazing, heat recovery unit, and sealing can be added to improve the energy efficiency. Using the shape of a catamaran, applying an occupant responsive louvre control system, and adding a balcony with a minimum depth of 1.5m are measures that also fall under this first step. The second step is to reuse the waste flows from the cruise ship. Royal Caribbean recirculate the air inside the ship and uses a heat exchanger. Heat and steam can be produced from the waste heat of the main and auxiliary engines. A dual pressure system with an exhaust gas boiler, an ORC, and a low-temperature water heat pump should be added to improve the overall energy efficiency. To even further optimize the energy efficiency of the ship, the energy exchange principle should be applied. Functions with high cooling demand can exchange their heat with a function that has a higher heating demand and the other way around. The last step to optimize the energy efficiency is by adding energy-specific functions when the energy is in disbalance, like a pool or an ice rink. The last step of the New Stepped Strategy is to use renewable energy sources for the remaining demand and use the waste as food. The remaining energy demand can come from PV panels on the deck, from PV panels on a retractable sail, from sails or wind turbines installed on the deck of the ship or from bio-fermentation installations inside the ship. Also, other techniques and methods as the Turntoo model with the material passport and Cradle to Cradle CertifiedTM products program normally used in the building industry should be used in the cruise industry. In the latter, a list can be found with sustainable products for the inside and outside of the ship with sustainable products as special carpets designed for disassembly, insulation made of seaweed, inorganic paints, cellulosic partition walls, fire-resistant glass and biopolymer shading. Currently, a lot of research is done into improving the indoor air quality of buildings with plants. Plants can improve the indoor air quality by removing VOCs from the air and by converting CO_2 in O_2, they also have a positive effect on the mental health of people. A specific design feature that can be implemented on cruise ships, next to general greenery, is the green wall which consists of multiple species. To visualize the intensity and impact of the greenhouse gases released into the air per ship, a virtual saltmarsh can be made to show how much hectares of saltmarsh is needed to absorb the equivalent amount of CO_2. The impact of the taken measures and added techniques can be visualised by the reduction of squares in the virtual saltmarsh land.

The design of a future sustainable cruise ship can contain one or more of the following options. It can be a catamaran shaped ship, with louvres and a second skin covered with solar filmed glass, which can be seen as a balcony to minimize solar gain and reduces the energy need of the ship. Or instead of the second skin, a special PV-film can be applied on the hull of the ship. The ship can have (retractable) sails with embedded PV-cells or wind turbines to generate energy. Other adjustments as the glow in the dark deck of Bolidt, plants, and Cradle to Cradle CertifiedTM products can also be incorporated. To optimize the energy efficiency of the ship, insulation should be used together with a dual pressure system with an exhaust gas boiler, an ORC, and a low-temperature water heat pump. The energy exchange principle is applied to optimize the energy efficiency even further. It can be seen that the possible design interventions find their origin in techniques and methods developed for the building industry, as the New Stepped Strategy, the Cradle to Cradle method, and the Turntoo model with the material passport. Figure 163 and figure 164 shows a cruise ship with the options mentioned above together with the glass observatory room for climate research.

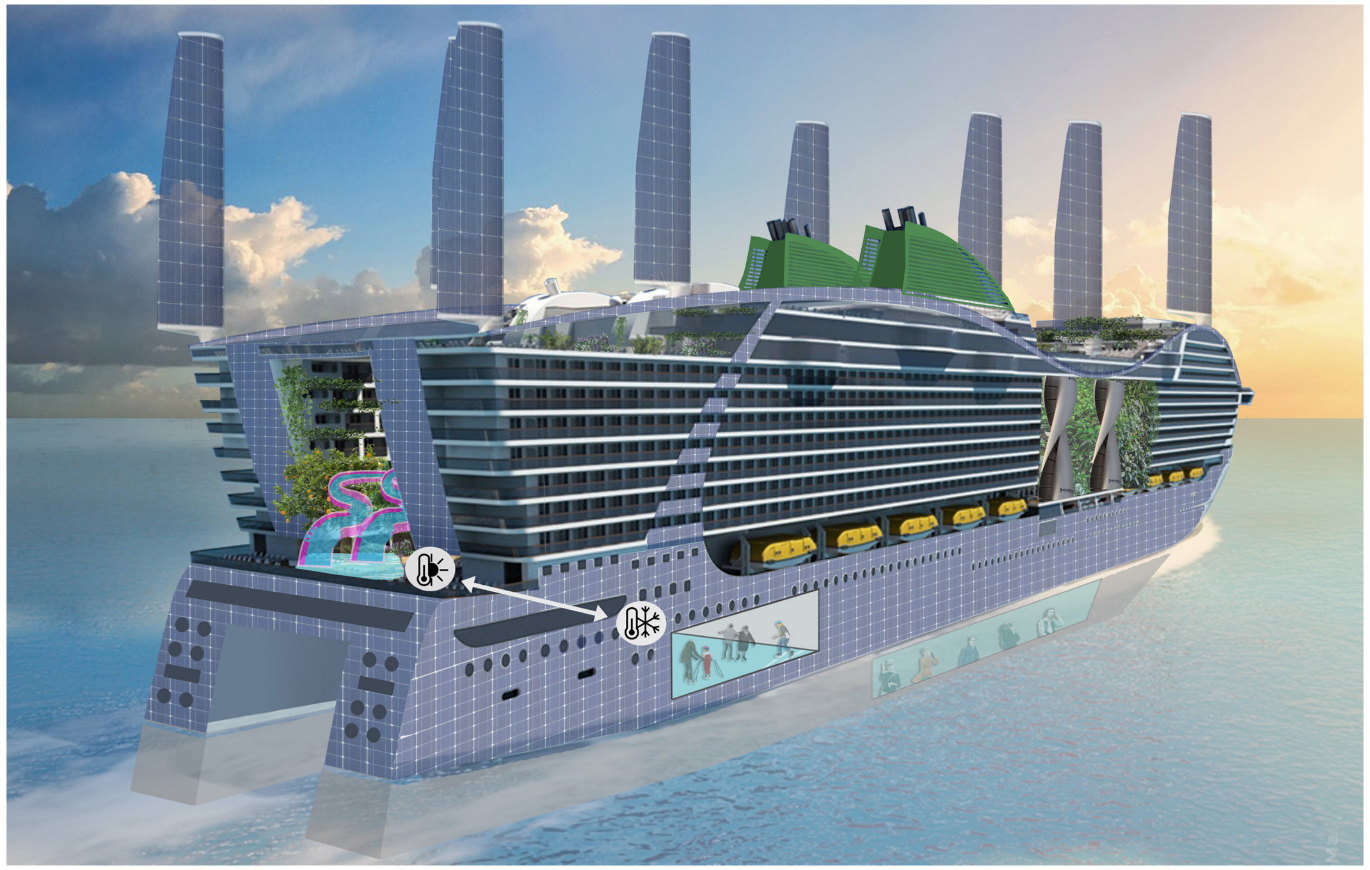

Figure 163: Future Cruise Ship with PV-film, sails with embedded PV-cells, wind turbine, algae, greenery, energy exchange principle, glass research lab.

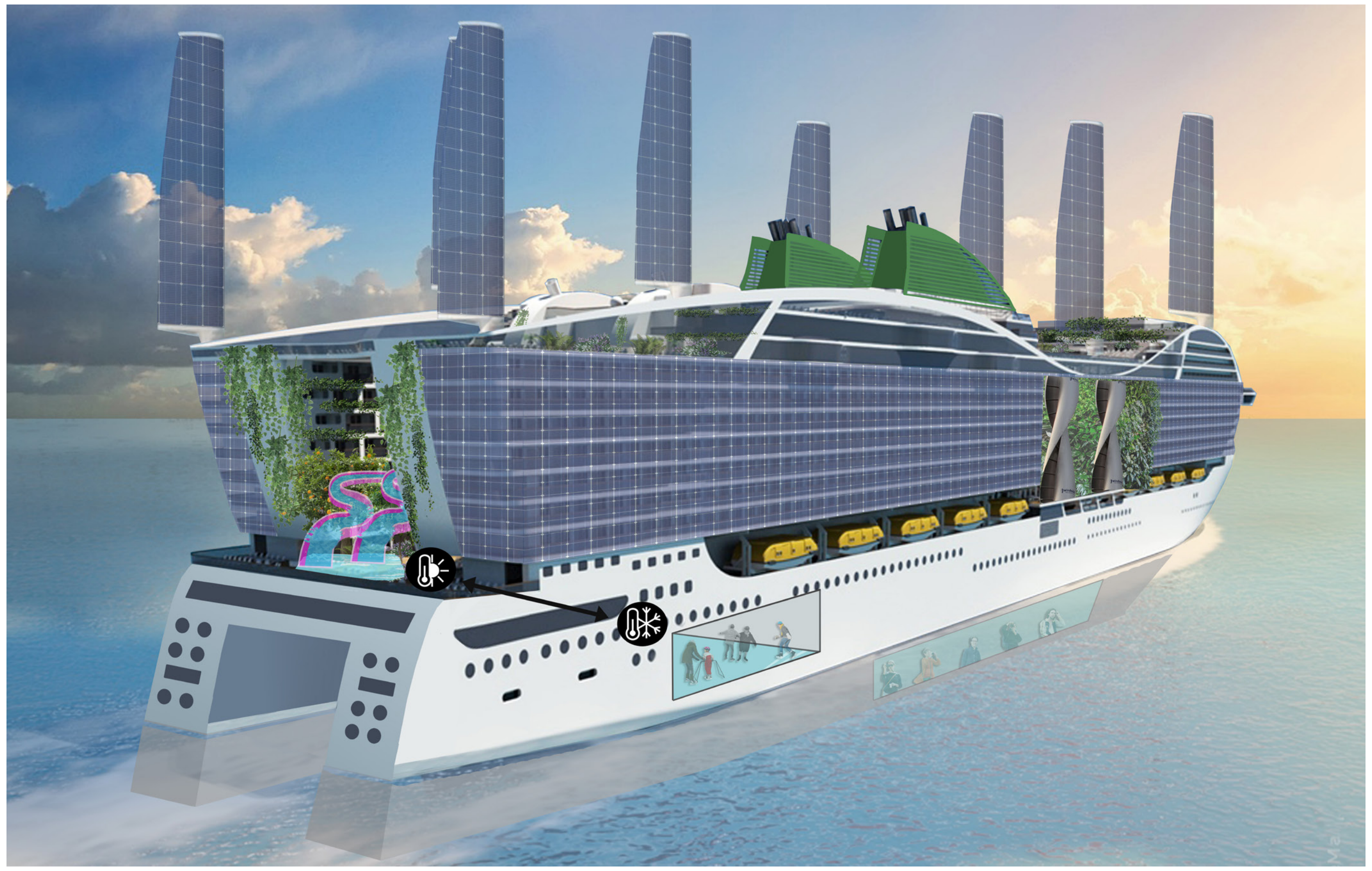

Figure 164: Future Cruise Ship with second skin with embedded PV-cells, sails with embedded PV-cells, wind turbine, algae, greenery, energy exchange principle, glass research lab.

4.6.4 Excursion on a circular cruise ship

The newest Royal Caribbean ship, the Ceremony of the seas, leaves the dockyard and arrives for the first time in the port of Rotterdam. The first excursion on the ship is for a select group of people working in the cruise industry. The Ceremony of the Seas is the first ever built cruise ship which completely implemented the future vision of a circular cruise ship. The story below describes how the passengers experienced their excursion.

When we walked to the ship, I could immediately see that this ship is nothing like its predecessors. The design of the ship looks like a catamaran, the second skin balconies are covered with solar filmed glass, there is a wind turbine incorporated in the design of the ship, algae pipes can be seen on the deck of the ship together with greenery. The ship radiates innovation and sustainability. When we get closer our bags are taken by the crew and we are escorted to the ship. Onboard there is again this combination of innovation and sustainability. We enter the main street of the ship with the central park. We see plants and trees all around us, and even a big green wall starting from the deck where we are (deck 6) all the way up to the sky (deck 16). We are in an open space where we can see the sky. We learn that the plants help with improving the indoor air quality of the ship and that they have a positive effect on the mental health *of the passengers and crew. Then a waiter brings us some drinks and bites. He explains that the ingredients of the bites are grown and cultured on board of the ship. The next stop of the excursion is the engine room. The Ceremony of the Seas sails on multiple fuel cells and batteries which run on hydrogen and renewable energy generated by the PV cells and wind turbines we have seen on the outside of the ship. No emissions are released into the air during the production and usage of the fuel. After the engine room, we went to the water treatment facility on board of the ship. Some smart adjustments and additions are made compared to previous ships. For example, an anaerobic digester is added to treat the wastewater and recovers biogas for other industries together with struvite which is used onboard as fertilizer for the food production. Algae are also added to recover nutrition's from the wastewater and produce biodiesel which is used in other industries. Also, the thermal energy is recovered. The waste heat from the showers is recovered through a heat exchanger and the remaining heat from the black and grey water is recovered at the end of the treatment system. On the previous ships, the remaining sludge is incinerated or discharged into the sea, on this ship the sludge is recycled and used for land applications or incorporated into the design of new products. No wastewater or sludge is discharged into the environment! To even further optimize the water system signs are placed into the toilets and showers to create awareness about water wastage. Other water streams that normally find their way back into the environment are the bilge water and ballast water. However, a new electrochemical treatment system is used that also removes the emulsified oils, heavy metals, grease, and organic matter from the bilge water and ballast water from the sea is replaced by treated black and grey water. Then we leave the crew space and go even further down in the ship. The guide leads us into a glass room with a lot of equipment. We are standing in the research lab. In this lab, research is done into the temperature change of the sea and air, into the quality of the air and seawater, but also into tidal changes, marine life and into the seabed. The ship tracks climate change and is allowed to intervene and help the environment by placing cultures and seeds. The ship even has special systems that clean plastic and other debris from the sea and captures pollutants from the air. Then we go back to the main street with shops and bars. Our guide points out that everything that we see around us is made from sustainable materials which comply with the Turntoo model or are Cradle to Cradle CertifiedTM. For example, the paint on the wall is non-fossil based, the carpet can be disassembled and is low in VOCs, the partition walls are made from cellulosic materials, the insulation is made from seaweed, and signs are mounted with a magnetic key. He explains that all the*

solid waste generated onboard is stored and recycled on the land according to their waste stream. Then we go for a nice lunch in the restaurant. The food and the drinks are all fresh and delicious, made onboard of the ship. One of the other passengers ask the guide about the ventilation system; How does it work and where does it get the energy from? The guide explains that a computer measures the CO2 levels and calculates the number of people in the room from that measurement. Then the air is conditioned to their need. The energy efficiency is optimized by adding a dual pressure system with an exhaust gas boiler, ORC, and a low-temperature water heat pump together with the energy exchange principle. Functions with high cooling demand can exchange their heat with functions that have a higher heating demand and the other way around. For example, the pools and the whirlpools have a heating demand, these facilities are coupled to facilities with a cooling demand for example the general public space like this restaurant or the ice rink and the food storage. A heat pump is not only used to recover the waste heat from the engines but also to recover the heat from the environment with a heat pump that uses air or water as source. After lunch, we find out where the food is grown and cultured. There is a beautiful greenhouse with all kinds of vegetable plants, fruit trees and a vertical farm where you can learn about their growth and impact, see figure 165. We go into the food lab where different type of meat is cultured. Apparently, the delicious sirloin steak I had during the lunch is cultured here. Our last stop is the top deck of the ship. From here we have a beautiful view over Rotterdam and the ship. We can see the wind turbine, the PV cells, and the algae pipes but also the pool, the sports deck, and the small Japanese garden. When the dusk comes the deck is illuminated by glow in the dark light that captured solar energy during the day. These lights show us the way back, see figure 166. This ship is truly a combination of innovation and sustainability. This ship has everything that a ''normal'' cruise ship has to offer and more, in a sustainable way. When I leave this ship, I know future passengers will be pampered and will leave the ship with more knowledge and awareness about the impact our daily activities and actions have on the environment and know how they can change this into a positive impact. I will take the lessons learned home with me and implement them in my daily life and work.

**This story is made up by the author to show the impact of these cruise ships on the passengers and the cruise industry.*

Figure 165: Vertical farm onboard
Note. Adapted from Urbanist (2016).

Figure 166: Glow in the dark Deck by Bolidt – Outside
Note. Adapted from Bolidt.

5 Conclusion

5. Conclusion

5.1 research question

This research aimed to identify the steps which need to be taken, focussing on the gas waste streams, fluid waste streams and solid waste streams to make the transition towards circular cruise ships following the City-zen method and comply with the UN sustainable development goals. Currently, waste streams from cruise ships come back into nature which negatively influences the environment. The main objective was to contribute to the development of sustainable, circular cruise ships.

To answer the research question, a literature study was conducted to find out what the current situation is and how it can be improved in the future. The research was divided into the waste stream analysis and the master planning. The waste stream analysis showed that the generated waste does not stay on board but finds its way to land or into the sea or air. During combustion, emissions are released into the air. Next to this, ballast water, black and grey water and bilge water are discharged into the sea still containing pollutants. Generated by-products as sludge are sent to land. The non-hazardous and hazardous solid waste is hand sorted and stored. Most of the waste is sent to land or incinerated onboard on or land.

To reduce and control the waste streams and prevent environmental hazards conventions are made. The international maritime organisation (IMO), is responsible for the development of new conventions. Cruise ships sail between multiple continents and countries with their own legislation. IMO, strives to establish universal standards that are internationally agreed on. These conventions cover the gas, fluid and solid waste streams. Some countries have their own stricter legislation on a national level. Cruise ships need to comply with this when they visit that specific country.

Besides the international and national legislation, the cruise industry, including the Royal Caribbean, has its own set of goals that they want to achieve. These goals go beyond the overall legislation. Royal Caribbean works with the Sustainable Development Goals from the UN and set 8 types of measurable environmental targets for 2020. Next to this, they established the Save the Waves Programme that follows four principles; 1. Reduce, Reuse, Recycle, 2. Practice Pollution Prevention, 3. Above and Beyond Compliance and 4. Continuous improvement. Royal Caribbean is working on the improvement of their waste streams, but in some cases, they still end up in the environment.

Royal Caribbean works together with 11 stakeholders which have a direct and indirect effect on their business. The Royal Caribbean and the stakeholders need each other to co-exist. The stakeholders can influence the future vision and goals. Therefore, they are an important party, and their influence has to be respected.

The master planning started with the future scenarios, to define the boundary conditions the cruise industry can develop itself in. Four scenarios are made through the different focus on: Global vs Local and Economic vs Environment. The four scenarios are called: Autarky, Technical Reality, Ecological Synergy, and Sustainable Communities. Regardless of the scenario, cruise ships can already anticipate on the future changes. The cruise industry should invest in sustainable fuel, sustainable environment, and in a collaboration with the local government and harbour to ensure their future.

There are three levels of ambition a cruise ship can strive to: 1. Fully Circular, 2. Collaboration Ship & Land, and 3. Positive effect on the environment. These scenario's influence the way a sustainable cruise ship will look like.

In order to design the roadmaps according to their level of ambition, elaborated research was needed into the existing treatment techniques and new techniques. Current cruise ships sail on HFO fuel and use scrubbers to reduce their sulfur emissions. Scrubbers are effective in removing sulfur but not in eliminating other pollutant emissions like NOx. Next to this, two by-products are formed: wash water and sludge. These by-products are often not properly handled and end in the environment. The black and grey water is treated by the advanced wastewater purification systems of Evac. The discharged wastewater complies to the current legislation set by IMO, that focusses on BODs, TSS, faecal coliform, free chlorine, and ph. From some other components, it is not verified that they are taken out, including micropollutants. This means that pollutants still enter the sea when wastewater is discharged. Royal Caribbean uses most likely the gravity oily water separator together with coagulation and flocculation, and adsorption. As with the black and grey water, the discharged bilge water complies to the current legislation set by IMO. However, the legislation only focusses on the oil content and not on other harmful particles as heavy metals. These particles come back into the environment. All the generated non-hazardous solid waste and hazardous waste end up in the air through incineration onboard or on land. The current treatment methods onboard focus on preparing the waste for disposal to land or for incineration. The gas, fluid and solid waste stream still end up into the environment with the current techniques. Research into new sustainable fuels and

engines showed that hydrogen, methanol, and the biofuels, biogas, biodiesel and dimethyl ether have the potential to reduce the gaseous emissions. These sustainable fuels can be combined with renewable electric energy generated onboard in combination with a battery and a fuel cell. No emissions come free when a fuel cell is used in combination with hydrogen and renewable electric energy. Renewable electric energy can also be produced on land for the private island from the Royal Caribbean. To improve the fluid wastewater stream several adjustments and additions can be done. Chemical and thermal energy can be recovered from the black and grey water stream. By implementing an anaerobic digester and algae the wastewater is treated and biogas and biodiesel are simultaneously produced. The biogas and biodiesel can be used onboard or disposed of to land when the ship uses another type of fuel. The struvite is recovered after the anaerobic digester and used onboard for greenery and food production or disposed of to land. A heat exchanger is used to recover the heat from the showers and immediately reuse it. The heat from the remaining grey water streams and black water stream is also recovered after the wastewater is treated. The treated black and grey water is reused onboard. Next to this, the water is also used as ballast water. Due to this, there is no need any more to use seawater as ballast water. A new technique is under development to treat the heavy metals, grease and organic matter in the discharged bilge water, called electrochemical treatment. This treatment should be used on new cruise ships. The biosolids and sludge produced during the treatment of black and grey water and bilge water should be recycled on land. The biosolids and sludge from the black and grey water should be used for land applications or composting. When this is not possible the sludge should be included in other products as mortar, concretes, and bricks and tiles. Thermal processing should be the last option due to the emissions that come free and landfilling should be prohibited. The ship produces its own freshwater through reverse osmosis and does not need to bunker freshwater from land. The solid waste stream cannot be eliminated due to the need for products. The best way to improve this waste stream is by using the reduce, reuse, and recycle method. When possible, unsustainable products should be replaced by sustainable, non-toxic alternatives. The number of needed products and produced waste should be reduced and when possible reused. The products should be recycled onboard or on land when the product reached the end of its life.

These new techniques are used to form the roadmaps for the three scenarios. Scenario 1 and 2 consist of two roadmaps, one for the retrofit ships and one for newly built ships. The circular sustainable cruise ship from roadmap A should be a ship that does not emit any pollutant substances into the environment and does not need any help to sustain itself. The ship can generate and treat everything the ship needs without damaging the environment. However, this is impossible to achieve for retrofit ships and newly built ships. The newly built ship from roadmap A can only be circular in the gas waste stream. Hydrogen and renewable electric energy can be produced onboard and used in a fuel cell without releasing any emissions. Waste from the fluid and solid stream are leaving the ship and entering the environment without any help from land. The cruise ships from roadmap B can collaborate with the harbour or companies on land to get rid of unavoidable and untreatable waste, provided this is done in a sustainable manner. Next to this, the ship can receive the needed supplies they cannot generate by themselves. Emissions come free when a combination of fuel produced on land and onboard should be used. Next to this, some pollutants still enter the environment when treated black and grey water, and bilge water is discharged into the sea. However, with the adjustments and additions the water is cleaner than the discharged wastewater in roadmap A. The products that reached the end of their life from the solid waste stream are recycled on land when they cannot be reused anymore. Biogas, biodiesel and struvite are produced on the newly built ships and used onboard or disposed of to land. Roadmap C does not focus on the waste stream from the ship but on the polluted environment. The future cruise ships contribute to the environment by doing research into the environment, measure the conditions, and cleaning the sea and air. By doing this, ships contribute to the research on climate change and clean the environment simultaneously.

Roadmap A and roadmap B focus both on the optimal scenario under the conditions made for that roadmap. To design the most sustainable cruise ship, a combination of roadmap A and B is needed. It is impossible to eliminate the gaseous emissions from the retrofit ships due to the type of engine; combustion engine or dual fuel engine. The emissions are reduced by using hydrogen, methanol, biodiesel, biogas or dimethyl ether. In the case of the fluid and solid waste streams, it is clear that a collaboration between the cruise line and land is needed. The generated waste and products are recycled on land. A heat recovery system is added to the wastewater treatment system to recover and reuse the heat. The treated black and grey water is used as ballast water and the ship produces its own drinking water through reverse osmosis. To remove the heavy metals from the bilge water, nanofiltration is added. Newly built ships should sail on hydrogen with renewable energy to power a fuel cell. No emissions come free when this option from roadmap A is used. As with the retrofit

ship, a collaboration with land is needed to take care of the fluid and solid waste streams. The generated waste, biosolids and sludge, and used products are recycled on land. Extra systems are added to recover the chemical and thermal energy from the wastewater and biodiesel, biogas and struvite are recovered. The treated black and grey water is used for ballast water and the ship makes its own drinking water from seawater. The bilge water is treated by an electrochemical treatment system which also removes emulsified oils, heavy metals, grease and organic matter.

It can be concluded that the final design for retrofit cruise ships and newly built cruise ships is not fully circular. The treated black and grey water and bilge water still contain pollutants that come back into the sea. However, the emissions from the gas stream are reduced or fully eliminated, more pollutants are removed from the black, grey and bilge water, pollutant by-products are recycled on land, heat is recovered and reused, clean products as biogas, biodiesel and struvite are produced, seawater as ballast water is not needed, and non-hazardous and hazardous waste is reduced, reused and recycled. The current cruise ships comply with the current legislation. However, these adjustments and additions should be added to prevent waste discharge into the environment. Next time a cruise ship set sail no harm is done to the environment.

The last chapter showed that the same design principles and interventions used in cities and building complexes can also be implemented on cruise ships. The three steps of the New Stepped Strategy, normally applied in the building industry, should be used to design a sustainable cruise ship. Also, the Cradle to Cradle model and the Turntoo model with the material passport are often used techniques in the building industry which should be applied on cruise ships. The cruise industry can set the next step, when these methods and techniques are used together with other design interventions that find their origin in the building sector, as adding plants, heat pumps, and using the energy exchange principle. The carbon accounting method should be used to visualize the impact of the current cruise ship and show the reduction of needed hectares of saltmarsh when sustainable measures are taken.

5.2 Limitations

This research, however, is subject to several limitations. Not all the needed information is publicly accessible due to the sensitive nature. Cruise lines prefer not to give the explicit numbers of their gaseous emissions, discharged wastewater, and solids waste. A combination of sources is used to be able to comment on this. However, these sources are not specifically about the chosen case study.

Next to this, some relevant research papers were not accessible to students. Most papers could be read through a TU Delft student account but not all. Because of this, not all the relevant information from existing papers could be used. Occasionally, access was granted by the author upon request.

The second limitation stems from the progressive nature of this research. This research aims for something that is not yet possible. The current techniques are not sufficiently developed to solve these problems. Used literature indicates that more research and developments are needed to answer the questions asked. As a result, for some streams, no final solution can be given.

The last category of limitations arises from the scope of this research. This research focusses on improving environmental sustainability. This criterion is used whether a new technique is applied and if that specific technique is better than another technique. The cost to make the techniques and the installation cost are not considered. Also, the energy consumption for the production, the energy consumption of the process itself, the needed materials, and the transportation cost and emissions are not included. The conclusion of this research could be different when these criteria are considered. However, this research focuses on the environmental aspects because this is seen as the most important challenge of today.

5.3 Recommendations

Further research is needed into this topic to be able to make more specific recommendations about the desired techniques. Research into the remaining pollutants in black and grey water is needed to design a treatment process that can extract these pollutants. This also applies to the remaining heavy metals, emulsified oil, and organic matter in the bilge water. Literature states that electrochemical wastewater treatment is developing and most likely the treatment system of the future. However, more research is needed into the efficiency of this treatment system and the final development before it can be applied on a cruise ship. There is also more research needed into using the sustainable fuels in a combustion engine, dual-fuel engine, or fuel cell and the produced exhaust gasses. The combinations of fuel and engines are in its infancy. These engines still need to be developed and optimized, and the emissions are not yet fully known. The same applies to the production of renewable energy. More research is needed into the application of batteries and wind, solar and wave energy on cruise ships. Also, the production of renewable energy on the private island requires more research. Wind, solar, geothermal, and hydrokinetic energy are all options

that can produce electricity on the private islands. More research is needed to find the best sustainable option, including cost, material, efficiency etcetera.

This research focusses on the production of fuels onboard as on land. The fuel needs to be transported to the ship when it is produced on land. Further research is needed in the possibilities to transport the different types of fuels, especially hydrogen. More research is also needed into the production itself. This research states that it is possible to produce biodiesel, biogas and dimethyl ether on land and use it on the cruise ships. However, more research is needed into the cost, the production method, and the efficiencies to find out which option is preferred.

To improve the solid waste stream more research is needed into sustainable alternative products that are not toxic for the environment and do not use scare materials. Next to this, more research is needed in product recycling. This already starts in the design phase of the product. Principles as design for disassembly, replaceable parts, minimal material types, and a proper take-back system should be included.

In general, more research is needed into other criteria like the cost, energy consumption, needed materials and emissions.

Also, the design principles and interventions used in to make the building industry more sustainable should be further analysed. It can be seen that these techniques and methods can also be applied – with some adjustments- in the cruise industry. More research is needed to exploit the potentials.

6 Epilogue

6. Epilogue

I started this thesis with a small introduction about me as a child, being in the fortunate position to go on a cruise vacation with my family. During my studies, I learned about environmental problems and the need for sustainable design. My broad interest in technique and sustainability brought me in the summer of 2019 to this research topic. During my research, I learned a lot about sustainability. Simultaneously, I have become familiar with the current techniques and methods used on cruise ships and in the built environment, and about possible new techniques and methods. I noticed that different sectors are facing similar problems. This research sparked my interest even more in this topic. In the future, I want to keep working on this transition so that no harm is done to the environment when the next generation goes on a cruise vacation.

7 References

7. References

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8 Appendices

8. Appendices

Appendix A: Emissions gas waste stream

CO_2 e

CO_2 e = 0.228 in kg/ ALB-km
ALB= the available guest beds on a cruise ship, assuming 2 people in each cabin.
0.228/2= 0.114 kg/p.-km
The occupancy rate is 1.09
0.114/ 1.09=0.104 kg/p.-km

Factor

4,369,021 metric ton CO_2 e
4,369,021,000 kg CO_2 e = 0.228 ALB-km
0.228/ 4,369,021,000 = 5.22 * 10^-11 (factor)

SO_x

55,315 metric ton SO_x
55,315,000 kg SO_x
55,315,000 * 5.22 * 10^-11 = 0.0029 kg/ ALB-km
0.0029/2 = 0.0014 kg/ p.-km
0.0014/ 1.09= 0.0013 kg/ p.-km including average occupancy rate

54,027 metric ton SO_x
54,027,000 kg SO_x
54,027,000 * 5.22 * 10^-11 = 0.0028 kg/ ALB-km
0.0028/2= 0.0014 kg/ p.-km
0.0014/ 1.09= 0,0013 kg/ p.-km including average occupancy rate

57,130 metric ton SO_x
57,130,000 kg SO_x
57,130,000 * 5.22 * 10^-11 = 0.0030 kg/ ALB-km
0.0030/2 = 0.0015 kg/ p.-km
0.0015/ 1.09= 0,0014 kg/ p.-km including average occupancy rate

NO_x

61,601 metric ton NO_x
61,601,000 kg NO_x
61,601,000 * 5.22 * 10^-11 = 0.0032 kg/ ALB-km
0.0032/ 2 = 0.0016 kg/ p.-km
0.0016. 1.09= 0.0015 kg/ p.-km including average occupancy rate

60,059 metric ton NO_x
60,059,000 kg NO_x
60,059,000 * 5.22 * 10^-11 = 0.0031 kg/ ALB-km
0.0031/ 2= 0.0016 kg/ p.-km
0.0016/2= 0.0014 kg/ p.-km including average occupancy rate

63,277 metric ton NO_x
63,277,000 kg NO_x
63,277,000 * 5.22 * 10^-11 = 0.0033 kg/ ALB-km
0.0033/ 2= 0.0016 kg/ p.-km
0.0016/ 1.09= 0.0015 kg/ p.-km including average occupancy rate

PM

6,807 metric ton PM
6,807,000 kg PM
6,807,000 * 5.22 * 10^-11 = 3.55 x 10^{-4} kg/ AL-km
3.55 x 10^{-4}/ 2= 1.78 x 10^{-4} kg/ p.-km
1.78 x 10^{-4}/ 1.09= 1.63 x 10^{-4} kg/ p.-km including average occupancy rate

6,650 metric ton PM
6,650,000 kg PM
6,650,000 * 5.22 * 10^-11 = 3,47 x 10^{-4} kg/ ALB-km
3.47 x 10^{-4}/ 2= 1.73 x 10^{-4} kg/ p.-km
1.73 x 10^{-4}/ 1.09= 1.59 x 10^{-4} kg/ p.-km including average occupancy rate

7,035metric ton PM
7,035,000 kg PM
7,035,000 * 5.22 * 10^-11 = 3.67 x 10^{-4} kg/ ALB-km
3.67 x 10^{-4}/ 2= 1.84 x 10^{-4} kg/ p.-km
1.84 x 10^{-4}/ 1.09= 1.68 x 10^{-4} kg/ p.-km including average occupancy rate

Medium-speed diesel engines and the Tier regulations

45 n-0.2 g/kWh	130 ≤ n < 2000	Medium-speed engine
45 * 130^-0.2=17.0 g/kWh		
45 * 2000^-0.2=	9.8 g/kWh	
44 n-0.23 g/kWh	130 ≤ n < 2000	Medium-speed engine
44 * 130^-0.23=	14.36 g/kWh	
44 * 2000^-0.23=	7.6 g/kWh	
9 n-0.2 g/kWh	130 ≤ n < 2000	Medium-speed engine
9 * 130^-0.2=	3.4 g/kWh	
9 * 2000^-0.2=	2.0 g/kWh	

Appendix B: List of facilities onboard of the Empress and Symphony of the Seas.

Table 1
Facilities on board of the Symphonie of the seas.

Symphonie of the Seas 2018			
Type of facility	**Facility**	**Type of facility**	**Facility**
Restaurant		**Entertainment**	
	Main Dining Room		Casino Royale
	Izumi		Sports Arcade
	Sorento's		Carousel
	Café Promenade		The Ultimate Abyss (slide)
	Vitality Café		Aqua theatre
	Sugar Beach		Rock Climbing Wall
	Johnny Rockets		Central Park
	150 Central Park		Solarium
	Chops Grille		Card Room
	Jamie's Italian		Whirlpool II
	Park Café		The perfect storm waterslides
	Wonderland		Main Pool
	Solarium Bistro		Beach pool
	El Loco Fresh		Sports Pool
	Hooked Seafood		Padi – Scuba diving
	Windjammer Marketplace		Flowrider
	Coastal Kitchen		Sports Court
Bar			Mini Golf
	Diamond Club		Zip-Line
	Boleros		Suite Sun Deck
	Coffee shop	**Health**	
	On air club		Vitality at sea spa
	English Pub		Running track & Fitness
	Bionic bar	**Shop**	
	Schooner bar		8 shops
	Sports bar	**Children**	
	Dazzles		Adventure Ocean
	Rising Tide bar		Nursery
	Central park bar		Puzzle break centre
	Vintages		Splash away Bay
	Solarium bar		Video Arcade
	Pool Bar		The Living Room
	Sand Bar		Fuel Teen Disco
	Mast Bar		The Back Deck
	Wipe Out Bar		Table Tennis
	Sun Deck Bar	**Other**	
	Suite Lounge		Next cruise
Entertainment			Guest Services
	Royal Theatre		Shore Excursion
	The Attic (lounge/podium)		Loyalty Desk
	Jazz on 4		Picture This (Photos)
	Centre Ice Rink		Conference centre

Note. Data retrieved from: Royal Caribbean Cruises Ltd., (n.d.-b)

Table 2
Facilities on board of the Empress of the Seas.

Empress of the seas 1990			
Type of Activity	**Activity**	**Type of Activity**	**Activity**
Restaurant		**Health**	
	Main Dining Room		Spa
	Chops Grille		Fitness Centre
	Windjammer Café	**Shop**	
Bar			I
	Schooner Bar	**Children**	
	Boleros		Arcade
	Pool Bar		Adventure Ocean
	Viking Crown Lounge	**Other**	
Entertainment			Shore Excursions
	Royal Theatre		Guest Service
	Casino Royale		Next Cruise
	Card Room		Focus (Gallery)
	Pool		Picture This (photos)
	Rock climbing wall		Loyalty Desk

Note. Data retrieved from: Royal Caribbean Cruises Ltd., (n.d.-a)

Appendix C: Building year of Royal Caribbean fleet.

Ship	Built	''End of life''
Wonder of the seas	2021	2051
Odyssey of the seas	2020	2050
Spectrum of the seas	2019	2049
Symphony of the seas	2018	2048
Harmony of the seas	2016	2046
Ovation of the seas	2016	2046
Anthem of the seas	2015	2045
Quantum of the seas	2014	2044
Allure of the seas	2010	2040
Oasis of the seas	2009	2039
Independence of the seas	2008	2038
Liberty of the seas	2007	2037
Freedom of the seas	2006	2036
Jewel of the seas	2004	2034
Serenade of the seas	2003	2033
Mariner of the seas	2003	2033
Navigator of the seas	2002	2032
Brilliance of the seas	2002	2032
Radiance of the seas	2001	2031
Adventure of the seas	2001	2031
Explorer of the seas	2000	2030
Voyager of the seas	1999	2029
Vision of the seas	1998	2028
Rhapsody of the seas	1997	2027
Enchantment of the seas	1997	2027
Grandeur of the seas	1996	2026
Majesty of the seas	1992	2022
Empress of the seas	1990	2020

Note. Data retrieved from: iCruise., (n.d.)