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Improving the energy efficiency of a cruise ship stateroom

Master's thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Technology.

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Abstract of master's thesis

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Abstract
The energy consumption of cruise ships has traditionally been improved by enhancing the properties of the ship's hull or efficiency of its propulsion. Latest research has concentrated on the ship's power plant and how to utilize most of the energy in the fuel. As reducing the energy consumption means reduced operating costs new research topics are searched all the time. In this thesis, the focus is on the passenger stateroom and its energy consumption. Despite the small consumption of one cabin, together the hundreds make a large impact on the ship's energy consumption.

Systems that are studied include solutions for the water system, ventilation system and electrical system. For the water system two different water recycling showers are studied and a waste water heat recovery system. Ventilation system solutions are replacing the cabin air handling unit with a more efficient type, adding automation to main ventilation and improving the cabin balcony door properties and shading to prevent solar radiation from heating the cabin. Electrical system solutions are cabin appliances and the cabin lighting. Some lighting automation is discussed as well.

Ship is a delicate balanced system in which changes to any system may cause problems with other systems. During the research for this thesis many ideas and options were found unsuitable for the ship environment. Another problematic aspect is the ship owner's unwillingness to invest in new and untested equipment.

Research is based on estimated user profiles.

Keywords Cruise ship, stateroom, cabin, energy efficiency

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Tiivistelmä

Risteilyalusten energiankulutusta on perinteisesti pienennetty rungon ominaisuuksia parantamalla tai aluksen voimalinjan häviöitä vähentämällä. Viimeisimpiä tutkimuskohteita on ollut aluksen voimantuotanto ja se, kuinka siitä saadaan mahdollisimman paljon tehoa. Koska energiatehokkuuden parantuminen pienentää polttoaineen kulutusta, ja siten aluksen elinkaarikustannuksia, uusia tutkimuskohteita etsitään koko ajan. Tässä työssä keskitytään matkustajahyttiin ja sen järjestelmiin. Risteilyaluksen hytit ovat pieniä osasia, jotka yhdessä muodostavat ison osan laivan energiankulutuksesta.

Laivan isoista järjestelmistä hytit liittyvät ilmastointijärjestelmään, vesijärjestelmään ja sähköjärjestelmään. Vesijärjestelmän ratkaisuja, joita tässä työssä tutkittiin, olivat erilaiset vettä kierrättävät suihkut ja lämmöntalteenotto harmaavedestä. Ilmanvaihtojärjestelmän ratkaisuina tutkittiin sekä automaation lisäämistä nykyiseen järjestelmään, että mahdollisuuksia vaihtaa hytin päätelaite tehokkaampaan. Samassa yhteydessä selvitettiin myös ikkunoiden ja hytin varjostuksen vaikutus tarvittavaan ilmanvaihtotehoon. Sähköjärjestelmiin puututtiin käyttölaitteiden ja valaistuksen kautta.

Laiva on herkkä kokonaisuus, jossa muutokset yhteen järjestelmään saattavat heijastua toisiin järjestelmiin. Tämän diplomityön tutkimuksen aikana monet ratkaisut osoittautuivat laivakäyttöön sopimattomiksi. Toinen hankaluus järjestelmien käyttöön saamisessa on varustamoiden haluttomuus investoida uuteen ja aiemmin testaamattomaan kalustoon.

Ratkaisujen energiansäästöpotentiaalia tutkittiin mallintamalla, käyttäen muodostettuja käyttäjäprofiileja.

Avainsanat Risteilyalus, hytti, energiatehokkuus

In memoriam
Armas Pönkä
1926 - 2017

Foreword

Someday, somehow. Work behind this thesis has been testing and educating. In late spring 2016 theme of the thesis was presented by Meyer Turku. After that not a day has passed that this work has not been on my mind. Now that the work is in its covers I feel glad.

Being able to complete this work help has been needed and received from many directions. Firstly, I would like to thank Tero Mäki-Jouppila for taking the time and effort in familiarizing me to shipbuilding world and the methods of Meyer Turku as a workplace. Tero has as well taken great effort in proofing this thesis and bouncing ideas on how to present results. Other people from Meyer Turku I would like to thank are Olli Jantunen, Kari Sillanpää, Mika Kirjavainen and Vesa Heikkilä. Touko Lehdonvirta and Risto Nurminen from Piikkiö Works also deserve my gratitude.

From Aalto-university I would like to thank my supervising professor Risto Kosonen for accurate work and on demand knowledge of scientific world. Thanks also to professor Liisa Halonen and Paulo Pinho from lighting unit on bringing me up to date on why electricity is blue and hurts if you touch it.

No work is done without time off the work. This time has been made worth living by many people, not least by Jari Isaksson. Jari has been the person to drag me through the studies despite plans to leave technological studies and head somewhere else. Latest heroic effort from this humble man since his graduation has been to ask on daily basis what is the word count of my thesis.

Life is a journey to be travelled with someone. Roughly at the same time as I was given the topic for this thesis I met my girlfriend Salla. Not only is she a sweet person but also a kind-hearted one who has given many advices to avoid the potholes that lurk on the way of writing a master's thesis. Salla has provided vital support to me during this process.

Last but definitely not the least I like to thank my parents and my little brother Heikki who has despite the two-year difference closed the gap in our study progress. Heikki you made this last stretch a race and luckily, I did not lose to you by much. To mom and dad: it took a while but here we are. Thank you for all the support during my studies.

Friends who I have not mentioned by name. You all are important and one way or the other you have helped me to complete this thesis.

To anyone reading this foreword and being at the beginning of your work make sure that you start early enough and give time for the work as well. It can be done during the last night, but it is not fun.

Espoo, April 18th, 2017

Matti Nurmi

Contents

Symbols

A	[m^2]	Area of the balcony door
c_p	[kJ/kgK]	Specific heat capacity in constant pressure
$\dot{m}$	[kg/s]	Mass flow
P	[W]	Heating or cooling power used in the fan coil unit
P_{fan}	[W]	Electrical power that the fan operates on
P_{fanmax}	[W]	Maximum electrical power of the fan
P_{max}	[W]	Maximum heating or cooling power of the fan coil unit
Q	[J]	Thermal energy
Q_{cond}	[W]	Heat load conducted out through the cabin balcony door
Q_{elec}	[W]	Heat load from the electrical devices in the cabin
$Q_{heating}$	[kW]	Heating power needed for the water
Q_{people}	[W]	Heat load from the people in the cabin
Q_{rec}	[kW]	Heating energy collected from the water flow
Q_{sun}	[W]	Heat load from the sun after the window
Q_{tot}	[W]	Total heat load to the cabin during each moment
Q_{vent}	[W]	Heat load from ventilation
T	[K] or [˚C]	Temperature
T_c	[°C]	Temperature of cold potable water
T_e	[°C]	Temperature of the water entering the cabin
T_h	[°C]	Temperature of hot potable water
T_i	[°C]	Inside air temperature
T_o	[°C]	Outside air temperature
T_r	[°C]	Temperature of the raw water
T_s	[°C]	Temperature of the supply air entering the cabin
T_T	[°C]	Target temperature for used water
U	[W/m^{2}K]	U-value of the window
V	[m^3]	Volume
$\dot{V}$	[m^3/s]	Volume flow
$\dot{V}$	[m^3/s]	Air flow from the ventilation system to the cabin
$\dot{V}$	[m^3/s]	Water flow to the cabin appliance
$\dot{V}_{sh}$	[l/s]	Volume flow of the shower
$\dot{V}_{wb}$	[l/s]	Volume flow of the washbasin
x	[-]	Portion of hot potable water
η	[-]	Efficiency of the heat recovery system
ρ	[kg/m^3]	Density

Abbreviations

AC	Alternating Current
CO_2	Carbon Dioxide
COP	Coefficient Of Power
DC	Direct Current
EC	Electronically Commutated
HVAC	Heating, Ventilation and Air Conditioning
HT	High Temperature
LED	Light Emitting Diode
LOA	Length OverAll
LT	Low Temperature
MS	Mein Schiff
PWM	Pulse Width Modulation
RF	Radio Frequency
USB	Universal Serial Bus
UPS	Uninterrupted Power Supply
USPH	United States Public Health Service
UV	Ultra Violet

1 Introduction

1.1 Background

Traditionally, improving energy efficiency of ships has concentrated mainly on optimizing hydrodynamic properties of the hull or utilizing machinery waste heat to maximize electricity production (Quach 2014). Now, when the easy ways to improve machinery efficiency are implemented, action has to be taken to reduce the energy consumption and therefore runtime of ships engines. Research has been done on the influence of the insulation of the deck structure and on the ships ventilation systems (Rimpiläinen 2012; Oinas 2007). As the more energy consuming systems have been investigated, the focus can be turned to the smaller energy consumers such as the cabins.

The ship building industry has relied on tested, and therefore trusted technologies in numerous solutions. These technologies are not necessarily the most energy efficient. Noticeable energy savings can be achieved by implementing new technologies already in use on dry land. One of these technologies is e.g. LED (Light Emitting Diode) lighting that still has not made its breakthrough in the ship building industry. Other methods considered in this thesis are the overall electricity consumption, the water usage and the heat loads from other sources. Renewable electricity production is also discussed.

Calculations and comparisons to present solutions refer to the Mein Schiff 3, 4 and 5 (abbreviated MS 3, 4 and 5) ships built by Meyer Turku shipyard. Key figures of the ships are presented in Table 1. These values are power needs. The difference between power need and power delivered is discussed in Chapter 2.2.

Table 1 Key figures of reference ships Mein Schiff 3, 4 and 5 (Meyer 2016; TUICruises 2016).

Length	293.2 m (LOA(Length OverAll))
Width	35.8 m
Average height	66 m
Tonnage	99 526 GT
Number of passenger cabins	1 253 (MS 3, 4) 1267 (MS 5)
Number of passengers	2 506 (MS 3, 4) 2534 (MS 5)
Launched	2014 (MS 3), 2015 (MS 4), 2016 (MS 5)
Maximum produced electrical power	48 MW
Air handling units	
Ventilation supply air	215 m^3/s
Air-conditioning cooling power	9 100 kW
Ventilation pre-heating power	1 500 kW
Ventilation re-heating power	2 600 kW
Potable water system	
Potable water production power	220 kW
Potable water heating power	1 450 kW

Of the 1 267 cabins, 928 are equipped with a balcony. Of the normal cabins, 89 are outer cabins without balcony and 127 are inner cabins with no view to outside. The rest of the cabins are 123 special staterooms or suites divided in 9 categories. In this thesis, normal cabin is an outside 15.4 m² cabin with a balcony. These 1 017 cabins are 80 % of all the cabins in the ship. (TUICruises 2016)

Calculations in this study are based on estimations and simplified steady-state models so results should be considered more as guidelines. Working procedure at the company ordering this thesis is such that these results will be presented to customers and customer will decide if solutions are tested in practice. If so decided, testing is first performed in a few cabins scale. In the whole ship's scale these solutions are used earliest in 6 to 8 years.

1.2 Objectives

The goals of this thesis are to analyze the passenger cabins energy usage currently and using different available technologies to reduce energy consumption. Technologies are listed in Table 2. Analyzation concentrates on the water system, the ventilation and the electrical system. Targets are:

1. to examine if there is equipment available with better efficiency,
2. if better solutions exist,
3. are there solutions in use on land that are applicable to ships,
4. can ship's systems be integrated so that the total energy consumption can be reduced and
5. is it possible to integrate renewable energy sources into the passenger cabin.

Table 2 Technologies studied in this thesis.

Technology	**System effected**
Water recycling shower, Orbital Systems	Water system
Water recycling shower, Upfall	Water system
Waste water heat recovery, Ensavetec	Water system
Waste water heat recovery, Wasenco	Water system
LED luminaires	Electrical system
Solar lighting, collector	Electrical system
Solar lighting, light tunnel	Electrical system
Utilizing corridor lighting, prism	Electrical system
Central cooled fridge	Electrical system
Renewable energy sources	Electrical system
Active chilled beam	Ventilation and electrical system
Cabin windows and balcony doors	Ventilation and electrical system

Analyzation is based on estimated user profiles. This is because usable data does not exist on how passengers use services of the cabin. In addition to the analyzation, this thesis produces graphs to illustrate energy and electricity consumption and show peak loads of these consumptions on selected user profiles.

1.3 Energy flows

This thesis concentrates on the cabin itself. Energy flows such as water and air from outside of the cabin are considered just as flows adding to or decreasing from the energy used by the cabin. Larger systems such as air-conditioning and fresh water are considered only as energy entering or exiting the cabin and the daily variation in their energy usage i.e. pumps turning on and off is not considered. Effects caused by the changes in the cabin systems to other systems are not covered extensively. Energy flows assessed in this thesis are presented in Figure 1 and their volumes are presented in Table 3.

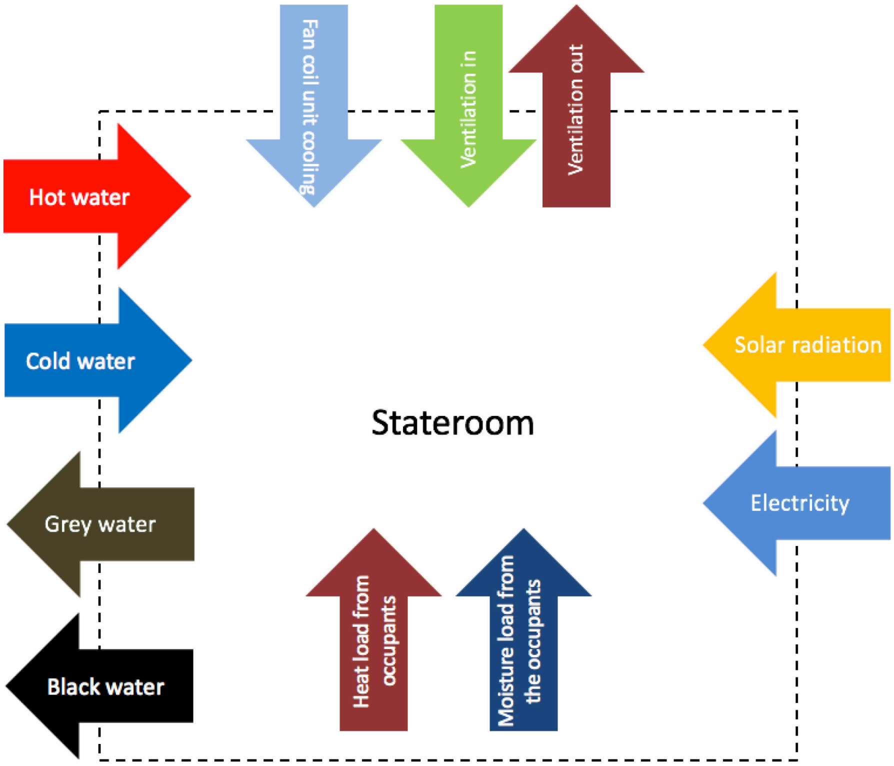


Figure 1 System boundaries and energy flows of the stateroom. Arrows are energy flows and the dash line is system boundary.

As can be seen from Figure 1, the heat loads to and from surrounding spaces and air leakage are not considered in this thesis. According to Rimpiläinen (2012), insulation in the walls resulted in marginal savings compared to other solutions such as heat recovery in the ventilation system or better windows. Increasing the insulation thickness in the walls by 30 % reduced the energy consumption only by 3 %. In cruise ships, interior space is valuable for delivering as much experiences to the passengers as possible. Therefore, such low gains do not appeal to companies ordering cruise ships. Rimpiläinen (2012) analyzed icebreaker’s deck structure and its potential to energy savings. Climate data used is from the arctic region where the temperature difference between inside and outside air temperatures is far greater than on a cruise ship in its normal environment. Temperatures in Rimpiläinen’s research were -60 - 30 °C staying below zero for 60 % of the year. Reference ships operate mainly in above zero temperatures and their heating has been designed for winter conditions no colder than -7 °C. This means that the benefit of the changes on a cruise ship would be even lower.

Table 3 Energy flows and their quantities into a cabin (Meyer 2016).

Energy flow	Quantity in a day	Energy consumption	Energy source used
Hot water	60 l	2440 - 3690 Wh	Waste heat / electricity
Cold water	120 l	420 Wh	Electricity
Grey water	170 l	N/A	Electricity
Black water	10 l	N/A	Electricity
Heat load from occupants	1 700 Wh	1 700 Wh	Cooling
Electricity	2 300 - 3 100 Wh	2 300 - 3 100 Wh	Electricity
Solar radiation	4 200 - 9 100 Wh	4 200 - 9 100 Wh	Cooling
Ventilation in	1 814 m^3	37 870 Wh	Electricity / cooling
Ventilation out	1 814 m^3	1 590 Wh	Electricity
Fan coil unit cooling	760 - 4 900 Wh	760 - 4 900 Wh	Cooling

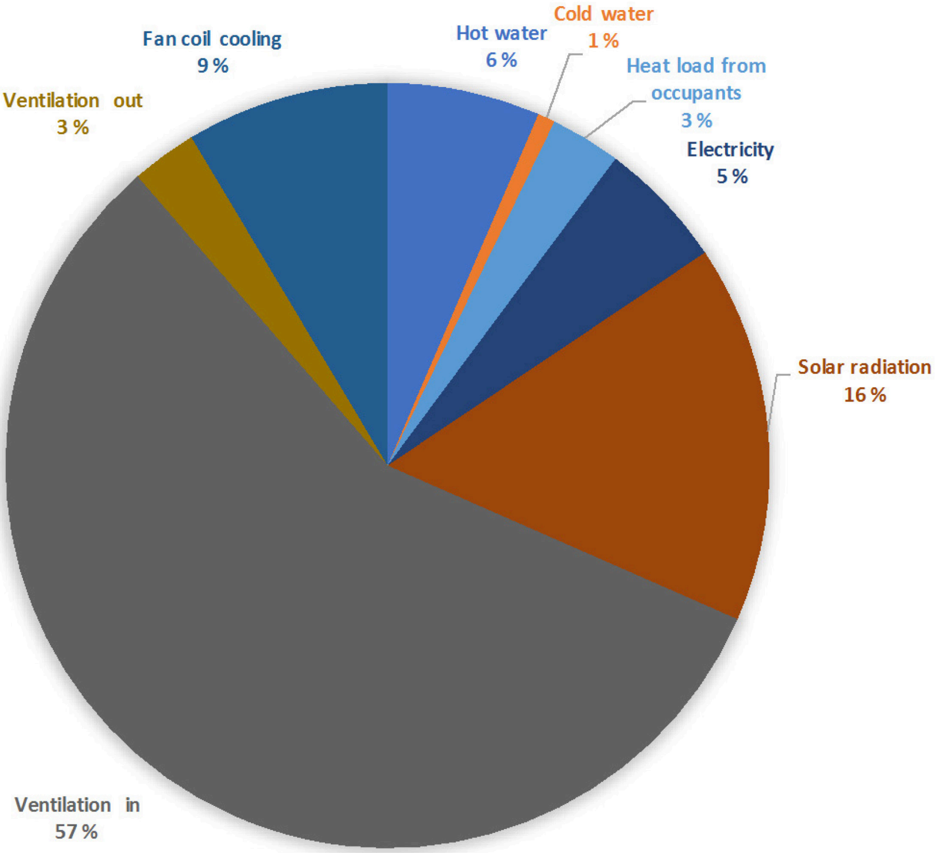


Figure 2 Maximum energy flows in relation to each other.

Table 3 and Figure 2 present the heat flows of the cabin. Values presented in Table 3 and Figure 2 are energy needs. The difference between energy need and energy delivered is discussed in Chapter 2.2. Presented in the Table 3, the largest consumer is ventilation into the cabin. Currently there are no means to optimize this flow. Air handling units adjust themselves to be as efficient as possible, but the consumption is not controlled, as the airflow to the cabin is constant. Solar radiation is the second largest flow. The windows ability to reflect solar heat is important to keep the cabin cool. Better windows not only cut the solar radiation, but also reduce the need to cool the cabin with the fan coil and ventilation. Solar radiation can increase and decrease the energy consumption as it can heat or overheat the cabin. The cabins energy balance determines the effect of solar radiation. If in total energy is flowing outwards of the cabin solar radiation reduces the consumption and vice versa. The same applies to ventilation as it can cool the cabin too much.

Resulting from the solar radiation third largest consumer is the fan coil cooling that is fed by the cooling water network in the ship. This is quite well controlled flow as fan coil switches off when the cabin is unoccupied or when the balcony door opens. Next flow in decreasing order is hot water. The flow consists of producing the water and heating the water. Water usage at the cabin is controlled only by flow restrictions, but there is room for improvement and promising options exist to reduce water need and to harness the heat from the grey water.

Electricity flow presented in Table 3 and Figure 2 has many devices in it. Fan coil fan, -heating, fridge, lighting and TV make the flow. The same applies to other fan coil components what has been told about the fan coil cooling. TV is not controlled in any way, some automatic turn off solution would be good choice as the TV can otherwise be left on. Fridge could be more efficient model or utilize the central cooling. For lighting consumption automation would bring some savings as will the LED technology. One of the smallest loads is heat load from occupants and nothing can be done to it. Ventilation out actually produces savings as the return air can heat or cool the incoming air at the air handling unit enthalpy recovery wheels and lessen the need for air processing. Cold water requires quite little energy, but the flow will be reduced along with hot water usage if water consumption reduces.

Economical aspects are ruled out of this thesis. This is because some solutions are not produced in such quantities that their price would be on corresponding level with the final price. The amount of systems for a cruise ship is so large that for some manufacturers the production of the devices can be a real challenge. This can result in new investments and changes to the pricing of the product. Likewise, the ships operate around the world and the prices of labor and common materials vary greatly so retrofitting prices would not be accurate.

1.4 Outline of the Thesis

In this thesis, Chapter one introduces reader to the research problem. Background of the problem and objectives of thesis are presented as well. Main energy flows of the ship are introduced with the current consumption of the passenger cabin.

Chapter two gets deeper into background of the problem. Ship is presented as an ecosystem having its own specialties in energy production and consumption. The systems producing energy are introduced and energy efficient solutions are defined.

Chapter three describes the research methods. The profiles used to calculate consumptions and possible savings are defined here. Calculations are described in this chapter as well.

Chapter four specifies the technical systems currently in use. Systems are categorized according to the energy flow that they affect. Categories are water production and delivery, cabin lighting, electric appliances, cabin heating, ventilation and air-conditioning and cabin windows and balcony doors.

Chapter five describes in detail the new technologies studied. Solutions listed in mentioned categories are such that have at least made market and seem appropriate for marine use. Chapter five is structured in same style as Chapter four to ease comparisons.

Chapter six is about adding intelligence to the system operation. Automation systems have improved during recent years and considerable energy savings can be achieved by taking them into use (Moisio 2016). Chapter starts with current solution and ends with possibilities to improve automation systems.

Chapter seven presents the results of the energy saving analysis. Different solutions and their energy consumptions are collected into tables to provide easy possibility for comparison. Some systems interfere with each other so the one with the most saving potential is selected as for example installing both types of shower in a cabin with one shower is not possible.

Chapter eight is for discussion and benefits and disadvantages of each system. Chapter nine presents conclusions of the study and topics to continue research on.

2 Improving the energy efficiency of the stateroom

2.1 Energy production on a ship

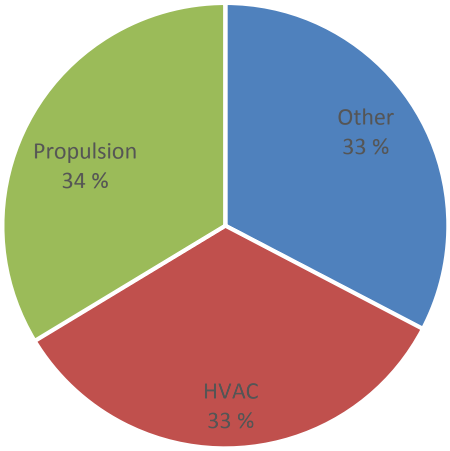


Figure 3 Energy usage distribution on a cruise ship (Kanerva 2005).

Figure 3 illustrates how the energy is used on a cruise ship. HVAC systems (Heating, Ventilation and Air Conditioning) use one third of the energy used on a ship. Hence optimizing ventilation needs and finding efficient solutions is a key element to saving energy. In the cabins this means minimizing the need for outside ventilation, heat loads and uncontrolled air leakage. Only the outside ventilation, meaning air handling units, and minimizing heat loads are studied in this thesis.

Engines installed in the Mein Schiffs are two Wärtsilä 8L46F and two Wärtsilä 12V46F. These have maximum continuous rated power of 9.6 MW and 14.4 MW respectively (Meyer 2016). Total installed engine power for the whole ship is 48 MW. Fuel efficiency of the marine diesel or gas engine ranges between 42 - 52 % and generator efficiency is up to 99 % (Wärtsilä 2014; Siemens 2016). The highest fuel efficiencies for the engines are achieved when the engine load is at 85 - 90 %. This means that in the harbor engines are running at low efficiency, as the hotel load is only half of the minimum efficient load, which is 8.2 MW that is achieved from 8L46F engine at 85 % load. Electricity production can be varied slightly by adjusting steam turbine running on steam from exhaust gas boiler, but the main means to adjust electricity produced is to turn on different engine combinations to spin their generators (El Geneidy 2016; Korhonen 2016).

Energy used in the ship is divided into propulsion and hotel consumption. Propulsion consumption is the energy that is used during cruising and maneuvering by the propulsion motors and the thrusters. Hotel consumption is everything else on the ship including necessary technical consumption from i.e. making fresh water and ventilation to electricity used in night clubs and cabins. The energy to satisfy the need of hotel consumption is delivered in many forms by producing new energy such as electricity, steam or cooling water and by recovering waste heat from different sources to heat water or supply air. The hotel load of a cruise ship is around 4 000 kW both in harbor and at sea (Korhonen 2016).

Energy consumption in an individual passenger cabin is quite small compared to the whole ship's consumption, but when there are 1 267 cabins, even small changes make an impact on the energy balance of the whole ship. The maximum load per cabin is 2.2 kW including electricity, heating and cooling. This results in the total maximum cabin load of 2 787 kW. Average load over one day in an individual cabin is around 350 W resulting in total load of 444 kW. (Meyer 2016)

Reducing energy consumption in the cabins is important because they consume energy all the time. Energy is used to sustain desired temperature range and to cool the fridge. If cabin load and other hotel load can be decreased to a level that makes shutting the engine off possible, this would result in savings. When cabins are unoccupied the cabin load is 154 - 295 W per cabin and respectively totals at 195 - 374 kW for all the cabins in total. This is 5 - 9 % of the average hotel load of 4 MW. Values are calculated based on the values from Meyer (2016).

In other than cruise ships energy can come from other sources such as batteries (E-ferry), photovoltaics (MS Tûranor PlanetSolar) or from wind (E-Ship 1). E-Ship 1 utilizes Magnus effect in its propulsion that is discussed more accurately in Chapter 5.8 discussing the renewable energy sources. For cruise ships, the amounts of energy needed are so large that these methods cannot produce enough energy by themselves and thereby a combustion engine is needed to feed the need for energy. Not only the methods to produce the propulsion power can be energy efficient, but the way to transfer the energy as well. Some of the propulsion methods and the largest ships using these methods are presented in Table 4.

Table 4 The largest ships of some propulsion types and the reference ship (Clean Technica 2012; E-ferry 2015; ABB 2013; Meyer 2016).

Ship's name	Propulsion power [kW]	Powered by
E-ferry	1 500	Batteries
E-Ship 1	7 000	Wind (Magnus effect)
Dina Star	4 400	DC network
Mein Schiff	28 000	Diesel engine

Ships propulsion has transferred from traditional shaft driven propellers to electrical motors running propellers. This is done to save space for passenger utilities and reduce passenger comfort as vibrations are reduced. Saved space comes from the long shaft lines. The shaft lines are presented in Figure 4. This propulsion solution together with experiences from the Dina Star vessel encourages applying DC (Direct Current) technology to cruise ships as well. On a DC grid equipped platform supply vessel Dina Star 27 % reduction in fuel consumption has been reported in comparison to traditional AC (Alternating Current) grid (ABB 2013). Results from the master's thesis of Korhonen (2016) also support the implementing of DC technology on a cruise ship. Cruise ship cabins readiness to accept DC technology is discussed in Chapter 5.5.

Figure 4 Cruise vessel with traditional shaft drive in the upper left picture and modern propulsion with electrical motor running the propeller in the lower picture (ABB 2003).

2.2 Energy efficient solutions

Solutions that reduce energy consumption in the scale of a whole ship are considered energy efficient. If solution reduces energy consumption only in the cabin and causes additional loads elsewhere, the solution is not considered energy efficient. Solutions examined in this thesis are cabin systems or operating methods that affect the cabin directly and reduce the energy consumption of the whole ship.

Solutions that reduce the weight of the ship can also save energy. The lesser the ship’s weight, the lesser propulsion power the ship needs to travel through water. Weight savings do not only come from cabin itself but also from reduction caused in systems serving the cabin.

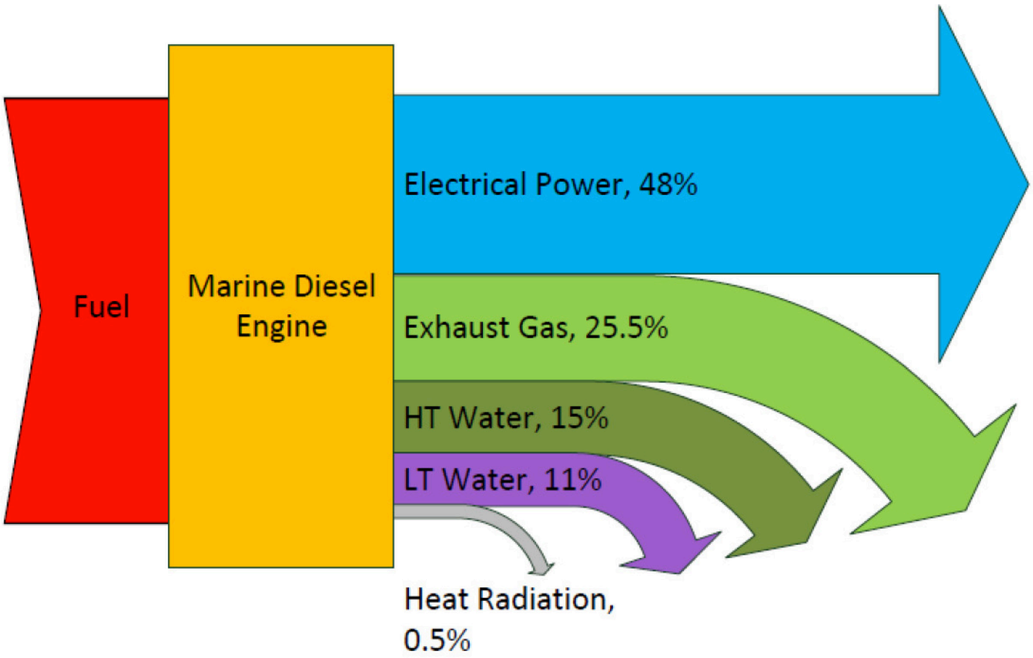


Figure 5 An example of energy distribution of a typical marine diesel engine (Zou et al. 2013).

Energy from the fuel is utilized as electricity or heat. The generators that are directly connected to the engines produce electricity. Typical use of the energy is shown in Figure 5. HT water is high temperature cooling water and LT water is low temperature cooling water. HT water's main use is to produce technical water from the sea water in the evaporators and the rest of the HT water is used to heat the fresh water used in the cabins and other places such as galleys. LT water does not have any use on the ship and the heat in the water is transferred to the sea water via heat exchangers. Propellers are not connected directly to the engines, but are run by electric motors so the propulsion power is included in the electrical consumption as well. Energy in the exhaust gas is turned into electricity in an exhaust gas boiler. The boiler collects heat into water that turns to steam and the steam is passed through a steam turbine to run a generator that makes electricity. (Meyer 2016)

Technologies already implemented on ships to reduce energy consumption are frequency controllers on large fans and pumps, waste heat recovery in engine room and air handling units. Waste heat recovery is done with an exhaust gas boiler in the engine room and with an enthalpy recovery wheel in air handling units. Latest trend is to optimize propulsion power to travelled speeds to reduce non-optimal loading of the engines. (Quach 2014; Baldi et al. 2015; Meyer 2016)

Heating in the air handling units is done using multiple systems. Pre-heating of the air is done primarily with enthalpy recovery wheels and if that is not enough then a heating coil is used. In the heating coil circulates water that is heated with steam. Re-heating of the processed air is done in similar method but only with heating coils. These heating coils have two sources of energy. Primary ones run on hot cooling water from the engines. Secondary ones use steam to heat the supply air to the desired level if the power from the primary coils is not enough.

In order to monitor energy usage on a ship there needs to be instrumentation on consumers and production to calculate how efficiently energy is used. There is room for large improvements in instrumentation, but a lot has been done in recent years. For example, the reference ships are equipped with EMMA that is energy consumption monitoring software. This allows possibility for the ship owner and the ship crew to monitor the parameters and use the equipment as efficiently as possible. (Quach 2014; Meyer 2016)

Energy need on a ship and the energy delivered to a system two different things. Energy need is the total need for some solution and energy delivered is the external or new energy delivered to the solution. Examples of such differences are the solar load and the cabin heating as well as the enthalpy recovery wheel of the air handling unit. According to the calculations, the need to heat the cabin is 20 - 200 W and the solar load to the cabin is 0 - 1 600 W so normally the heating need is satisfied with the solar load during the daylight hours. This is called free energy. The enthalpy recovery wheel similarly satisfies the need for ventilation heating or cooling depending on the operating mode of the ventilation system. If the outside air is in need of heating, the recovery wheel transfers heat and moisture from the exhaust air to save energy. If the outside air needs to be dried and cooled the recovery wheel can transfer heat and moisture to the exhaust air. This is called recycling energy.

2.3 Ship as an ecosystem

In maritime engineering, common practice is to use circulating systems in multiple solutions such as heating and cooling. Solutions in a ship have to be compact because space for them is limited. Every resource has to be carried or manufactured onboard so for example fresh water consumption needs to be minimized. The smaller the need for fresh water, the lighter the system providing the fresh water and therefore less weight must be carried onboard. Smaller weight of the ship results in decreased need for propulsion power and therefore fuel consumption.

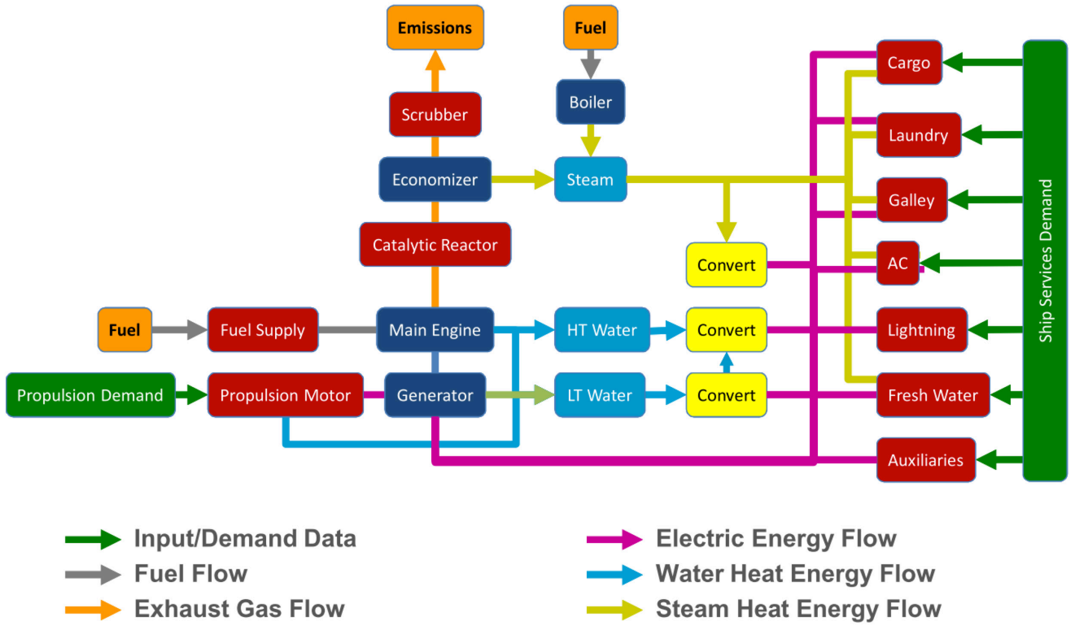


Figure 6 Energy flows on a passenger ship (Sillanpää 2016).

The energy onboard a ship comes most commonly from the ship's engines as illustrated in Figure 6. Heat is available from hot or cold cooling water (90 – 95 °C or 40 – 47 °C respectively) (MAN 2016; El Geneidy 2016) and electricity through generators that are run by the engines. Heat and steam can also be produced in gas- or oil-fired boilers, but this increases the ship's fuel consumption. Using waste heat from the engines, if possible, is therefore a better solution. As can be seen from the Figure 6 ships energy system is looped. This is a benefit as the system can adapt to different proportions of heat and electricity need. The adjustment is not limitless, as catalytic reactor requires certain temperature to operate. Similarly, the steam turbine that converts steam to electricity has a quite narrow operating window.

Energy is a new perspective in ship building. Traditionally things have been seen in cubic meters, liters or kilograms. Watt-hours and joules are new perspectives and thus should be minimized as they correlate quite directly to the lifetime costs of a ship. Energy on a ship is used as heat, warmth or cooling, steam or as electricity. As on the land, heat, steam and electricity have different values and different usability. Heat and steam are freely available at the engine room, but they become much more difficult to transfer to the upper decks because of confined spaces of the ship. On the other hand, electricity is easily transportable and already available in almost all parts of the ship, but its generation is not as efficient as on land because of the limitations of the combustion engine turning the generator.

Ships build today do not have main and auxiliary engines as their predecessors. Engines are chosen according to the propulsion power needed and space requirements of the ship hull. Engines are referred to as the power plant. This describes how the engines do not just spin the propeller to move the ship, but provide energy for every use from propulsion motors to cabin appliances. Energy is produced online according to the need. Energy is not stored anywhere and enough generator capacity should be online to be ready to react if a sudden rise in consumption arises. This results in engines idling or running at a low efficiency. If consumption can be reduced, the capacity to respond to the consumption spikes might be available from a single engine. Using a single engine would cause savings, as no unnecessary engines would need to be running.

Above described power plant operation is the same working principle as on land. On land a designer of for example ventilation system does not need to take these facts into account. On a ship, every system designer must take these facts into account. Using excess energy or using one energy source instead of another can mean additional consumption for another system. On Mein Schiffs is a good example of this. If technical water would be produced with reverse osmosis the hot cooling water from the ship's engines could be saved for heating hot potable water. Now when the waste heat of the engine is used to produce technical water and the potable water is both produced and heated with electricity the energy consumption in total is greater than needed. If technical water would be produced with a more efficient system such as the reverse osmosis, the waste heat energy could be used on heating the water and electricity would be saved. The savings would be around 20 kWh/m^3 of heat energy for every cubic meter of technical water produced. Heating of hot potable water is discussed more detailed in Chapter 4.1. (Meyer 2016)

Safety on a ship is an important issue and this aspect reflects on all the systems. Ventilation has to be separated into fire-zones to prevent fire and smoke spreading to the whole ship in case of a fire. This is normally done by installing air handling units individually into every fire-zone. Safety sets requirements for the electricity as well. As ship is an enclosed structure, lamps are needed to provide light into the corridors and other interior parts. In case of a power out, blackout in ship terms, most places become dark and difficult to find out. Therefore, lighting and other vital systems have to have backed up power supplies such as UPS devices (Uninterrupted Power Supply) or emergency electricity grid (Räisänen 1997).

3 Research methods

3.1 Research Approach

Actual data of a cabin's energy usage is not available and therefore a lot of the values are estimations or from dry land. Different systems such as ventilation, water and electricity are examined for methods to increase their efficiency. Possibilities to integrate existing systems into each other are also investigated. Calculations are done using consumption information from product manuals and manufacturers' websites and from the estimated user profiles for usage of cabin systems. Energy balance is created along the cabin walls as presented in Figure 1. This is done to simplify the calculation to not include the daily variation in water consumption. Including the water consumption variation into the calculations would not give any additional information as results are handled on daily or yearly consumption. Calculations are done assuming steady state conditions in the cabin.

Many of the technologies or solutions proposed or examined will not directly cause savings in the energy consumption of the ship although energy usage in the cabin is reduced. Options can increase consumption at the air conditioning systems cooling water chillers or in the water system in terms of added need to pump fluids from one place to another. One of the water recycling showers, the Orbital Systems shower, is a good example of this difference between cabin and ship consumption. The shower adds 4 kW of electrical load to cabin when used, but this does not increase energy consumption on the ship, as the same energy would otherwise be used at the machinery room to heat the water. Also, reducing electrical consumption from the cabin can result in added need to heat the cabin.

Different systems are studied separately to get the best possible picture of the system itself. Integration and systems effects to each other are considered in Chapter 6. Weather data is selected not to include clouds or rain as their influence is presented in the solar values and average temperatures of the season.

3.2 User and operational profiles

Because actual data from a cruise ship is not available three user profiles are created to evaluate the energy consumption and possible savings achieved. Profiles are for situations when passengers are staying in the cabin for the whole day, passengers staying out of the cabin for the whole day and passengers staying in the cabin for half of a day.

Between the profiles water and electricity usage are varied to create scenarios for different usages. Main parameters for the profiles are described in Table 5. Profile 1 is estimation done by the writer of this thesis. Background information to form this profile is gathered from the senior personnel of Meyer Turku Oy. Profile 2 is the user profile used by Oinas in his thesis (2007). Profile 3 is a profile where the people stay in the cabin for the whole day and this profile represents the worst case for consumption.

Table 5 User profiles used in the calculation.

	Lighting on [h]	Shower used [min]	WC used [times]	Washbasin used [l]	Occupancy [h]
Profile 1	2.5	15	8	42	9.5
Profile 2	4	25	8	42	12
Profile 3	19	30	14	84	24

The operating profile of the ship causes also variation to the energy consumption. Cruise ships operate in the sunny and warm regions for the majority of the year. Popular places for cruising are the Caribbean, the Mediterranean and the Canary Islands. Some ships sail in exotic places such as Svalbard and the Mein Schiff series is designed to be able to operate there during the summer. Operational regions of the Mein Schiff series are the Baltic Sea in the summer (Jun., Jul., Aug.), Mediterranean in the fall (Sep., Oct., Nov.), Caribbean in the winter (Dec., Jan., Feb.) and Canary Islands in the spring (Mar., Apr., May).

The arctic regions set their own requirements for ships. These requirements are regarding hull strength against ice, heating and insulation of interior spaces and stability calculations for ice building up to the ships superstructure. Anti-icing equipment must also be on necessary level for thawing mooring ropes, decks and such. Therefore, the ship's operating area and climate have to be considered in the designed process and ships are designed as above or below zero ship (Meyer 2016).

The operation area affects in the amount of the sun's radiation, air temperature and sea water temperature. Each of these climatic factors influences the cabins energy consumption. The sun's radiation heats the cabin directly if the cabin is not shaded by any structures. The air temperature affects to the amount of heat conducted out from the cabin and the energy consumption of the air handling units. Air conditioning has to cool the air to the same level to dry the incoming air not depending on the air temperature outside. The sea water temperature effects on the amount that hot potable water has to be heated. The sea water temperature also affects the efficiency of chillers producing cooling to the ship. When sea water warms from the Baltic waters +10 °C to Caribbean +28 °C coefficient of power for air conditioning chillers changes from 7.3 to 5.7 respectively (Meyer 2016). This means that chillers produce 20 % less cooling for the same input power. The variation for the energy needed in heating the water is 35 % of the maximum consumption. The energy usage of heating potable water is discussed in more detail in Chapter 3.3 with Formula 6 and its description.

3.3 Calculation

Calculations are done assuming steady state conditions in the cabin. Each consumer and consumption is factored in using the user profiles. Climate data and sun's trajectory are considered in the calculations as well as ships position in relation to the sun. After consumption of electricity, climate data and presence of occupants is known, the consumption of the cabin fan coil unit can be calculated. Consumption of potable water and energy to heat the water up is considered as well. Calculations are done by using Microsoft Excel spreadsheet covering one day in 15 minute intervals. Sample day starts at midnight and continues for 24 h. One sample day is calculated for every month in every region. Sample day is 15th for months with 30 days and 16th for months with

31 days. This is done to achieve the middle of each month for the weather and the solar data to be as accurate as possible.

The trajectory information is from Hoffman (2017) and the solar radiation information is from Boxwell (2017). The solar radiation is chosen for south facing wall and east facing wall. The east facing wall has the same values as west facing wall. Shading from the balcony and its structures is calculated in three phases. Phases are described in Table 6. These steps are mapped from the trajectory information and the amount of solar radiation is reduced from the shaded hours. The last step is 90 % because ship sails in highly reflective environment and some reflected radiation would make it to the cabin even if the cabin were shaded from the sun.

Table 6 Shading of the balcony door.

The sun's altitude angle [°]	Shading of the balcony door [%]
0.0 - 26.1	0
26.1 - 39.8	30
39.8 - 48.4	60
48.4 -	90

After the solar load to the cabin has been calculated the load is reduced by the windows g-value. The g-value indicates how much of the solar radiation hitting the window penetrates the window glass and effectively heats the room. When the solar load is calculated into the final load heating the cabin, other heat loads such as the people in the cabin and electrical devices are added to the solar load to from the total heat load. Then cooling heat loads are subtracted from the total and resulting load is divided linearly from the sunrise to the sunset peaking at midday.

Conductivity of the balcony door is calculated as follows:

$$Q_{cond} = UA(T_o - T_i) \tag{1}$$

In which		
	Q_{cond}	is the heat load conducted out through the cabin balcony door [W]
	U	is the U-value of the window [W/m²K]
	A	is the area of the balcony door [m²]
	T_o	is the outside air temperature [°C]
	T_i	is the inside air temperature [°C]

Cooling power of the ventilation to the cabin is calculated as follows:

$$Q_{vent} = \dot{V}\rho c_p(T_s - T_i) \tag{2}$$

In which		
	Q_{vent}	is the heat load of the ventilation [kW]
	$\dot{V}$	is the air flow from the ventilation system to the cabin [m³/s]
	ρ	is the density of the air [kg/m³]
	c_p	is the specific heat of air [kJ/kgK]
	T_s	is the temperature of the supply air entering the cabin [°C]
	T_i	is the inside air temperature [°C]

Value used for ρ is 1.2 kg/m³ and c_p is 1.005 kJ/kgK. (Engineering ToolBox 2017).

Heat load of the cabin is calculated as follows:

$$Q_{tot} = Q_{sun} + Q_{people} + Q_{elec} + Q_{vent} + Q_{cond} \tag{3}$$

In which		
	Q_{tot}	is the total heat load to the cabin during each moment [W]
	Q_{sun}	is the heat load from the sun after the window [W]
	Q_{people}	is the heat load from the people in the cabin [W]
	Q_{elec}	is the heat load from the electrical devices in the cabin [W]
	Q_{vent}	is the heat load from ventilation [W]
	Q_{cond}	is the heat load conducted out through the cabin balcony door [W]

Normally Q_{vent} and Q_{cond} reduce the temperature in the cabin, hence be negative, but in hot climate such as in the Caribbean Q_{cond} can heat the cabin, as outer air is hotter than the air inside the cabin. If the Q_{tot} is negative cabin needs to be heated by the fan coil unit and if Q_{tot} is positive cabin needs to be cooled down by the fan coil unit. The fan coil fan is operated in relation to the heating or cooling power of the fan coil. Q_{elec}, Q_{peop} and Q_{sun} are specified in Chapters 4.2, 4.4 and 5.7 respectably.

Power used by the cabin fan coil unit fan is calculated as follows:

$$\frac{P_{fan}}{P_{fanmax}} = \frac{P}{P_{max}} \tag{4}$$

In which		
	P_{fan}	is the electrical power that the fan operates on [W]
	P_{fanmax}	is the maximum electrical power of the fan [W]
	P	is the heating or cooling power used in the fan coil unit [W]
	P_{max}	is the maximum heating or cooling power of the fan coil unit [W]

The energy usage of the cabin fan coil unit's fan is calculated through the power the unit runs on as the energy usage is in relation to the heating/cooling power instead of heating/cooling energy. This is because to deliver small power the fan does not need to run faster than the minimum speed. The water flow in the cooling coil of the fan coil unit is kept constant so only the water flow is adjusted to control the cooling power.

For the water system is assumed that the WC uses only cold water and washbasin as well as shower use 41 °C water. This is a temperature of average shower according to Orbital Systems (2016).

Need for hot potable water in relation to cold potable water to reach desired 41 °C temperature is calculated as follows:

$$xT_h + (1 - x)T_c = T_T \tag{5}$$

From which can be solved:

$$x = \frac{T_T - T_c}{T_h - T_c} \tag{6}$$

In which	x	is the portion of hot potable water [-]
	T_h	is the temperature of hot potable water [°C]
	T_c	is the temperature of cold potable water [°C]
	T_T	is the target temperature for used water [°C]

Hot potable water is always kept at 60 °C. If the water is too cold, there is a risk for pathogens to breed in the water. If the water is too hot, there is a risk of burn injuries in the cabin. Cold potable water is the same temperature as the sea water is because the water is either produced from the sea water or stored in such temperature (below the waterline of the ship) that the water reaches the same temperature as the sea water.

Energy needed to heat the hot potable water is calculated as follows:

$$Q_{heating} = \dot{V}\rho c_p(T_e - T_r) \tag{7}$$

In which	$Q_{heating}$	is the heating power needed for the water [kW]
	$\dot{V}$	is the water flow to the cabin appliance [m^3/s]
	ρ	is the density of the water [kg/m^3]
	c_p	is the specific heat of water [kJ/kgK]
	T_e	is the temperature of the water entering the cabin [°C]
	T_r	is the temperature of the raw water [°C]

Value used for ρ is 1 kg/m^3 and c_p is 4.18 kJ/kgK. (Engineering ToolBox 2017).

Efficiency of the Ensavetec heat recovery system is calculated as follows:

$$Q_{rec} = ((xT_h + (1-x)T_r - T_r)\dot{V}_{sh} + (xT_h + (1-x)T_r - T_r)\dot{V}_{wb})\eta c_p \tag{8}$$

In which	Q_{rec}	is the heating energy collected from the water flow [kW]
	x	is the portion of hot potable water [-]
	T_h	is the temperature of hot potable water [°C]
	T_r	is the temperature of the raw water [°C]
	$\dot{V}_{sh}$	is the volume flow of the shower [l/s]
	$\dot{V}_{wb}$	is the volume flow of the washbasin [l/s]
	η	is the efficiency of the heat recovery system [-]
	c_p	is the specific heat of water [kJ/kgK]

From the calculated values, stacked graphs are drawn and they are used to compare results. Calculations are done using both measured values and design values of passenger cabins, as there was no possibility to arrange measuring of all the actual values. Some of the values are from equipment manufacturers brochures. The TV's consumption is corrected to values presented in its energy certificate.

4 Technical systems of a ship

4.1 Water production and delivery

Cabins water usage consumes energy in numerous ways. Heating the hot water requires most of the energy. Generating the potable water from the seawater using reverse osmosis and pumping water from tanks below waterline to the cabins on the higher decks requires lots of energy as well.

Ships water system consists of multiple different waters. Fresh water, seawater and waste water are divided into sub categories depending on the salt content, dirtiness and the place they are used in. Cabins use only cold and hot potable water, which is fresh water for food and sanitation use. When potable water is used in the cabin the potable water becomes grey or black water. Black water is water flushed down the toilet i.e. water contaminated with urine or feces. Other waste water is grey water that comes from the washbasin or from the shower. Air conditioning produces some condensate water in the cabin that is also led to the grey water system. Different waters and their names are presented in Table 7.

Table 7 Different water names and usages.

Name	**Use**
Potable water	Fresh drinking and sanitation water.
Condensed water	Fresh water condensed in air conditioning.
Technical water	Fresh water used to generate steam and used in other non-drinking or sanitation uses.
Grey water	Shower and washbasin waste water.
Black water	Waste water from toilets.
Raw water	Sea or lake water that has not been processed on the ship.

Potable water is made onboard or bunkered from land (Royal Caribbean Cruises Ltd. 2016). Preferred option is to make water onboard because water can be made when excessive electricity is available (Honka 2016). Making water onboard eliminates the need to test bunkered water for contaminants. While testing is not needed therefore no dead weight needs to be carried as water is used straight away. The tests take a few days to complete and otherwise water would need to wait in the tanks for the time the tests take to complete. When all necessary water is made onboard, water storage can be kept to the minimum set by standards. Another advantage in making water onboard is the reduced risk of microbes or other pathogens getting into the ship's drinking water system. These risks vary depending on the method used but in any case, the risk is smaller than in bunkering water from the shore.

Water can be made using two different systems. The older one of them is by using evaporators that use engines hot cooling water and under pressurization to boil sea water and distil the sea water into drinking water (Royal Caribbean Cruises Ltd. 2016). The hot cooling water is not mixed with sea water as the cooling water may be contaminated with oil or similar impurities from the engine. Instead the hot cooling water heats the vessel that sea water is in and thus creates fresh water. This method does not kill pathogens because of low temperature of the cooling water (70 ˚C) and therefore requires disinfection afterwards (Räisänen 2000). Disinfection of potable water produced with evaporators does not add to energy consumption because of USPH (United States Public Health) regulations require the potable water to always be chlorinated before use.

The newer method is to use reverse osmosis in which sea water is pushed through a semi-permeable membrane to produce fresh water (Royal Caribbean Cruises Ltd. 2016). Holes in the membrane are so small that they stop salt and other impurities from transferring to the clean side of the membrane. Osmotic pressure of sea water is about 25 bar and the pressure needed to reverse osmosis process is around 50 bar (Räisänen 2000). Because of the high pressure, reverse osmosis requires electric power to run pumps providing the required pressure. Energy needed in evaporators is 60 - 70 kWh/m³ depending on the sea water temperature and in reverse osmosis unit only 3.5 kWh/m³ (Meyer 2016). Difference between the used energies is that evaporator uses heat from the engines, which is waste energy, and reverse osmosis requires electrical energy that needs to be generated. On the other hand the waste heat could be utilized for example to the heating of hot potable water or other uses such as producing electricity in exhaust gas boiler.

After the potable water has been generated the water is lead to the potable water tank. Water is analyzed and chlorinated or de-chlorinated after the tank to meet chlorine levels required by USPH. From the tank water is lead to the hydroforic pumps that provide the pressure to the water delivery system. After the hydroforic pump cold water is mineralized to add flavor and minerals to plain distilled water.

Heating of the potable water is done by one of the following ways: using engines hot cooling water, using steam from exhaust gas boiler or using electrical heating element (Meyer 2016). Methods are listed in preferred order. In normal situation, engines hot cooling water is used for evaporators generating technical water and thus heating of potable water is done with steam from the exhaust gas boiler. Depending on the need of steam in other uses such as laundry, hot water can be heated with electricity. (Honka 2016; Mäki-Jouppila 2016)

In the cabin, only shut off valves control the water flow before the faucets. Currently the energy saving methods in use are low-flow showerheads and faucet aerators (Royal Caribbean Cruises Ltd. 2016). The target is to reduce water consumption especially in the shower. Reducing the water flow is an effective way to reduce energy used, but passenger satisfaction will decrease if water flow in shower is reduced too much. Recommended water flow in shower is 12 l/min (Motiva 2012) and shower on a ship runs on as little as 5 l/min (Mäki-Jouppila 2016). This is really low considering that water saving faucet on land runs with 7-8 l/min (Oras 2014).

After leaving the cabin black water is sucked by vacuum system into holding tanks before leading into bioreactor for processing. Grey water is collected gravitationally to pumping stations that deliver the grey water to holding tanks. From the holding tanks, grey water is delivered to the bioreactor to water down the black water. Some other waste flows are lead to the reactor as well. These flows originate from the galley or from the laundry.

In the bioreactor, solids are separated from the flow in two main stages. The first stage is screening larger parts such as plastic, hairs and paper in the pre-treatment module. After pre-treatment, waste water is processed in the biological module to separate organic content. The second stage of solid separation is floating bio-residue to the surface of the fluid in flotation module. Floated sludge is then scraped of the surface and dried from excess water. Remaining suspended solids are removed with a filter in polishing module. Finally, UV (Ultra Violet) lamps in UV module disinfect the waste water before being lead back to sea. Separated solids are bagged and incinerated onboard. Bioreactor process is described in Figure 7.

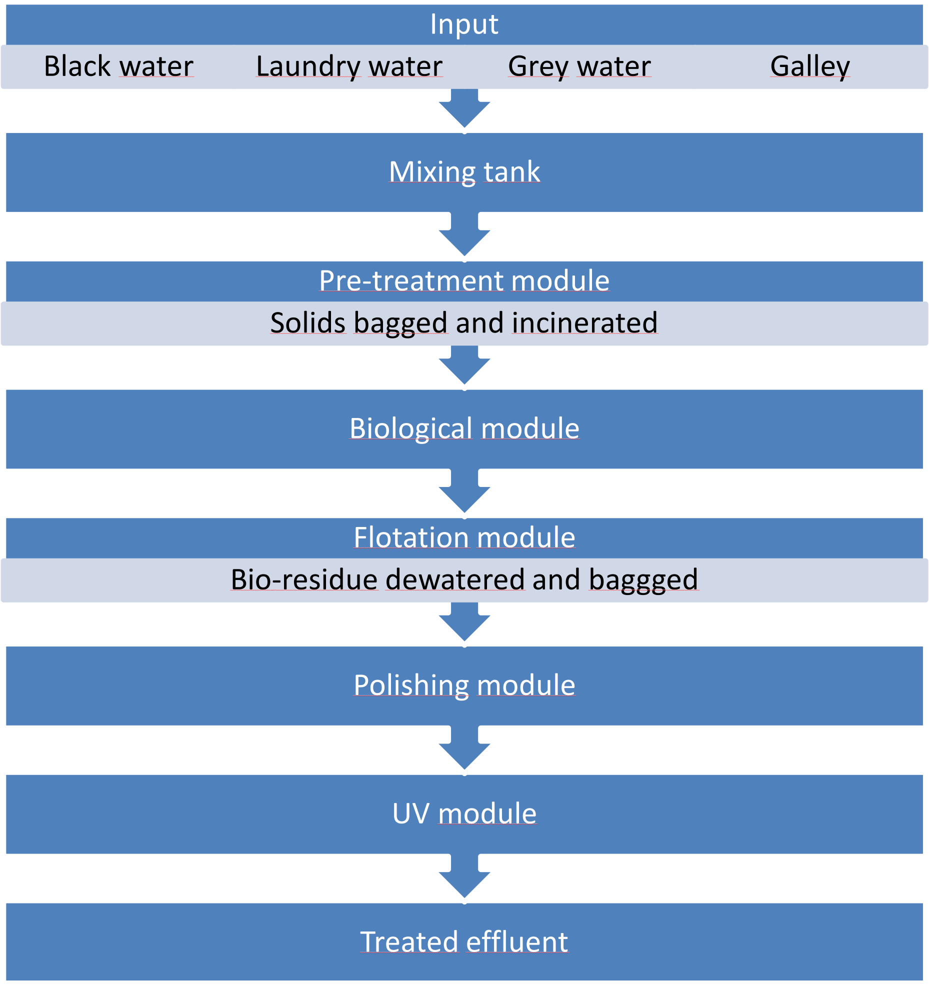


Figure 7 Waste water treatment process.

4.2 Cabin lighting

Electricity is used in lighting and appliances in cabin. Lighting is presently done using compact fluorescent lamps and some single LEDs such as reading lights or LED ribbon around the bathroom mirror. Normal cruise ship cabin has installed lighting power of 106 W, which is divided into luminaires according to Table 8. All other lighting is connected to ship's main electricity network except emergency lighting that draws its power from battery back-upped emergency network (Lehdonvirta 2016). Main lighting in the cabin comes from downlights installed to the cabin ceiling. Other lights are installed to the walls except the balcony light.

Table 8 Cabin luminaires electrical powers and their placement (Meyer 2016).

Amount [pcs]	Power [W]	Use	Type
4	13	General lighting	Fluorescent
1	4	Spotlight	LED
1	13	Wall light	Fluorescent
1	20	Mirror light	LED-ribbon
1	10	Balcony light	LED
2	2	Bed light	LED
1	1,5	Emergency light	LED
1	1,5	Night light for the WC	LED
Total			
12	106		

To serve the cabin lighting, electrical appliances and the cabin fan coil unit ships have a 110 V, 60 Hz or 220 V, 50 Hz networks in the cabins. Electricity network has multiple different voltage levels for achieving best possible efficiency in transferring electrical power, but only low voltages are delivered to the cabin. Different voltage levels are presented more detailed in Chapter 5.5.

Fuses in the reference ship cabins are 10 A for lighting, 16 A for electrical outlets and 16 A for fan coil unit. Two adjacent cabins divide each of these fuses because it is assumed that the peak loads will not occur at the same time. For some applications, there is more than enough headroom. For example, the lighting fuse has maximum load of 212 W and the fuse is capable to handle 2 200 W. Fuses and their maximum loads are presented in Table 9. The electrical load connected to electrical outlets is unknown and therefore not marked in the table. Passengers can bring their own appliances and thus the load can be anything. If a hairdryer and a coffee machine are installed in a cabin it is possible to blow the fuse. This requires both cabins to use all four appliances at the same time, which is not likely.

Table 9 Electrical load connected to each fuse and their maximum loads (Meyer 2016).

Fuse name	Electrical load [W]	Fuse can maintain [W]
Lighting	212	2 200
Fan coil unit	1 800	3 520
Electrical outlets	N/A	3 520

4.3 Electric appliances

Appliances in the cabin vary from ship to ship and they may be some of the following: coffee machine, fridge or cooler, hair drier and TV. TV and fridge are excluded from cabins master electricity switch because sudden power off can harm the devices. Fuses and other electrical components are located in maintenance space in the corner of the cabin module. The space is common for two cabins next to each other (Lehdonvirta 2016).

Requirements for the cabin equipment vary depending on the operating area. Normally in Europe, cabins have lower equipment level than in the United States market area. Devices selected to cabins are average on their energy consumption and their nominal electrical powers are presented in Table 10 (Lehdonvirta 2016). Power for the appliances is delivered to electrical sockets around the cabin.

Table 10 Electric appliances installed in the cabin and their powers (Lehdonvirta 2016).

Appliance	**Power [W]**
Coffee machine	1 000
Fridge	100
Hair drier, two power settings	1200 / 600
TV 40”	80

4.4 Cabin heating, ventilation and air-conditioning

As told in Chapter 2.3 of this thesis, ventilation is divided into service areas according to the fire zones to prevent fire and smoke spreading to the whole ship in case of a fire. Cabins in one fire zone are further divided into two groups. The sides and the middle of the ship are served by their own air handling units. This way the effect of the solar radiation heating the cabins can be handled easily. The middle of the ship requires its own air handling unit to provide slightly warmer air than on the outsides as the sun does not heat the middle cabins. This can be handled also by splitting reheating into two zones that are heated accordingly. Similar spaces are allocated to each air handling unit. Units that serve cabins normally deliver air only to cabins and cabin corridors. Other similar group of spaces is for example the restaurants. (Oinas 2007)

Figure 8 Picture of an air handling unit (Meyer 2016).

Mein Schiffs have 50 different air handling units onboard. Of these, 15 units serve the cabins typical cabin serving unit is presented in Figure 8. Each air handling unit serves 90 cabins and their corridors or similar area. 90 cabins are 1 400 m^2 in area and they are situated on three decks along one fire zone. The supply side of an air handling unit consist of a closing damper, a filter, an enthalpy recovery wheel, a supply fan, a preheating/-cooling coil, a droplet eliminator and reheating coil. Exhaust side consist of a filter, an enthalpy wheel, a fan and a closing damper. Of these components only the enthalpy wheel, the fans, cooling- and heating elements require energy and thus energy savings can be achieved by needing less air, resulting in lesser fan usage and need for heating, or lesser need to cool/heat incoming air. Air handling units' fan requires 15 - 19 kW of electrical power and provides respectively air flow of 3.9 – 4.4 m³/s. This yields specific fan power of 3.8 – 4.3 kW / m³/s. Pressure loss for the air handling units is 740 - 1140 Pa. Air volume to the cabins is kept constant. Air handling units are located in air-conditioning rooms that are situated in multiple deck high air conditioning rooms on the midline of the ship. (Meyer 2016)

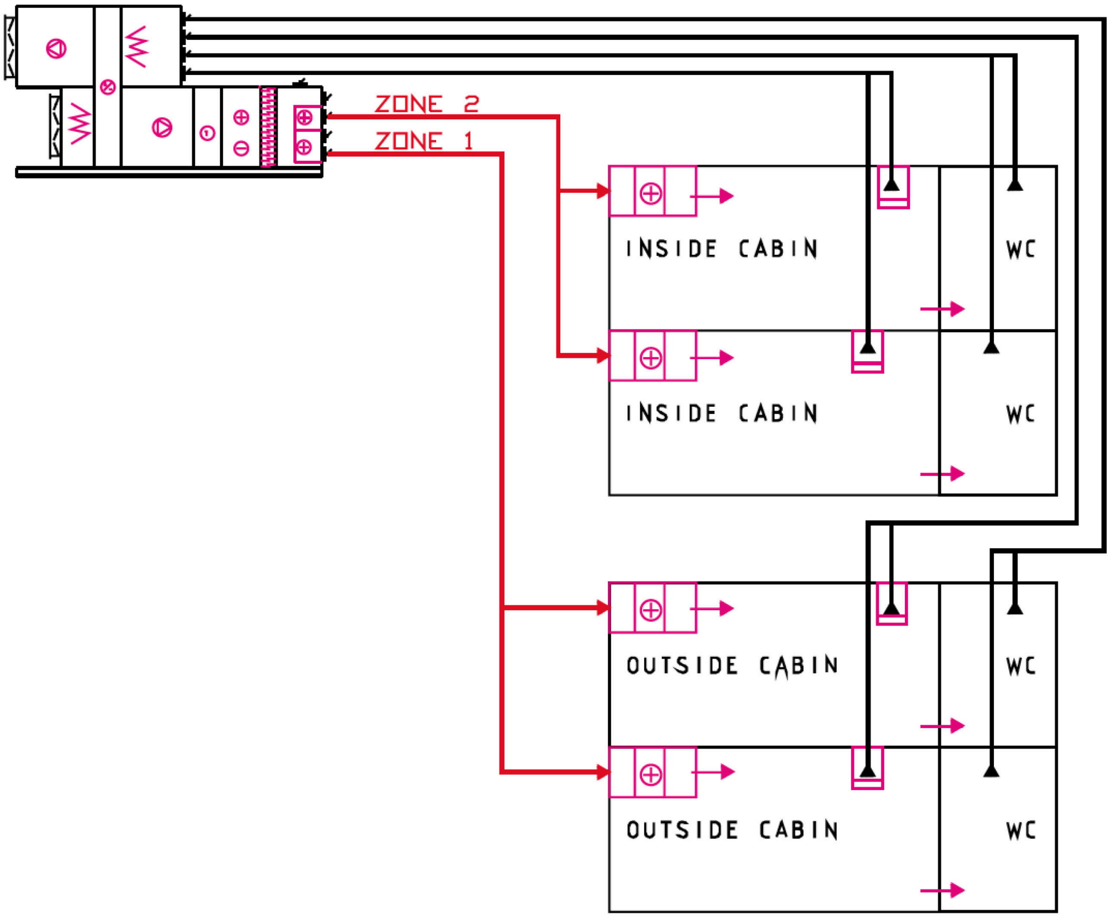


Figure 9 Structure and working principle of the ventilation system (Meyer 2016).

Working principle of the ventilation system is presented in Figure 9. Depending on the temperature of the outside air the air sucked to the air handling system is heated or cooled. Air comes through the filter into the air handling unit. Afterwards the air is cooled down or heated up by enthalpy wheel, cooled or heated further by combined cooling and heating coil to dry the air, pushed into the network by the fan and reheated if needed. In the ducts air flows through sound attenuators to reduce noise and dampers to balance out the network. In the cabin, air flows through a fan coil unit in which the air is heated or cooled down depending on the need and then lead into the cabin. Extraction of the air is done from the toilet of the cabin.

Heating, ventilation and cooling are integrated into cabin units in same maintenance space as the electrical components. Incoming air is processed with a larger air handling unit, which cools incoming air to 12 – 14 ˚C. This air is the either lead directly to the cabin or mixed with circulated cabin air to achieve desired temperature. Temperature is controlled by passengers via thermostat in temperature range of 20 – 23 ˚C and accuracy of the fan coil control is ± 0.5 °C. The same master switch that controls the lights operates as presence sensor for the ventilation. When the cabin is unoccupied, the cabin temperature can vary slightly more, ± 3 °C from set temperature. Regulation diagram of the fan coil unit is presented in Figure 10. Exhaust air is sucked from the cabin bathroom through ductwork to air handling unit and blown out from there. Heat is transferred between supply and exhaust air at air handling unit with enthalpy recovery wheel. Enthalpy recovery wheel transfers heat to cooler flow thus enhancing heating/cooling efficiency of air handling unit. (Kirjavainen 2016)

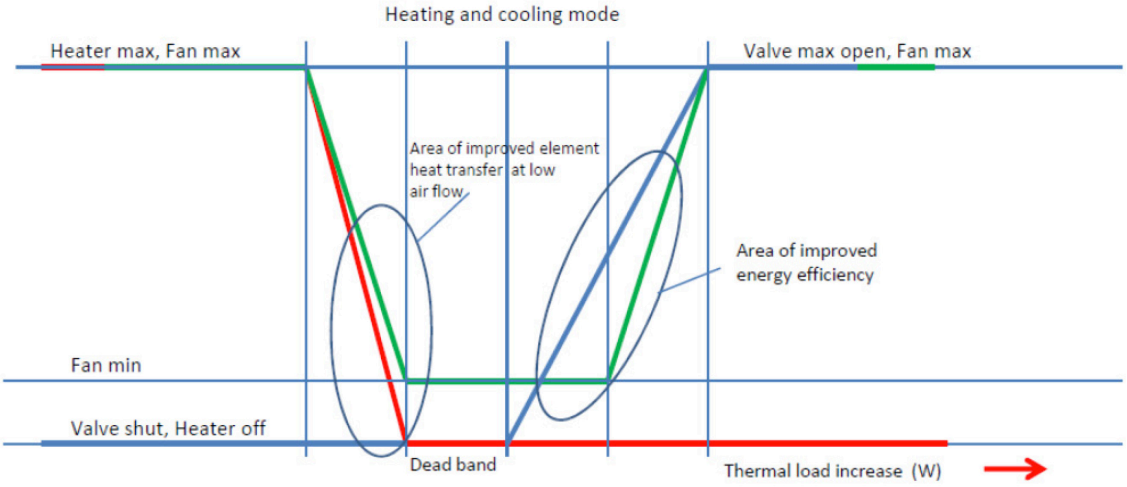


Figure 10 Regulation diagram of the cabin fan coil unit. © Halton (Meyer 2016).

The fan coil is used to maintain desired temperature in the cabin. When the temperature sensor in the cabin detects an anomaly in the temperature the fan coil unit starts to suck air from the cabin and then heats or cools the air to meet the temperature set to the cabin thermostat. Heating is done using an electric element in the heat exchanger of the fan coil unit. Cooling is done in the same exchanger using cooling water. Fan coil also dries the air circulating through the fan coil. Circulated air is mixed to fresh air coming from air handling unit. The fan coil control unit can adjust fan coil power by varying the running speed of the fan or by adjusting on - off -ratio of the heating element or the cooling coil. Structure of the fan coil unit is presented in Figure 11.

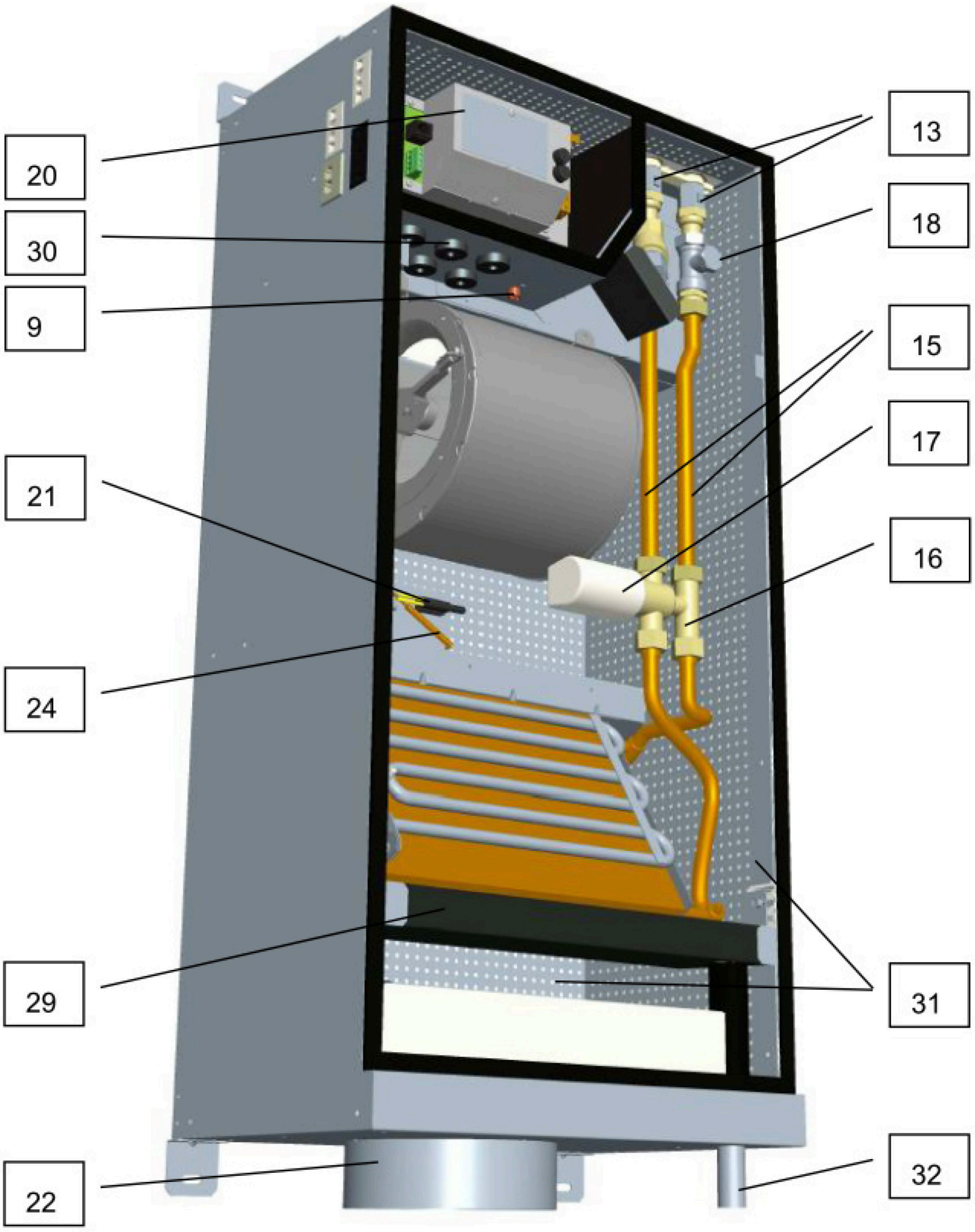


Figure 11 The structure of cabin fan coil unit. © Halton (Meyer 2016).

In the Figure 11 is presented how the air from the cabin enters from the bottom (22) of the fan coil unit and air from the air handling unit enters from top right corner. Air exits through the fan, which is the grey part in the middle below line (9). Heating and cooling coils are between lines (24) and (29). Line (29) is connected to the drip pan that collects the condensation droplets of the cooling coil.

Energy consumed to air handling in the cabin is due to fan coil fan, heating coil and cooling coil. Installed powers of the fan coil devices are presented in Table 11. Specific fan power of the fan coil unit is 1 W / l/s. To reduce energy consumption, air flow or its processing has to be reduced. This cannot be done maximally, because on a cruise there are always empty cabins that are serviced by air handling units although they do not require heating, cooling or air supply. Air flow to the empty cabins is not stopped despite they are unoccupied, because there is no equipment in the ductwork for this and air delivering system is balanced to run air into every cabin (Oinas 2007). To reduce energy consumption the cabin fan coil is dialed down meaning heating and cooling are reduced at the fan coil.

Table 11 Energy consumption in fan coil devices.

Device	Power [W]	Type of energy used
Heating element	800	electricity
Cooling coil	1 200	cooling water
Fan	100	electricity

Required electric reheating power for the fan coil is between 390 - 560 W depending on the deck where the cabin is situated. Highest consumption is on the top decks that lose heat through the ceiling and lowest in the normal cabins in the middle of the side of the ship. The heating need originates at the air being too cool when entering the cabin fan coil unit. In the design phase it is assumed, that two persons occupy the cabin and that all the electronic devices and lights are on. This leads to the air coming from the air handling unit being too cold if heat loads are smaller than calculated and thus the supply air has to be heated at the fan coil. The sun has also a great effect to the cabins heat balance, but normally the solar load causes need to cool the cabin. Heat loads and their magnitudes are presented in Table 12.

Table 12 Heat loads in the cabin (Seppänen 1996; Meyer 2016).

Heat source	Power [W]
People	85 – 125 each
Lighting	0 – 110
TV	0 – 80
Solar heat load (window area 3.4 m^2)	0 – 450
Electrical appliances	0 – 4 000

Heat from the people varies depending on their activity. Heat produced by different humans does not vary in relation to gender, size or individual. Sensitivity to draft and temperature preferred do vary and cause preferring of one temperature to another. Clothing insulates humans from the air in the cabin. Different clothing has different insulating properties that are described in unit called clo. In SI-units 1 clo is 0.155 m^2K/W this is the amount of insulation needed by average person in 21 °C temperature and 0.1 m/s air movement. Generally, women's clothing has lower clo rating than men's and that is why men are considered to withstand cold better (Seppänen 1996). Different ratings for clothing are presented in Table 13. Difference in insulation of clothing causes dissatisfaction in people while temperatures cannot be held on a level that satisfies everyone. People in more insulating clothing feel that the room would need to be cooler when people in less insulating clothing feel the room temperature is comfortable.

Table 13 Insulation values for different clothing (Seppänen 1996).

Clothing	Insulation [clo]
Naked	0
Thin dress	0.2
Skirt, blouse and pullover	0.8
Pants and shirt	0.4
Suit	1.0 – 1.2

4.5 Cabin windows and balcony doors

The windows are triple glazed and the balcony doors double glazed. Between the layers of glass is air. Properties of the cabin windows and the balcony doors are presented in Table 14. Size of the average balcony door is 1 750 mm wide and 1 955 mm high and average window is 1 100 mm wide and 1 200 mm high. On comparison, maximum U-value for windows in the new buildings in Finland is 1.0 and for zero energy houses 0.9 (Ikkunawiki 2016). Major difference in ship windows and glasses compared to their counterparts on dry land is that ship glasses have only air layered between them. On dry land argon, krypton or other inert gasses are used for better insulation, but on ships it is difficult to maintain gas tightness of the window frame due to vibration and therefore only air is used. (Pilkington 2014; Meyer 2016)

Table 14 Properties of the cabin window and the balcony door (Meyer 2016).

	Window	Balcony door
Area [m²]	1.32	3.42
U-value	1.0	1.4
g-value [%]	41	78
Glass structure [mm]	25 + 25 + 6	10 + 6

Most of the outside cabins have balconies in them. Some lower deck outside cabins do not have balconies and therefore they have only windows. Reason for this is because they are situated below lifeboat deck and lifeboats cannot be lowered over balconies due to performance requirements when ship is listed. Windows are well selected and their insulation values are in line with for example the Finnish building regulations part D3, which states the U-value should be below 1.8 (Finnish Ministry of the Environment 2012). Also, the other values of the windows such as the g-value that measures the heat reflectivity of the window are on the same level as similar sun protection windows. G-value tells how much of the solar radiation hitting the window penetrates it.

Balcony doors on the other hand are poorly insulated and being quite large better insulation would mean a lot for the cabin's energy balance. Effects of the cabin door properties are presented in Chapter 7 of this thesis. Because the balcony doors are so large, their weight is considerable, and therefore insulation and weight have to be optimized accordingly. Now the construction of the cabin window is two 25 mm thick layers and one 6 mm layer. The balcony doors are 10 mm and 6 mm layers. If the balcony door should achieve the same performance values its weight would be 3.5 times its current weight. This is calculated only in relation to the thickness of the glass. In reality the surrounding structure, slide tracks, framework etc. would need to be enhanced resulting in larger weight gain. As reference ships do not operate in freezing conditions their windows and doors are selected prioritizing low weight instead of insulation. In addition, the balcony structure is quite well shading as the balcony is two meters deep and creates a tunnel for the light to travel trough.

5 Novel technologies

5.1 Water usage

Shower water recycling and heat recovery from the waste water are technologies studied, that save energy from the cabins total energy usage. They save energy by reducing the water usage or reducing the energy needed to heat the hot water. Water recycling is done by collecting the waste water from the shower into a small container and purifying the collected water for reuse in the shower. Some new water is required to refresh the water and to lead contaminants out of the shower cycle. Utilizing the water recycle system also adds to passenger comfort because water flow in the shower does not have to be restricted. Because water is collected into a container the water can be used for unlimited cycles through the system without greatly increasing the water consumption. Electricity is used to reheat the water to the desired temperature and to pump the water from the container to the shower head (Orbital Systems 2016). Recycling can also be done without reheating, but then the water consumption is slightly greater (Upfall 2016).

Not only does the shower draw energy through the production of the used fresh water, but also heating of the water requires energy. Most of the heating is done with the waste heat of the engines by using the engines high temperature cooling fluid or steam from the exhaust gas boiler to heat the potable water (Mäki-Jouppila 2016). Exact proportions for each method are not known. If there is not enough waste heat available to heat the water to the required temperature, the rest of the heating is done using electricity. The electric heating coil installed in the water boiler is the least preferred option to heat the water (Meyer 2016). Therefore, heating the water in the cabins using the shower water recycling system does not necessarily increase the total energy consumption.

Heat recovery in the cabin utilizes the waste heat from the grey water that enters the network and is used to heat the incoming cold fresh water. This system includes also a filter, a pump and heat exchangers. Grey water is ran through a heat exchanger that transfers heat from the waste water to the heat exchanger fluid that is pumped into another heat exchanger to heat the incoming cold water. If shower water recycling and heat recovery systems are both installed, filter and/or pump units can probably be integrated. Integration requires co-operation from the manufacturers.

Heat recovery can be done in the whole ship’s scale if recovery at the cabin level does not appear feasible. Then a heat exchanger is installed into the main grey water line at collection tanks. Heat recovery works on the same principle as in the cabins for added safety. To prevent fresh water contamination with grey water, a heat transfer fluid is used. The grey water first heats up heat transfer fluid in the exchanger and the transfer fluid heats cold water running through a coil in the fluid (Wasenco 2016).

Studied options in this thesis to reduce the water consumption of the cabin are two water recycling showers: Orbital Systems and Upfall. Other two solutions are heat recovery from waste water and solutions are from Ensavetec and Wasenco.

5.1.1 Water recycling shower, Orbital Systems

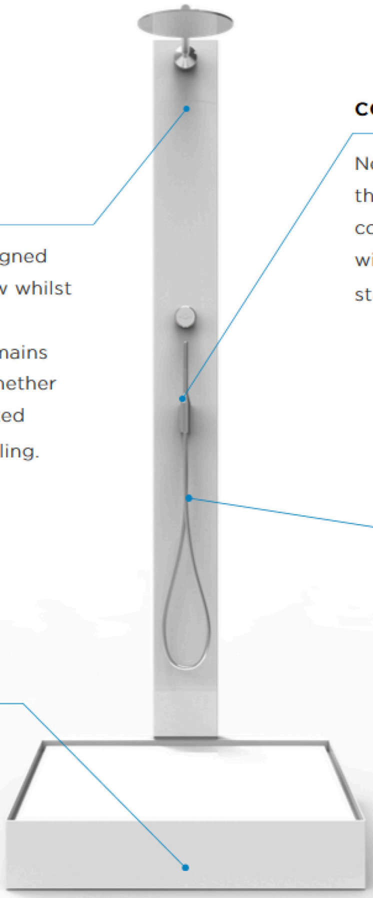
The Orbital Systems shower uses the least water of studied options. Orbital Systems claim that their shower can run on as little as 5 liters per shower. They add a disclaimer to that, saying that depending on the impurities gathering to water, shower may consume more water because the shower system flushes impurities to the sewer. For electricity consumption, Orbital Systems is not a good option as the shower uses electricity to heat the recycling water. Electrical load in the cabin is increased by 1.8 - 7.5 kW depending on the installation. 220 V single-phase installation runs typically on 1.8 kW and maximum of 2.2 kW and 400 V three-phase installation runs typically on 3.0 kW and maximally 7.5 kW. Most of the energy is used to heat the water and a marginal amount goes to pumping the water through the filters and up to the shower head. Idea of the heating is to keep the water in the system at the temperature set by the person in the shower. (Orbital Systems 2016.) Power of the circulating pump is not specified on Orbital Systems website, but because both shower systems are so similar the pump can be assumed to use the same amount of power as the Upfall shower pump. This means that the power of the pump is 400 - 500 W of electrical power (Upfall 2016).

Filtration in the Orbital Systems shower is in two stages that are filters called micro- and nano capsule. The micro capsule removes micron sized objects from the water and the nano capsule removes viruses, bacteria and most of toxins. Orbital Systems claim that their shower water is cleaner than in most conventional showers. On ships the shower does not make the water cleaner because the water is made with reverse osmosis that produces as pure water as the nano capsule (Meyer 2016). Service interval for the capsules is 10 000 - 30 000 l of water passing through the capsule for the micro capsule and 50 000 - 100 000 l of water for the nano capsule. This translates to showering hours by dividing the service interval with the water flow in the shower that is 40 l/min. Results are that the micro filter last for 4.2 - 12.5 h of shower use and nano filter last for 13.9 – 41.7 hours. According to Orbital Systems this would mean approximately one year of use in a regular family. Capsules are not re-useable, but they can be changed without tools and the need to change them can be observed without entering the cabin. The shower system observes the condition of the filters and informs user with LED-lights to change the filter or remotely using a smart phone app. (Orbital Systems 2016.)

In case of a blackout the shower can be used as a traditional shower. Then water is not recycled and the water flows directly through the system. The shower unit can be retrofitted in a cabin panel installation, installed integrated into the cabin WC or as a shower cabin depending on the design solutions needed. Different options are presented in Figure 12. The shower unit has the option to select between a hand shower and a large shower head. The structure of the shower unit is presented in Figure 13. Water is not contained in the system between showers, after two minutes the water is released from the system. (Orbital Systems 2016.)

PANEL FLOOR CABIN

Figure 12 Different Orbital Systems shower installation options (Orbital Systems 2016).



HEAD SHOWER

An all new shower head designed to enhance pressure and flow whilst delicately reassuring the temperature. It's only job remains to rejuvenate and refresh, whether it's free-standing, or integrated within your shower cabin ceiling.

CONTROL WHEEL

Never has it been this easy to save the earth. Clockwise for hot, counter-clockwise for cold, and with the simple push you either start or stop.

HAND SHOWER

The hand shower continuously adapts to the high pressure and water flow, creating endless possibilities for your eco-luxury experience.

SHOWER BASE

Encased within a standard shower tray (90x90 cm) lies the heart of this revolutionary technology. Smaller than your staircase, it is all stored within 15 centimeters of endless possibilities.

Figure 13 The structure and components of the Orbital Systems shower (Orbital Systems 2016).

5.1.2 Water recycling shower, Upfall

The Upfall shower system is highly similar to the Orbital Systems shower, but there are two major differences. Water is not heated in the Upfall shower. As water cools down, new warm water is taken into the shower system and the desired temperature is maintained. Other difference is that filtration is done with only a micro filter, and disinfection of the water is done with a UV-lamp. The structure and the size of the system are similar to the Orbital Systems shower. Service interval of the filter is not specified, neither is the type of the filter and if the filter is washable or not. Similar lifespan is to be expected as on the Orbital Systems shower micro capsule meaning 10 000 - 30 000 l of water.

The Upfall shower uses 1.5 liters of water per minute. The size of the reservoir in the circulating system is not specified, but assumably the reservoir is the same size as in the Orbital Systems shower as the components and working principle is similar. The electrical consumption of the Upfall shower is, depending on the model, from 370 W to 500 W and is considerably less than in the Orbital Systems shower. The structure of Upfall system is presented in Figure 14. As the Orbital Systems shower Upfall shower can also be operated without electricity. Then the shower works as traditional shower. (Upfall 2016.)

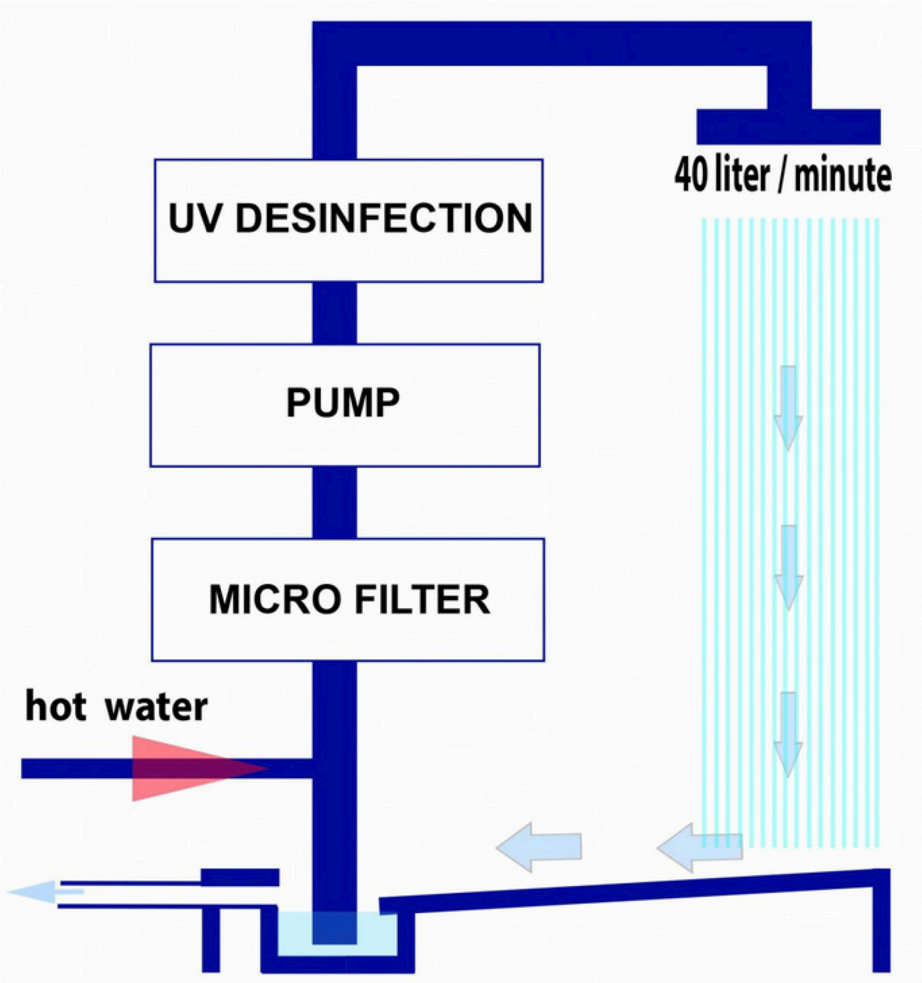


Figure 14 The working principle of the Upfall shower (Upfall 2016).

5.1.3 Heat recovery, Ensavetec

Ensavetec is a heat recovery system that collects heat from the used shower water. The Ensavetec system is installed in the shower basin and heat exchangers transfer heat from the waste water to the fresh cold water entering the shower. The system consists of a filter unit, a heat exchanger unit and a pump. First the water coming down the drain is filtered from hairs and other impurities that might block the heat exchanger and then the filtered water is lead to the heat exchanger unit where heat is transferred from the waste water to the cold water coming to the shower. The system is presented in Figure 15 and the working principle of the system in Figure 16.

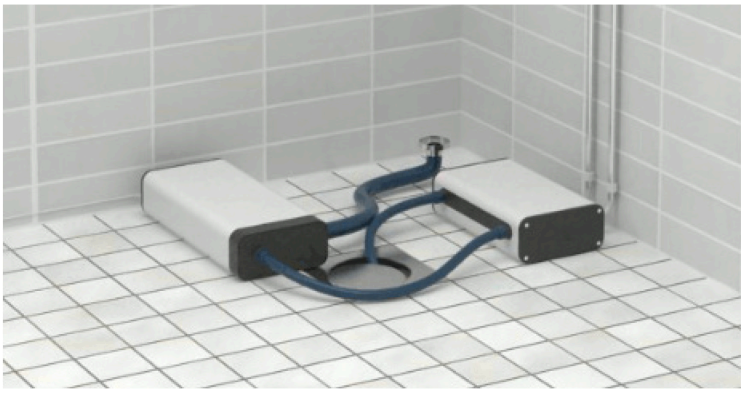


Figure 15 The Ensavetec system and the additional plumbing the system requires pictured without the shower basin (Ensavetec 2016).

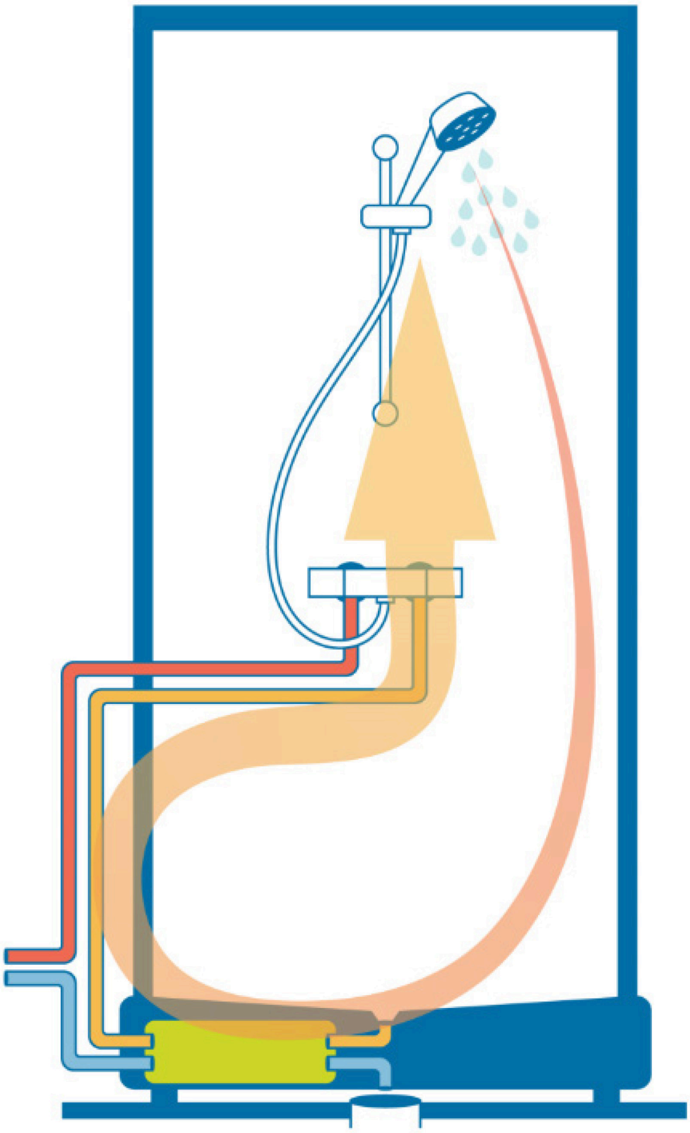


Figure 16 The working principle of the Ensavetec system. Notice that the water from the shower does not circulate back as the colors imply (Ensavetec 2016).

As opposed to the Orbital Systems and the Upfall systems the Ensavetec system requires some additional plumbing. The cold water coming to the shower has to be cycled through the heat exchanger in the shower basin to collect the recycled heat. After warming up, the water is lead to the tap and to the shower head. The additional plumbing is pictured in Figure 17.

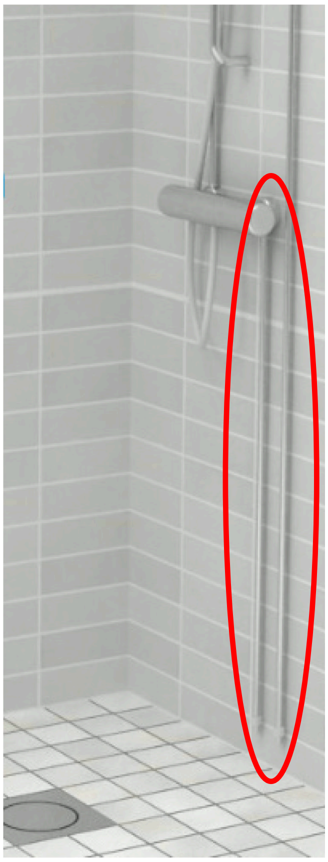


Figure 17 The additional plumbing required by the Ensavetec system. (Ensavetec 2016).

In the Ensavetec system up to 40 % of the energy in the shower waste water is recycled to the incoming cold water. The system is rated to 12 kW heat power and to the maximum water temperature of 65˚C. The system uses some energy to pump the water through the system, but the required electrical power is low voltage of 12 V and only 12 W. The heat exchanger causes some pressure drop into the water system, as water has to pass through it. According to the manufacturer the pressure drop would be 30 kPa when the water flow is 12 l/min, which is the normal flow rate for a normal shower. (Ensavetec 2016.) The service interval of the filter is not indicated on the manufacturer's website, but just stated to clean the filter when needed. Filter is washable so the filter can be changed when suitable not having to wait for the maximal lifespan of the filter. Similar lifespan is to be expected as on the Orbital Systems shower micro capsule meaning 10 000 - 30 000 l of water. When utilizing one of the recycling showers the lifespan of an Ensavetec filter will become quite long as the showers produce only 8 - 12.5 l of waste water during a 5 min shower. Traditional shower would produce the same amount in one minute.

5.1.4 Heat recovery, Wasenco

The heat recovery can also be done at the grey water holding tanks. The Wasenco system is a large heat exchanger with coils for heating and cooling flows and a heat transfer fluid in between to prevent contamination from the grey water to the potable water. The heat from the grey water is transferred to the hot potable water before the hot potable water is heated with primary means as described in Chapter 5.1. In other words, the Wasenco system works as a preheater for the system heating the potable water. The Wasenco system consists of a vessel that takes roughly 1 m^2 of room space and 2 m in height. No pumps are included in the system but instead the Wasenco system works with the existing hydroforic pumps. The system causes some pressure loss that should be compensated with a larger pump.

According to the manufacturer, the efficiency of the Wasenco heat exchanger is 30 - 70 % when used to heat the fresh water with the waste water. The Wasenco system does not require filtration or storage of the waste water. The system works on flow through principle and with almost any heat source. The Wasenco system has been used with process waters and steam condensate with great results (Wasenco 2016). The working principle of the Wasenco system is shown in Figure 18.

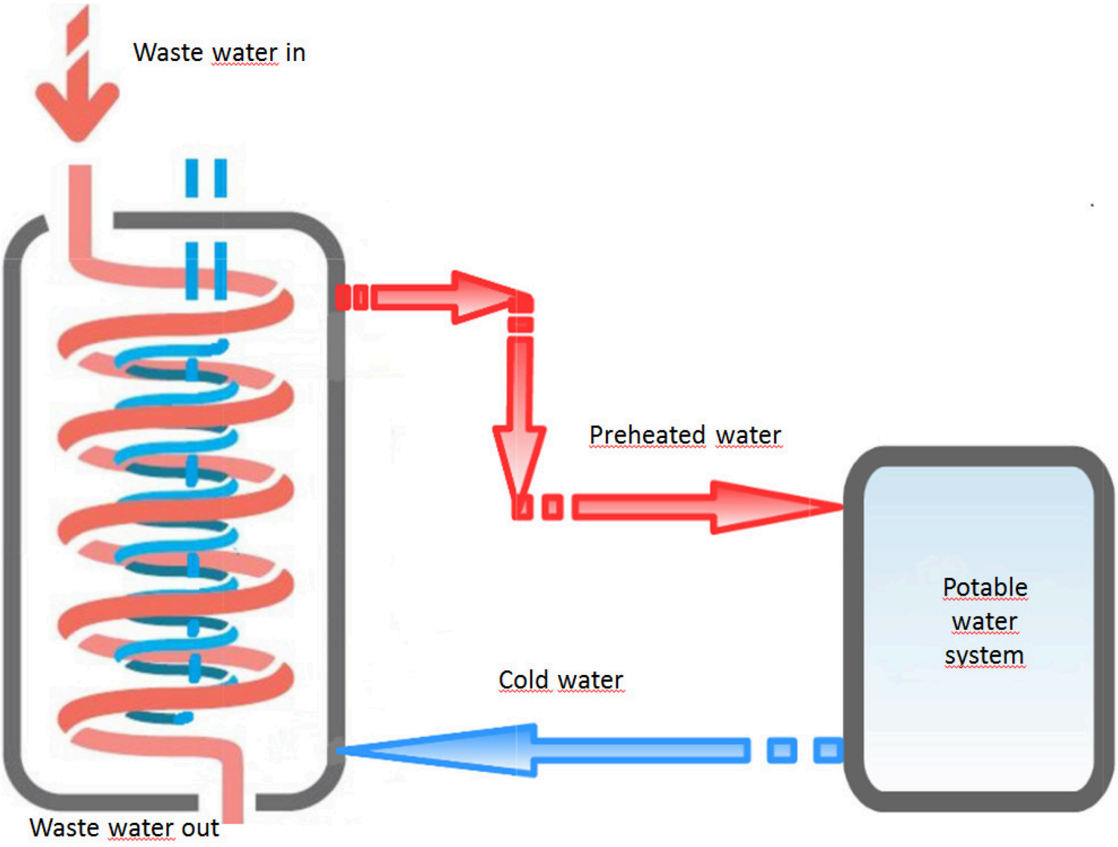


Figure 18 The working principle of the Wasenco heat exchanger system (Wasenco 2016).

5.2 Cabin lighting

5.2.1 Luminaires, LED

In lighting LEDs are the most efficient way to produce light. The difference in lumen per watt output is 20 - 40 lumens per watt compared to the compact fluorescent lights. This translates into electricity saving of 20 % meaning 20 W. Changing the illumination of the cabin to LED lights does not only save energy, but maintenance cost as well. The average lifetime of a compact fluorescent lamp is 6 000 - 20 000 hours compared to LED lamp’s 50 000 hours. (Halonen et. al. 2010)

Lifetime of LEDs is not calculated until the luminaire breaks down, but until the brightness of the light source has dimmed to a certain point. Such points are called

L-value and typical L-value set points are 70, 80 or 90 % of original brightness. LED’s keep on burning beyond these points, but their performance is dropping from the original design values.

Using LEDs instead of compact fluorescent lamps also reduces disturbances in the electricity network. Some components, mainly the ballast, cause RF (Radio Frequency) disturbances into the electricity network and these disturbances can interfere with speaker systems, computers or navigational equipment. Such interference is not normally a problem, but if the interference becomes a problem the origin of the problem is difficult to solve. (Pinho 2016a)

The largest problems in using LEDs are the color of the light they produce and the ability to reproduce colors. In the recent years, the white light produced by LEDs has become whiter and has a broader spectrum (Pinho 2016a). Because of the broader spectrum current LEDs have better color rendering than their predecessors.

Changing luminaires to LED based models gives new opportunities to architects and interior designers as large reflectors are no longer needed. LED luminaires can vary in shape and size to accommodate different needs in interior lighting. Depending on the luminaire selected replacing LEDs can also be challenging, but replacing is not a problem if the replacement is considered during planning of the cabin illumination.

Changing the cabin luminaires to LED’s causes also reduction to cabin’s heat load. Reduction is the difference between electrical powers of the original and new luminaire. In the case of reference ships, the difference would be 15 W for the whole cabin (Meyer 2016).

5.2.2 Solar lighting, collector

Daylight can be utilized in many ways. One method is to install collectors on sunny parts of a ship and run optical fibers down to cabins from the collectors. System is not the best possible for ships because of massive shading structures such as chimney, but the solar lighting can improve the feeling of passengers by bringing natural variation to the lighting.

Figure 19 Parans solar collector (Parans 2016).

One example of this kind of collectors is Parans solar collector that resembles radar antenna. Picture of the collector is presented in Figure 19. Collector has suspended collector head that is kept heading directly to the sun using motors to turn the head. The head unit consists of rows of lenses that are connected to optical fibers leading light to the spaces being illuminated by the solar collector. Different unit sizes and number of cables they can feed are listed in Table 15.

Table 15 Different Parans solar collector unit sizes (Parans 2016).

Head model	**SP4 – 4**	**SP4 – 6**	**SP4 – 8**	**SP4 – 12**	**SP4 – 20**
Width [mm]	1 100	1 100	1 950	1 950	1 950
Height [mm]	880	1 180	880	1 180	1 180
Weight [kg]	50	55	55	65	85
Number of cables	4	6	8	12	20

One cable can provide 900 - 1 300 lumens, which is 1.5 - 2 times the luminous flux of a 60 W incandescent lamp (Parans 2016; Airam 2016). Therefore, two cables would be sufficient to light up cabin without bathroom. Amount of the light would be sufficient to light the toilet as well, but connecting the luminaires would be too difficult thus the toilet requires third cable if desired to be illuminated as well.

Parans system has four different luminaires to distribute the light from the cables. Luminaires are in shape of traditional luminaire resembling skylight or spotlight. There is also a hybrid model that has 15 W of LEDs installed for the situations when not enough sunlight is available. Parans system does not transfer the solar heat to the cabins. (Parans 2016)

5.2.3 Solar lighting, light tunnel

Other ways to utilize daylight is to use a light tunnel to bring light from balcony to the back parts of cabin or to the toilet. Light tunnel (or light tube) is basically a mirror box that collects sun’s rays into a tunnel and reflects them forward through a tunnel.

Operating method is similar to optical fibers just instead of a fiber light travels in air and reflects from surfaces of the tunnel. The structure of a light tunnel is presented in Figure 20. The challenge in using light tunnels is that the cabin height is already at minimum so there is no room for structures in the ceiling. Small tunnel might be possible to install into the top corner of the cabin leading light to the bathroom. The collector of the light can be an issue, because to be efficient the collector head has to protrude from the side of the ship and aesthetically this is a problem. (Solatube 2015)

Figure 20 Structure of the light tunnel (Solatube 2015).

Light tunnels require a luminaire to reduce glare and disperse the light at the space being lighted. As solar collectors presented in Chapter 5.2.2 so do light tunnels have luminaires in shape of traditional luminaires and there is a hybrid model with LED lights in the luminaire to provide light when there is not enough sunlight. (Solatube 2015)

5.2.4 Improving cabin light distribution, prisms

An old way to bring light into ships interior is deck prisms. Deck prism is a piece of class cut to prismatic shape and installed in deck or side of a ship. The amount of light that the prisms reflect is small, but sufficient for moving around. Deck prisms could be used in cabins under the walking decks and another place to install them could be in the wall between cabin bathroom and cabin corridor. Savings could be achieved when move around –light would be provided from the corridor that is lit around the day. This installation has some aesthetical issues as the prism is practically a window from the toilet to the corridor, but placement and smeared class could solve this issue. Unfortunately, manufacturers for such a solution were not found. Savings from the prism system would be some watt-hours from electricity used in lighting. Structure of a deck prism is shown in Figure 21.

Figure 21 Deck prism's structure. Upper part is glass and lower brass or similar metal. Light enters from top and space below is illuminated (Davey 2016).

5.3 Electric appliances

Electrical appliances cause not only energy consumption but need for maximal power. These are different aspects to be optimized, as large powers do not cause large energy consumption if the time used is short. On the other hand, maximum powers, also known as peak loads, are most easily cut down by rhyming usage of the devices to lower the peak consumption.

TV is a necessity in a passenger cabin and the bigger the TV the better for the passengers (Meyer 2016). Energy consumption differences between various resolutions and screen technologies make a difference of 20 to 40 W; in percentages the difference is around 25% while maintaining same screen size of 43”. (Samsung 2016) Selecting an energy efficient model is an easy way to reduce electricity being used as TV is casually left on when nobody is watching.

Hair drier and coffee machine can make even larger difference. Proper sizing to 1200/600 W for hair drier instead of more powerful model and for coffeemaker 1400 W versus 2000 W accounts for a significant saving as well. Of course, these appliances are not used as much as TV and therefore their effect is not so large.

5.4 Fridge

Fridge is not installed in every cabin, but in so many cabins that the fridge will be discussed in this thesis. Nowadays fridges installed are electrical and drain around 1 - 1.5 kWh a day. Fridges can be connected to ships AC chilling water network so that electricity usage can be eliminated from cabin. Temperature control can be a way to decrease consumption as well because fridge does not need to be grocery compatible, just cold enough to cool drinks.

Current fridges have COP (Coefficient Of Power) of 0.6 - 1.2 based on their operating method which is absorption cooling (Koljonen & Sipilä 1998; Dometic 2016). Alternative method of using chilling water network chillers to produce the cooling has COP of 5.7 - 7.3 (Meyer 2016). This indicates that changing from an electrically cooled fridge to central cooled one would result in savings of 79 - 92 % of the energy used, depending on fridges actual COP and the area where the ship is being operated as the sea water temperature effects the chillers. In addition, the source for the cooling energy would change from electricity at the cabin to excess heat of the engine.

5.5 Direct current electrical network

During recent years, direct current networks have become into spotlight of marine engineers. In river cruise boats, ferries and work ships (anchor handling vessels, tugs etc.) direct current provides considerable savings in propulsion electricity consumption while electricity does not have to be converted back and from alternative current to direct current. Examples of such ships are Dina Star done with ABB machinery and Viking cruises done with Evacs machinery. (ABB 2013; Vacon 2014)

Ships electricity grid has traditionally been the same as on land meaning single phase 230 V AC. Main distribution lines have been tree phase 400 V AC. Voltage levels used in the networks are presented in Table 16 Voltage levels used in different electricity networks (Häkkinen 2007). Incandescent and compact fluorescent lights benefit from alternative current, as do old fans. Nowadays EC (Electronically Commutated) fans operate on direct current, as do LED lights. Similarly, other appliances work on DC as well. Connection of the device might not be DC, but internally most devices operate on DC (TV). Other usage of electrical sockets is charging passengers different mobile devices and many of them charge using DC from USB socket (Universal Serial Bus). Changing the ships electrical system or at least part of the system into DC would result in weight and size savings in cabins. If luminaires would change from fluorescent lights to LED effect would be noticeable. Light size would decrease from 20x30 cm into 10x10 cm or less. Weight would be lost on every light source when transformers from every lamp and unnecessary socket adaptors are removed. Distribution lines of 220 V DC and 24 or 48 V DC would result near optimal electricity grid (Viitanen 2015).

Table 16 Voltage levels used in different electricity networks (Häkkinen 2007).

50 Hz network voltages [V]	60 Hz network voltages [V]
220	110
400	440
660	660
1 000	1 100
3 000	3 300
6 000	6 000

Every transformer on a ship is in its own way unnecessary. In cruise ships 84% of electrical devices will consume electrical power as direct current (Bosich et. al. 2015). Therefore, arranging electricity distribution as direct current as well is a compelling possibility. Cabin consumers are mostly direct current devices by nature: Lighting as LEDs, EC fan and TV internally. Additional appliances are available or adaptable to direct current use as well. Heating element devices such as hair drier or coffee machine work the same on direct as on alternative current. Transfer cables work the same on direct and alternative currents so no additional weight would be added. Only thing that would hinder from transferring electrical network to direct current in cabin areas would be possibility to use normal 230 V alternative current devices such as laptop chargers or electric shavers. This can of course be solved by inverters in cabins service area (one corner of the cabin), but avoiding transformers and then adding them would be counter intuitive.

5.6 Cabin heating, ventilation and air-conditioning

Fan coil used in cabins is old technology on dry land but still in use on ships. Different, much more energy efficient solutions have replaced the fan coil in cooling and heating solutions. Active chilled beam is the modern solution for this kind of use and such technologies for ships have surfaced during recent years. Active chilled beam would eliminate need of fan in the cabin and heating could be done with the beams using hot water instead of electricity. Versions using electrical heating are also available.

Active chilled beam circulates cabin air in similar method as fan coil unit, but the power to circulate the air comes from the flow of the fresh air. This is called induction. Inducted airflow passes through heating/cooling coil and takes care of the desired temperature of the cabin. Active chilled beam would require more room from the cabin itself as construction is different than in fan coil but the beam would free space from the service area as the fan coil unit can be removed. Different shapes of active chilled beams do exist so fitting them to the cabin is quite easy. Working principle of active chilled beam is presented in Figure 22. Solutions presented in these pictures are installed in lowered ceiling. Some active chilled beams can also be installed directly to the ceiling.

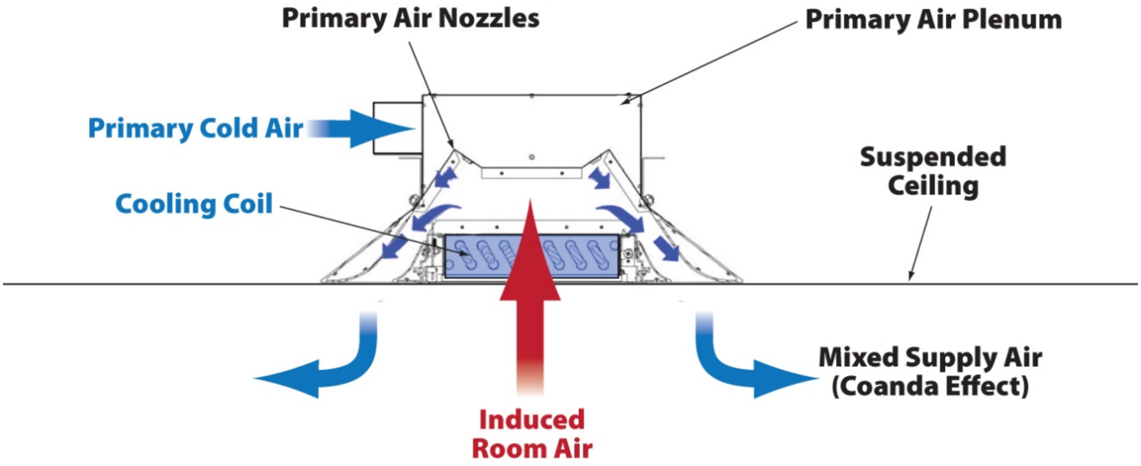


Figure 22 Working principle of active chilled beam pictured from the side (Taco Comfort Solutions 2011).

Active chilled beam does not only reduce electricity used in the cabin but the beam runs on warmer cooling water than the condensing fan coil and this reduces the cooling power and energy needed at the air conditioning chillers in the machinery room. The active chilled beam is also quieter than the fan coil unit and distributes cool air around the room evenly. Spreading the air to the cabin can be a problem with the fan coil as the fan coil has only one discharge point. Active chilled beam has one problem that needs to be solved and the problem is the condensing water. Fan coil has a condensation water collection tray in the housing that gathers the water and leads the condensate to the grey water system. Active chilled beam is open structure and the condensation would result in water dripping out of the beam if the problem is not solved. On land active chilled beams are used only in non-condensing environments such as offices and meeting rooms that do not have straight connection to possibly humid outside air and where the condensing problem is possible to solve.

The reason for more even distribution of the supply air is that air sticks to the roof because of Coanda Effect. Coanda Effect is the phenomenon when fluid jet tends to stay attached to a surface. (Kojacool 2016) This causes the air flow to stay close to the roof and fall down at the walls in a small room like cruise ship stateroom. Behavior of the air flow is presented in Figure 23.

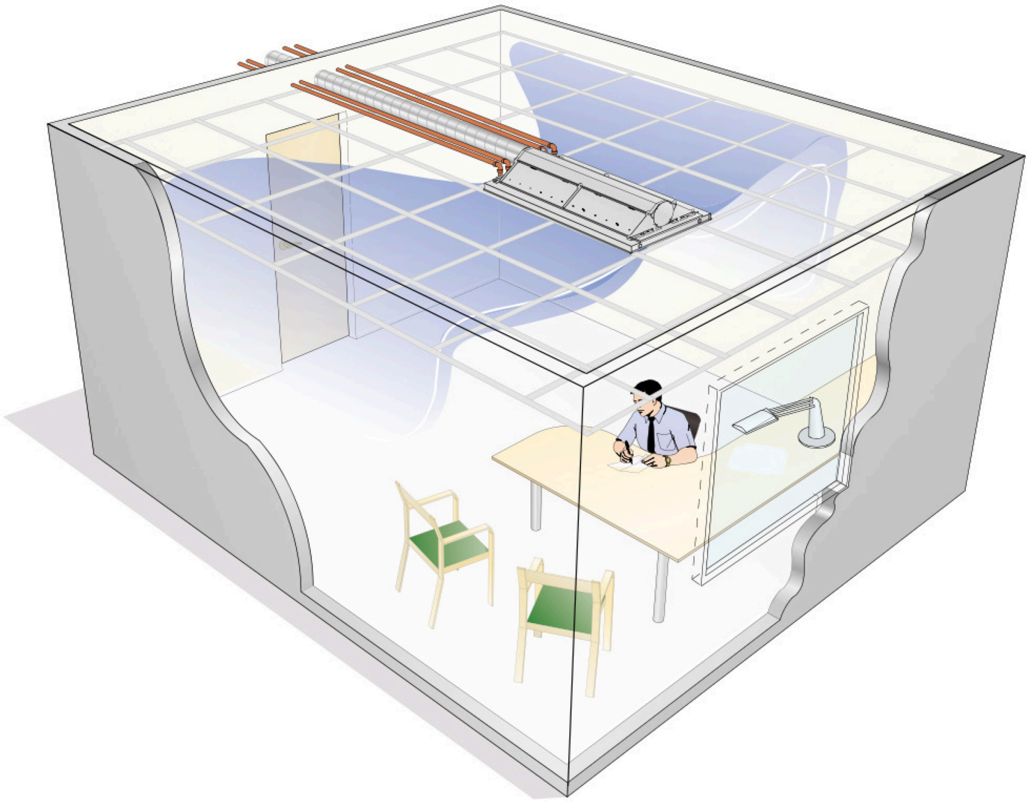


Figure 23 Air flow pattern from an active chilled beam (Swegon 2016).

5.7 Cabin windows and balcony doors

Because of the cruise ship's operating scheme, the solar heat load is major reason for the need of air conditioning in the cabins. If insulation in the wall is increased the effect of the heat loads normally increases, because the cabin cannot transfer heat into outside air. The solar heat load is not only a disadvantage as the load reduces the need to heat the cabin during cold seasons. This is a minor benefit, as these ships normally do not operate in cold climates.

As ship currently has quite good windows, as presented in Table 14 in Chapter 4.5, changing them to better ones would not make big improvement, but improving the windows is possible. Changing window glass especially in balcony doors to better options does not save energy by itself, but through savings in heating and/or cooling of the cabin. Current heat load to the cabin from the sun is 380 – 450 W depending on cabin heading which is two times the load from two persons (145 W) that are calculated to be in the cabin. (Meyer 2016)

Good windows decrease the need to cool the cabin but they influence the scenery from the cabin, because solar protected windows normally are tinted. Windows with fewer layers and less protection are a lot cheaper and not so heavy. Especially adding layers to window will increase the weight of the ship a lot.

5.8 Renewable energy sources

On ship, renewable energy sources seem compelling because ships are usually in sunny and windy places. Wind turbines are not considered in this thesis, because utilizing them in cabin scale is cumbersome. Rotors are around one meter in diameter, which is too much to be placed on cabins balcony. In general spaces and on upper decks wind turbines are usable option. Vertical wind turbines, also known as Flettner rotors, can increase the propulsion of the ship because of Magnus effect. Magnus effect occurs when a spinning ball or cylinder travels through air generating a pressure difference and thus a force effecting the object. Magnus effect and the force generated to the spinning object are presented in Figure 24. This method is in use on E-Ship 1 and it has been reported effective. (CleanTechnica 2012)

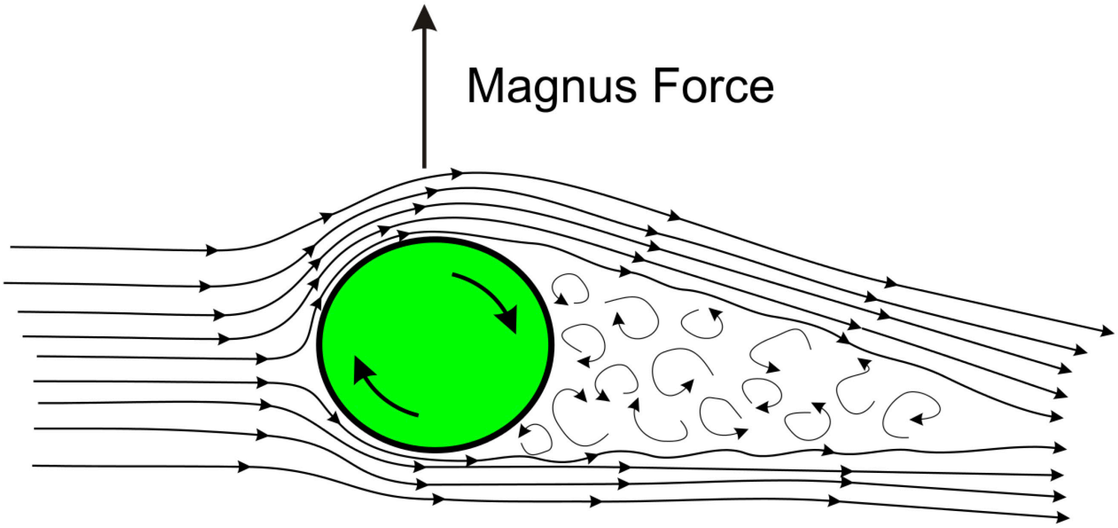


Figure 24 The Magnus effect and force effecting the spinning object (Wikimedia Commons 2014).

Photovoltaics are an interesting method to counterbalance cabins consumption. Cruise ships normally operate in a highly reflective environment (the sea) and follow the nice weather around the year. Therefore, traditional seasonal changes do not apply to cruise ships solar potential as they do apply on dry land. Places for the panels are quite limited as style comes before functionality on ships looks and black panel does not look good on a white ship. Modern panels can be printed on class but this requires creativity from the interior designers and willingness of the ship owner to be ready to place uneven black bars around the class surfaces. (Meyer 2016)

One suitable place for the panels is the space between decks just below the balcony glass rail. Adding to the area on the top deck a noticeable number of panels can be placed on a ship. Unfortunately, consumption is more than any amount of panel can produce as the best panels currently produce 168 W/m². As ship's hotel load is around 4 MW the area needed to serve the whole need would be 23 810 m². If we approximate ship to be rectangular, area of one deck would be only 10 550 m². Therefore, adding photovoltaics to the ship would be mostly a marketing benefit making the ship greener.

Photovoltaics are not an option for cabins because of area of panel per cabin is so small. Small units add unnecessary weight as there needs to be controlling electronics and cabling to connect the panels to the electrical network. It might be best to harness the sun in whole ships scale, then the panels could be connected in suitable pieces to the electricity network. Photovoltaic systems weight is currently so high that placing the panels to the whole ship is not feasible. Increased weight reduces the electrical gain from the panels as more energy is taken to propulse the ship forward. (Meyer 2016)

Solar collectors would be usable on the ship, but they weigh a lot, as they require fluid to circulate in the system and plumbing to connect them to point of use. In addition, they produce water in the same temperature range as the ship's engines low temperature cooling water is so no added benefit would come as the LT water is ran into sea currently.

6 Integration and operation of cabin systems

6.1 Present solution

Currently automation systems are used very sparingly in the cabin. The most noticeable piece of automation is the master switch next to the cabin door that switches all lighting and appliances off. This way the electricity consumption is minimized for the time the cabin is unoccupied. The only exceptions to the switch are the TV and the fridge. TV is bypassed because the TV does not withstand possible rapid turning on and off which does occur if people decide to come back to get something from the cabin when they have just left the cabin. The same master switch increases the allowed temperature range for the fan coil control unit so that the fan coil unit does not need to react to every change in the cabin temperature. Downside to the wider range of the temperature is the effect of passengers turning the room thermostat to cooler setting to speed up the cooling of the cabin while returning to cabin. Therefore, the change in the temperature range is minor, only 2 - 3 °C.

Another piece of automation in the cabin is a sensor in the balcony door. This sensor controls the fan coil unit. The fan coil unit is turned off when the balcony door is open. Otherwise the system would turn to full power when hot air from the open door rushes to the room. It does not matter if the outside air is cooler than the cabin air or if the air is warmer because the fan coil both warms and cools the air. Operating the fan coil unit when the balcony door is open would waste energy, as the air temperature would escape from the desired range.

The final part of the automation is the temperature control of the cabin fan coil unit itself. The temperature sensor is placed to the middle of the cabin ceiling. The temperature control unit adjusts all the functions of the cabin fan coil unit. This includes fan revolutions, heating and cooling. Fan control is done by feeding 0 - 10 V DC control signal from the temperature control unit to the fan's integrated control unit. This is possible due the EC fan in the fan coil unit. Instead of frequency converter used on older AC motor operated fans, the EC motor has integrated possibility to change the spinning speed by varying the internal timing of the electronics. (Ebmpapst 2008)

Cooling is controlled by a three-way valve that is opened or closed depending on the cooling need. For heating control, there is an on-off control for the heating coil. Valve control and operation of the heating is done using PWM (Pulse Width Modulation). This means that the valve or coil is only on or off and adjusting the runtime does the power adjustment. For the heating coil the adjustment time is 1 s and for cooling 5 min. If heating is needed on 50 % power then the heating coil will be on for half of the cycle meaning 0.5 s and off for the rest of the cycle. For cooling the 50 % power time would be 2.5 min. Principle of the PWM control for the fan coil cooling coil is presented in Figure 25. Operation is similar for the heating, the only difference is the cycle time. The longer cycle time for the cooling allows fluid to flow through the cooling coil providing cooling for the air flow. The heating coil does not need any start up time because the electrical coil heats up instantly. That is why more precise, shorter cycle time can be used on the heating coil. (SMARTEH 2015)

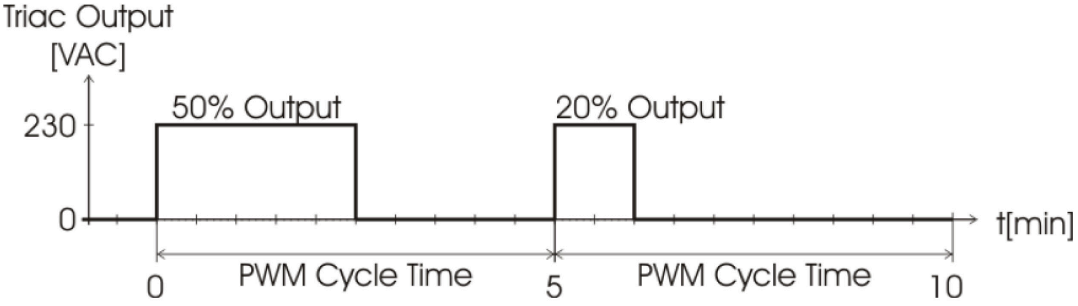


Figure 25 Principle of the PWM control for the cabin fan coil cooling (SMARTEH 2015).

6.2 Technologies studied

Installing a fieldbus system to the ship would make it possible to monitor energy consumption in real time. The attributes normally connected to a fieldbus network are access control, water consumption, air-conditioning, heating, ventilation and lighting. These all would have their use in a ship environment. Few possible network systems are KNX, LonWorks or BACnet. When the consumption is monitored, accurate information for optimization can be obtained and the easiest ways to cut consumption can be done first. (Rintala 2013)

In addition to the existing automation systems there are great possibilities to improve the energy efficiency of the cabin by adding more automation systems. There are easy and inexpensive systems to install and to gain noticeable benefits. Some systems are more expensive and require large changes to the existing systems, but their savings in energy consumption are equally large.

An easy way to save energy from lighting is lighting control. If lighting is dimmed depending on the ambient light level electricity can be saved, as lighting is not needed in bright environment. Electricity savings of 25 % can be achieved even in Finland during the summer months (Moisio 2016). These months are the months that the ship would be as north as Finland is. One dimming unit that is controlled by lighting sensor in the cabin does the dimming. When the weather is sunny and bright outside, lighting in the cabin is adequate without any luminaires as light from outside scatters to all around the cabin. The occupants in the cabin may still turn on luminaires from old habit. Impact from this old habit can be reduced when the lights are dimmed to a lower level. If a cloud covers the sun or some other anomaly decreases the lighting in the cabin, the luminaires are immediately brightened to the required level to provide adequate lighting in the cabin.

The dimming unit is installed to the electrical system and the required lights are connected to the unit. Depending on the smartness of the control unit some lights can even be disabled if the conditions are bright enough. For example, the balcony light is unnecessary if the sun is shining. The smartness of the control unit increases also the possibilities of controlling the lighting. For example, the control unit can be connected to a network and cabin lighting can be controlled remotely. This enables to remotely control the master switches of the cabins if for example the switch is left on in some cabin that is unoccupied for the whole cruise.

Another automation system or sensor to reduce energy consumption is a movement sensor in the cabin. It can be used to control the lighting. Movement sensors have been tested in cabins and cabin corridors, but there have been complaints especially from the passengers. Complaints are from unlit corridors feeling unsafe to lights switching off when someone still moves in the corridor or cabin. Premature switch off is usually caused by a misplaced sensor. The sensor must see the whole area to work as wanted.

Movement sensor is normally an infrared sensor that detects anomalies in its temperature environment. Normally this means a warmer object moving past a cooler background in the sensor's watch zone. Sensors work best when the movement happens past them. If movement comes directly to the sensor the detection distance is reduced. Normally there is a timer connected to the sensor so that once the sensor is triggered lights will stay on for a time set to the timer. (Ensto 2017)

Using movement sensors would cause reductions in energy consumption of the cabin by switching off luminaires when there is no one in the vicinity of the luminaire. Problems arise when people are present, but not moving. This can happen when occupants are for example reading or watching TV. Movement sensor can be connected to only some of the luminaires to reduce the problems caused by lights switching off. Then not all the luminaires switch off and some still deliver light to the cabin.

An automated curtain to shade the cabin would reduce the solar heat load to the cabin. Multiple ways exist to implement this technology. The solution can be a roller curtain right next to the balcony door that covers the whole door and operates with the master switch of the cabin. Issues with this kind of curtain are to ventilate the space behind the curtain so that the heat will not transfer conducting through the glass when heat rises behind the curtain. Another issue is the visual aspect. A curtain covering the balcony door will change the look of the ship so the curtain should be fitted with a picture of cabin door or similar solution to disguise it. Another way would be active shading with an awning that would be controlled according to the sun's trajectory providing additional shading to the cabin and reducing the solar load.

One major way to reduce the energy consumption related to the cabin would be to change the way the air delivery system works. Currently the ventilation system is balanced only to the full air flow. This means that if the air flow to the cabins would be reduced the air flow would not be reduced equally in every cabin. This is because the adjustment dampers in the ventilation system are operated manually and they are adjusted only during system calibration. Uneven reduction can result in inadequate air flow to the peripheral parts of the system. Inadequate air flow can cause headache and tiredness in people occupying the inadequately ventilated area.

Fixing uneven air flow would require remotely controlled dampers to each cabin that could adjust themselves to varying air flow. System working like this is called variable air volume system and this system has been recommended for cruise ships (Oinas 2007). The reason why the variable air volume system has not been taken into use is that the system is expensive to build. (Mäki-Jouppila 2016)

Variable air flow system would add possibility to adjust the air flow volume without problems with air distribution. Automation systems to control the adjustments could be a timer or CO_2 (Carbon Dioxide) control. Timer control to the air handling unit would save energy as the air flow could be dropped to a lower volume when the cabin is suspected to be unoccupied. This would mean the midday when passengers are not in the cabin. If air flow is controlled only with a timer, it does not matter if occupants have forgotten to flip the master switch off when leaving the cabin. Currently, the air handling unit is not controlled by the cabins' needs and the air handling unit has a minimum airflow of 21 l/s per cabin. If more accurate control is applied margins can be reduced and better energy efficiency achieved.

CO_2 control would be another technology to control the air flow of variable air volume system. This method would require a CO_2 sensor to the cabin and a network connection to the air handling unit. This would need additional feed from the temperature sensor that already is in the cabin, as the temperature can also indicate the need for larger air flow. CO_2 control would be the most on demand control for the cabin ventilation air volume as the air in the cabin can otherwise be kept good in regards of temperature by the fan coil unit.

7 Energy saving potential

7.1 Water usage

Recycling shower systems reduce the energy consumption of the cabin. Depending on the demand, water consumption can be reduced to minimum using the Orbital Systems system or total energy consumption can be reduced to minimum using the Upfall system. Water consumption and fresh water production figures are presented in Table 17. Energy used to heat the water used in the cabin is presented in Figure 26 and Figure 27.

Table 17 Water consumption and energy used to produce the water used during one day. Calculated according to user profile 1. Different user profiles are presented in Table 5 in Chapter 3.2.

	Water consumption [l]	**Water production [Wh]**	**Reduction [%]**
Current	163	570.5	0 %
Upfall	90.5	316.75	44 %
Orbital Systems	77	269.5	53 %

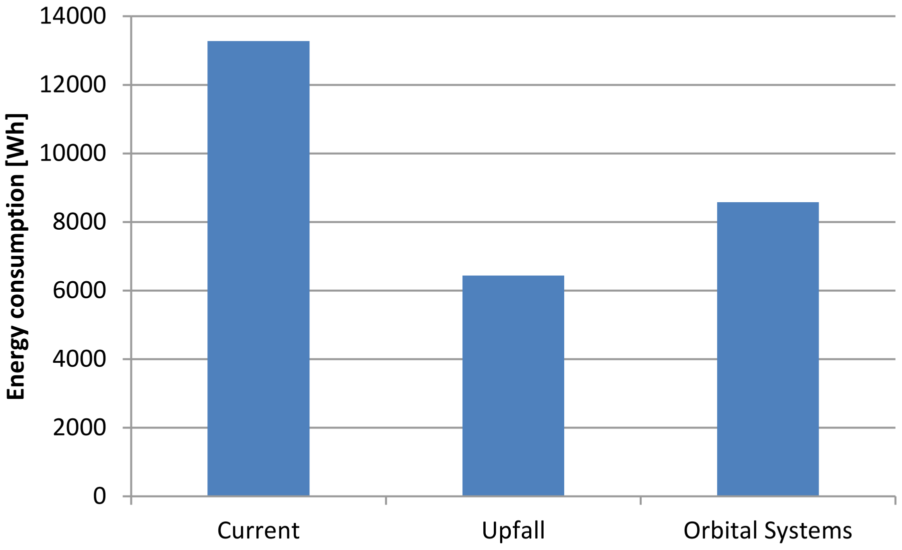


Figure 26 Energy used to heat the water used in the cabin during one day according to user profile 1.

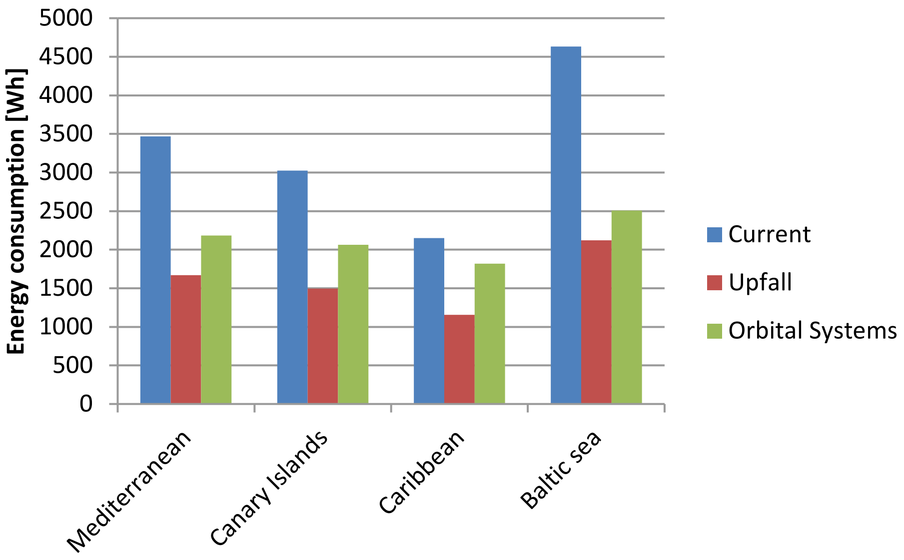


Figure 27 Energy used to heat the water used in the cabin during one day according to user profile 1. Different operating areas presented separately.

As presented in Figure 26, energy consumption is decreased significantly with both systems. Orbital Systems reduces energy used by 35 % and Upfall by 51 %. As presented in Figure 27 the energy consumption varies depending on the operating area. When geographical variation is taken into consideration, reduction of the energy used with Orbital Systems is 15 - 46 % and with Upfall 46 - 54 %. The difference is caused by the temperature difference of the sea water. This is because hot water used in the cabin needs to be heated up less when the sea water is warmer as the potable water in the tank is warmer. Orbital Systems' advantage over the traditional shower system narrows when the sea water gets warmer. This is because the shower uses continuously 4 kW of electrical power to retain the temperature of the circulating water and to pump the water in the system. On the other hand, Upfall shower takes full advantage of the warmer sea water and retains high efficiency as the Upfall system needs no additional energy than the 500 W pump.

Total energy consumption of the cabin water system follows the heating energy graphs, as water production is only circa 10 % of the heating consumption. Total energy consumption of the cabin water system is presented in Table 18. As presented in the Table 18, Upfall is the system to provide the largest reduction in the energy consumption of the cabin water system. Upfall provides reduction of 51 %. Orbital Systems provides noticeable reduction as well, but not as much as the Upfall. Orbital Systems reduces energy consumption by 36 %.

Table 18 Total energy consumption of the cabin water system during one day according to user profile 1.

	Total energy [Wh]	**Reduction [%]**
Current	13437.27	
Upfall	6531.978	51
Orbital Systems	8653.062	36

Adding heat recovery to the water system decreases the need for new energy to heat up the water. Simultaneously, waste heat in the grey water is reduced. Using a central system such as the Wasenco is not beneficial as the grey water cools down in piping on its way to the holding tank. Grey water cools down to about 30 °C before the water reaches the holding tank (Honka 2016). 30 °C is too low temperature to utilize in the machinery room as heat exchangers cannot utilize the heat flow to its full extent but leave a minor cap of a few degrees celsius. Likewise, low temperature cooling water is freely available at the engine room and the cooling water is hotter than the grey water while entering the tank. The temperatures are 40-47 °C and 30 °C respectively.

The Ensavetec system recovers 21 - 39 % of the total energy consumed by the cabin water system. This is calculated with the 40 % efficiency claimed by the manufacturer. When calculated using 30 % efficiency, the Ensavetec system delivers 14 - 29 % of the total energy consumed by the cabin water system. Same factors cause the variation in 30 % and 40 % efficiency cases. The lowest results are in combination with the Orbital Systems shower as Orbital Systems produces little waste water but uses a lot of heating energy. The efficiency for the Orbital Systems is low because Orbital Systems uses electricity to heat the water and there is no way to utilize the collected waste heat from the Ensavetec system. Results are 14 - 16 % for the Ensavetec heat recovery system paired with the Orbital Systems shower. These numbers are achieved with the 30 % efficiency. Traditional shower and Upfall shower provide more waste water and therefore their results are 27 - 29 % energy recovered of the total energy used by the cabin water system. Additionally, these systems do not use electricity or other outside energy to heat the water. Results for user profile 1 is presented in Table 19.

Table 19 Energy recovered with the Ensavetec heat recovery system with different efficiencies. Values calculated for one year with user profile 1.

System	Efficiency [%]	Energy recovered [Wh]	Total heating energy used [Wh]	Percentage of recovered energy [%]
Current	40	485 385	1 211 277	40
Upfall	40	217 205	587 785	37
Orbital Systems	40	167 269	782 566	21
Current	30	364 039	1 211 277	30
Upfall	30	162 904	587 785	28
Orbital Systems	30	125 451	782 566	16

7.2 Cabin lighting

Changing the cabin lighting from fluorescent lighting to LED lighting will result in savings of 20 W in the lighting load. If lighting automation is added, the electricity consumption can be reduced by at least 25 % based on the research conducted by Moisio (2016). Electricity used by the cabin lighting in different solutions is presented in Table 20.

Table 20 Electricity consumption of different lighting solutions for one day.

	Current solution [Wh]	**LED lighting [Wh]**	**LED lighting with automation [Wh]**
Profile 1	265	215	161
Profile 2	424	344	258
Profile 3	2014	1634	1226

For prisms, solar collector and light tunnel there is not enough data presented by the manufacturers to perform calculations. Parans collector would provide enough light for the cabin at the regions the ship operates in. The collector units could be placed on the top of the ship or to the sides of the chimney where they would take use of unused space. Unfortunately, the systems current version (SP4) cannot keep up with the movements of a moving ship (Nilsson 2017). Therefore, lighting could only be done in harbors. Also, the cabins with balconies receive enough light through the windows so the saving from the system would be minimal. Parans system can still be used in interior lighting in the common spaces of the ship. There the active varying light of the sun would enhance the user experience of the cruise passengers.

Light tunnel structures are hard to place on a ship. Large, straight tubing for the light to travel and large collectors are too difficult to place on a ship. In difference to the Parans system, the collectors must have a straight connection from the collector to the luminaire, limiting the use to only the top decks of the ship, where a simple window could yield in similar results.

There was no information available considering the prisms performance. Therefore, possibilities to transfer light from the corridor or the cabin cannot be calculated. Based on the historical sources light can be transferred using deck prisms so the use of prisms remains an interesting aspect to continue research on. Savings would be achieved from the nighttime use of toilets as the corridor is illuminated throughout the day. Prism could possibly provide enough light for moving around and thus resulting in savings, as cabin lights would not be used. The same would apply to the daily use if the illumination level would be high enough. During the nighttime, the human eye is able to operate in lower illumination levels, as the eye is adapted to the dark. During the day, light level might be so low that the human eye has not enough time to adapt from the bright cabin to the dim toilet. (Sand et. al. 2006)

7.3 Reducing the solar load

7.3.1 Balcony door glass properties

Solar radiation is not only dependent on the position of the ship but also on the time of the year. Only the position in the north - south direction makes a difference as Earth spins and places on the same latitude follow the same track thus have the same solar conditions. The angle variation in one location depends on the time of the year. In the summer the sun is higher, shines for longer hours and the radiation is more intense. In the winter the sun shines from a lower angle, for a shorter time and the radiation spreads on a larger area due to the low angle. These differences in the solar load can be seen in the shading table in Chapter 7.3.2.

There are two ways to improve the glass in the balcony doors to reduce energy consumption. One is to improve the ability to block the solar radiation ergo g-value and the other is to improve the ability to prevent heat loss from the cabin through the window ergo U-value. As methods affect different heat flows their efficiency depends on the operating area of the ship. In general, enhancing the U-value improves the performance in two cases. Firstly, in colder regions where heat escapes through the window. Secondly, in hot climates where the outside air is hotter than the inside air and warms the cabin by conduction. Enhancing the g-value improves the performance in regions where the sun shines long hours at a low angle. Both values reduce as they improve.

Improving both the U- and g-values reduce the energy consumption at the cabin fan coil unit as the coil heats up or cools down the cabin inside air to maintain the desired temperature. Reducing the energy used to heat or to cool the cabin can achieve savings. Which energy consumption is reduced depends on the operating region. Generally, the energy used to heat the cabin increases when g-value is decreased and the energy used to cool the cabin decreases more so that savings are achieved. Some smaller savings are gained from the fan coil fan as the fan is not required to run so much, but these savings are only 2 - 10 % of the savings in the cooling consumption. Maximum and average reductions to the fan coil unit's energy consumption in one day are presented in Table 21. Original g-value is 0.58 and three variations are presented in Table 21. There are large differences in maximum and average reductions between different operating areas, therefore the ship's operating areas should be considered before investing into the windows or doors.

Table 21 The maximum and average reductions in one day achieved by changing the g-value of the door.

g-value	Maximum reduction [Wh]	Maximum reduction [%]	Average reduction [Wh]	Average reduction [%]
0.6	3	0.1	-80	-2
0.5	790	18	290	9
0.4	1780	36	620	19

From Table 21 can be seen, that on all operating areas improving the g-value does not gain savings, but increase the energy consumption. On these areas the increasing g-value brings savings as room does not need to be heated by the fan coil but the heating is done by the solar radiation. This is not a beneficial way to improve energy efficiency. The savings are small and on average energy consumption is increased 27-times the savings gained on some regions. Regions that benefit from the window glass letting more radiation pass through are regions, which have the sun shining from a high angle, and the balcony structure shades the cabin. In the scope of this thesis this happens mainly in the Mediterranean. There the latitude and the time of the year that the ship stays there are such that sun rises quickly and stays high for the day thus not shining into the cabin. This results in low gains in energy saving when improving g-value as can be seen from Figure 28. The maximum savings are achieved on regions with strong solar radiation and relatively low angle of the sun. Such region is for example the Caribbean. Large savings are achieved at the Baltic Sea as well, but these are result of the low sun angle and long hours of sunshine. The amount of radiation builds so that the relatively low level of radiation yields large energies. On average the energy savings from improving the g-value increase nearly linear with the g-value.

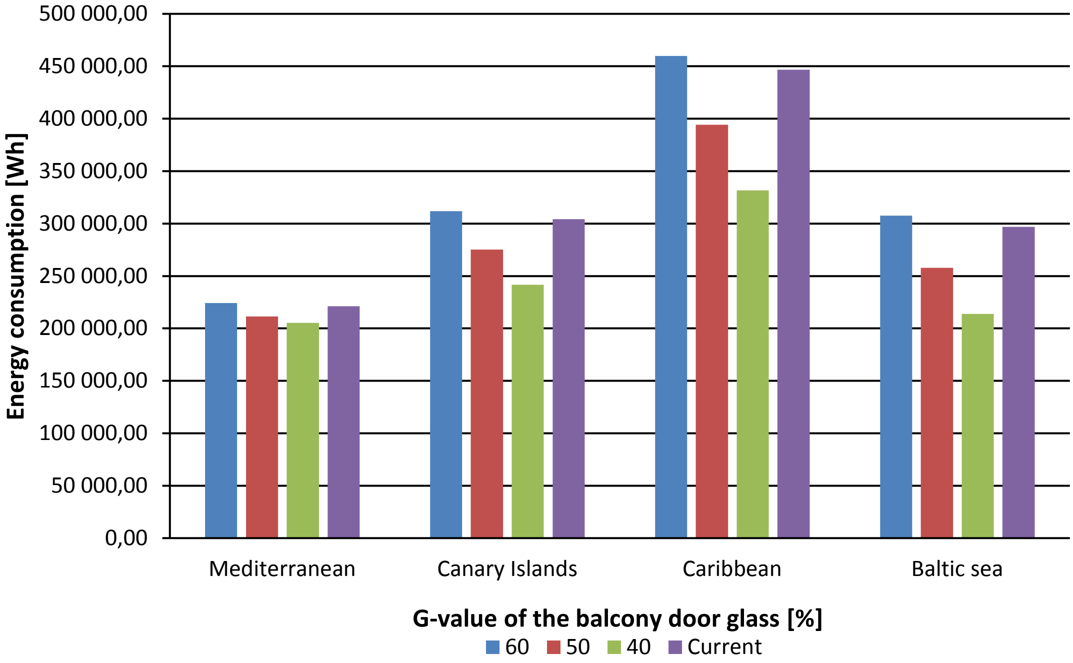


Figure 28 Energy consumed by the cabin fan coil unit in a year with different balcony door g-values.

In Figure 28 it is shown how improving the balcony doors glass's g-value affects the energy consumption of the cabin fan coil. The data is calculated to full year and current energy consumption is also presented in the figure. From the figure, it can be seen how the energy savings vary depending on the operating region. Best areas to benefit from the improved glass are places of strong solar radiation (the Caribbean) or places of long hours of low angle sunlight (the Baltic sea). Table 22 presents savings gained from the U-value.

Table 22 Reduction of the conducted energy through the balcony door in one year if U-value is decreased to 1.0.

Region	Heading south [Wh]	Heading east / west [Wh]
Mediterranean	-2 214	-942
Canary Islands	-1 975	-1 645
Caribbean	2 056	1 696
Baltic sea	-2 593	5 105
Total for a year	-4 726	4 214

These numbers are for the whole year as opposed to Table 21 that presents values for one day. Comparing the numbers reveals that the U-value has only a small difference to the heat load of the cabin. Savings in the energy consumption are gained in regions that have warmer outside air than the cabin's inside air such as the Caribbean or in climates that are cold such as the Baltic Sea. In outside air temperatures in the range of 10 - 21 °C decreasing the U-value mainly increases the energy consumed in the cabin. The increase is due to the increased need of cooling because cabin does not leak as much heat through the window. When the outside air is hotter than in the cabin inside air heat leaks into the cabin. Better U-value reduces this flow and thus reduces the need to cool the cabin. This results in reduced cooling energy consumption.

Adjusting the balcony door glass properties can adjust how much of the energy used in the cabin is electricity and how much is from the cooling water. This can be useful if there is a need to make everything run on battery power for example. Currently there is no way in the ship to store cold and to be able to deliver cooling without the chillers.

7.3.2 Active shading of the balcony

Shading of the cabin has a large impact on the solar radiation entering the cabin. Currently there are no active shading systems in the cabins, but they would be a potential method to reduce the heat load of the cabin. Cabins are estimated to be unoccupied for 12 - 14 h on average. From the calculations can be found that average shading for a cabin is 2.6 h at full 90 % shading. When the average length for a day is 13 h, there is room for improvement in the shading. In Table 23 and Table 24 there are examples of similar solar radiation levels with different shading profiles.

Table 23 Radiation to the cabin with and without shading and the length of the day.

Location	**Radiation without shading [Wh]**	**Radiation with shading [Wh]**	**Length of day [h]**
Baltic sea	5 655	4 510	12.5
Mediterranean	5 219	1 581	14.8

Table 24 Examples of the shaded time of the cabin during daylight time.

Location	**Shading min 90%**	**Shading min 60%**	**Shading min 30%**
Baltic sea	0 %	0 %	44 %
Mediterranean	41 %	51 %	67 %

As presented in the Table 23 cabin shading can reduce the solar radiation significantly. At the Baltic Sea, 80 % of the radiation enters the cabin. At the Mediterranean only 30 % enters the cabin. If automated shading would work with the master switch of the cabin and the shading gained 90 % coverage, energy consumption would drop 78 % on average. This is assuming that the cabin would be shaded from 9 a.m. to 3 p.m., which are the most intense hours for solar radiation. Table 24 presents the shaded time of a cabin during daylight at the Baltic Sea and the Mediterranean. Total shading differs only 23 %-units, as 30 % shading level is the lowest used. This indicates the need for efficient shading during the most intense solar radiation, meaning the midday. Effects of the shading level and the shaded time are presented in Table 25.

Table 25 Effects of the shading level and the shaded time to the solar load of the cabin. Results are for one cabin for one day.

Shading level [%]	Shading time [h]	Months benefitting [pcs]	Average reduction [Wh]
90	6	11	946
90	4	8	462
90	3	6	295
90	2	4	180
80	6	7	551
80	4	4	264
80	3	3	182
80	2	3	127
70	6	5	302
70	4	3	161
70	3	3	116
70	2	3	81
60	6	3	160
60	4	2	77
60	3	1	51
60	2	1	35
50	6	1	62
50	4	1	43
50	3	1	34
50	2	1	24

Figures presented in Table 25 are calculated from the weather data using the shading levels and shading time presented in the Table 25. Shading time is divided equally before and after the sun’s zenith. Months are calculated as benefitted if the active shading reduces the solar load of the cabin. Reductions resulted by the shading system vary between 0 - 2 800 Wh. The greatest reductions are achieved at the Caribbean and at the Baltic Sea. From Table 25 it can be established that the shading system has to shade at least 70 - 80 % and 4 - 6 h to be efficient for most of the months. If reductions at some operating regions are adequate then the 50 - 60 % shading level and upwards of 3 h shading time is enough to gain savings upwards of 360 Wh at the Baltic Sea.

Concerns about the automatic shading system include troubles with the rolling mechanism as the balconies get some salt spray from the ocean. This requires some maintenance and protection to the mechanism for it function properly. Other problem is that if the shading system is in use only at some regions, how will the long stand by period affect the shading mechanism. Mechanical devices normally tend to seize if they are not used regularly.

7.4 Automation systems

Savings of 25 % in energy consumption can be achieved when changing the ventilation system to a thermal comfort index control (Hongmin & Shuping 2011).

As heating, ventilating and air-conditioning consume large amounts of energy, automation systems reducing the consumption can easily save large amounts of energy. One automation system to reduce the consumption is Pressure Independent Balancing & Control Valve. These valves enable air-conditioning cooling water network to shut down partially to reduce the energy consumption. By closing the network in the parts that do not require cooling, the network pumps work on a lesser load and chillers work more efficiently as the temperature difference is larger. These changes result as saved energy. According to Boden (2014), for 80 % of the time the cooling demand is less than 25 %. Manual systems can not compensate this and therefore current systems run at larger power than needed. Pressure Independent Balancing & Control Valve is claimed to be able to reduce 25 - 30 % of the energy used in ships ventilation system. (Boden 2014)

7.5 Centrally cooled fridge

The fridge in a passenger cabin currently draws a steady 35 W of electrical power through the day on every day of the year. Energy consumption of the fridge is currently 800 Wh of electrical energy in a day. Changing the supply of the energy to the air-conditioning cooling water can yield large reductions in the energy consumption of the fridge. Savings are presented in Table 26.

Table 26 Differences of centrally cooled and traditional cabin fridges.

Fridge type	Electrical energy consumed [Wh/a]	COP
Current	292 000	0.6 - 1.2
Centrally cooled	24 000 - 31 000	5.7 - 7.3

Because the centrally cooled fridge is much more efficient in using energy the consumption is only 8 - 10 % of the current absorption cooled fridge as presented in Table 26. This is because the central cooling machines, also known as the chillers, have a COP of roughly 5-times the COP of the current fridge. This means that the centrally cooled fridge would be roughly 5-times more efficient. No centrally cooled fridge was found for this study so exact numbers are not available. It is probable that the efficiency is not 5-times the current one as the heat exchanger of the cabin fridge does not have 100 % efficiency.

Centrally cooled fridge is a heavier solution as piping has to be added and the volume of the cooling water network needs to be increased to accommodate the need of the fridges. In the modern ships, fridges are not installed in every cabin so minimizing this energy flow does not necessarily cause massive savings for the whole ship. Connecting the fridge to the chilled water network reduces the heat load in the cabin and causes additional heating need in the cabin. Similarly, the cooling need is reduced when the heat load of the fridge is removed from the cabin. These loads vary in magnitude and the net gain in a cabin varies between -500 - 420 Wh a day. The average gain is 3 Wh and 13 of 24 months benefit from installing centrally cooled fridge meaning the net gain is positive.

7.6 Error sources

Results received from the calculations present the estimated big picture of energy consumption but some error is caused due to different reasons. Exact starting values were not available and therefore especially electrical calculations are based on an estimation. There is and probably will not be statistics on hair dryer usage in the cabins. Reduction in percentages is usable for electrical consumption, as the percentages do not depend on actual usage in most cases.

Calculations involving the sun are prone to error because ships heading is not known. The heading indicates in which direction the ship's bow points to and the information is needed to calculate the solar radiation hitting the surfaces as radiation changes depending on orientation and angle of the target planes. Another variable affecting the cabin's solar input is shading from balcony structures. Balcony of the cabin above provides good shading to the cabin below and the screens between balconies do the same in the horizontal direction. Also, the glass rail of the balcony affects the solar load. These variables cause unknown error, in magnitude and direction, to the results.

Water usage is measured onboard and therefore the readings are accurate. The energy required to heat the water and source of that energy are unknowns as is energy needed to treat and transfer water to and from the cabin. Heating is done from seawater temperature to the temperature of the hot water network of 60 - 65 °C. Seawater temperature is not constant and as the water has high specific heat capacity of 4.18 kJ / kgK (Andersson 2006), small changes in water temperature have a great effect on the heating energy consumption. The energy consumption of hydroforic pumps for potable water, vacuum pumps for black water and transfer pumps are not instrumented on a ship and therefore energy used in transferring the water is not known. These reduce the energy consumption associated to the water and therefore actual consumption is greater than the one calculated here.

Air handling is instrumented quite accurately and exact data can be used for the calculations. Unfortunately, the last part of consumption, the cabin fan coil unit, is not instrumented and therefore its consumption is calculated based on theory and not on actual consumption. Air handling calculations are quite straightforward and are compared to reality, so values can be considered accurate.

7.7 Summary of the results

The methods described earlier in this chapter have a reducing effect on the energy consumption of the cabin. To compare them easily side by side they are collected into Table 27. Compared to original -column indicates how much the improved consumption is compared to the original consumption in percentages. Savings in one day -column make comparing the options easier as watt-hours are comparable between different consumers.

Table 27 Summary of energy saving methods.

Technology	Compared to original [%]	Savings in one day [Wh]
Water recycling shower, Orbital Systems	64	5 000
Water recycling shower, Upfall	49	7 100
Waste water heat recovery, Ensavetec	60 - 80	460 – 1300
Waste water heat recovery, Wasenco	N/A	N/A
LED luminaires	87	50 - 80
Lighting automation	75	60 - 90
Solar lighting, collector	N/A	N/A
Solar lighting, light tunnel	N/A	N/A
Utilizing corridor lighting, prism	N/A	N/A
Central cooled fridge	8 - 10	700
Renewable energy sources	N/A	N/A
Active chilled beam	N/A	N/A
Ventilation automation	75	9 500
Cabin windows and balcony doors	65 - 80	40 - 300
Active shading	53	946

8 Discussion

Energy used by the passenger cabin's services is largely consumed elsewhere on the ship. For example, the shower water is heated in the machinery room, hence not consuming energy at the cabin. Recycling shower system and heat recovery from the grey water reduce the energy used by the water system. For the ventilation and air handling, energy savings require changing the structure of the ventilation system. The system should be changed from the current continuous air volume system to a variable air volume system. This means that every cabin would get an individual damper to adjust the air volume. The supply fan of the air handling unit would then adjust itself to provide optimal pressure to the system and the volume adjustment would be done at the cabins. Air volume would be controlled by the cabin air temperature or a CO_2 sensor. Energy would be saved because the air volume flowing through the system would be reduced. This reduces the electricity used by the fans and the need to cool or heat the air to meet the desired temperature. According to Oinas (2007), the energy saving would be 26.5 %.

Lighting in the cabins is mainly needed when the sun is not shining. This means that the solar lighting systems do not cause large savings in the cabin lighting's energy consumption. Of course, some inner cabins and some specific areas, such as the toilets and dark corners, might need lighting during the day. The consumption from these areas is so marginal that the solar lighting system would not be efficient. Solar lighting remains a nice decorative solution and if used so it can be adapted it to cabins as well.

The active chilled beam presented in this thesis is an interesting option for marine industry. Unfortunately, the beam's effect could not be included in the calculations of this thesis. Preliminary specifications imply that the beam would work without a fan and with warmer cooling water than the fan coil unit (Kirjavainen 2016). Ability to use warmer cooling water saves energy at the air conditioning chillers as they do not need to cool the water as much.

Switching the ship's electrical network fully to DC would potentially make large savings in energy usage. On MV Dina Star, 27 % savings in energy usage were achieved (ABB 2013). The Dina Star is an anchor handling vessel that has to do more maneuvering than cruise ships. Cruise ships have a steadier consumption and the spikes in the power usage are lower compared to average use. This results in lower savings, but noticeable savings are still achieved. Energy savings from maneuvering consumption caused by utilizing DC network are more widely discussed in the thesis of Korhonen (2016).

According to Bosich et. al. (2015), 84 % of electrical devices on a cruise ship run internally on DC. This means that inside every one of these devices is an unnecessary transformer that loses energy when transforming alternating current to direct current. These AC to DC transformers have a wide efficiency range, but generally they operate in an 80 - 90 % range (Pinho 2016b). If the conversion was eliminated then the energy lost in the conversion would be saved.

Implementing DC network also makes integrating solar panels and other renewable energy sources easier. Most energy sources or energy storages output their energy in DC. This means that if AC network is used then every time a small amount of energy is lost into the conversion. AC network requires frequency synchronization, which is not needed in DC network as the network has a steady voltage and no frequency.

This thesis concentrates on reducing the energy consumption. There is another side to the energy efficiency and that is to use energy as efficiently as possible. On a ship this would mean utilizing the low temperature flows in the engine room and from other machinery. LT water has been talked a lot in this thesis. Other such flows are the lubrication oil and the grey water. A specific heat recovery system for the laundry might prove useful as the grey water is hotter there than from the cabins. Other such places can be the galleys where dishes are done using hot water.

To calculate the energy savings and to design more energy efficient solutions one needs to know where the energy is used. Currently the ship's functions are monitored only at a coarse level. For example, from the water system, it is known how much water is produced, but not known how the water is heated. More accurate monitoring systems should be implemented to be able to reduce energy flows efficiently. This is also recommended by Baldi et. al. (2015). Monitoring one cabin is not enough but one cabin corridor could provide gathered information of a dozen cabins. This information could be used to predict the consumption and to design energy saving solutions.

9 Conclusions

The goals of this thesis are to analyze the passenger cabins energy usage and the possibilities to reduce it by using different available technologies. The analyzation concentrates on the water system, the ventilation and the electrical system. The ship is a delicate system where changes to any system may cause problems in others. During the research for this thesis many ideas and options were found unsuitable for the ship environment. Another problematic aspect is the ship owner's unwillingness to invest in new and untested equipment.

Of the technologies studied the setup for the future would be water recycling shower by Upfall, waste water heat recovery with both Ensavetec and Wasenco systems, LED luminaires and active shading of the balcony door. Solar lighting with Parans system can be installed as well if the problems with solar tracking are solved. If fridges were installed on future ships then the centrally cooled option would be more energy efficient. Additionally, if the active chilled beam were installed, the amount of additional piping for the fridge could be smaller as the beam is deeper in the cabin than the fan coil unit.

Orbital Systems and Upfall showers lose their advantage over short repeated showers, as the reservoir needs to be filled every time. If the individual showers last over one minute the showers save water and heating energy. Depending on the operating area Orbital Systems can make only a little benefit over the traditional system. Upfall shower instead provides savings not depending where the ship operates.

Upfall is the recommended shower system to use because the system does not require installing tree phase electricity to the cabins as does the Orbital Systems. Upfall uses only slightly more water than the Orbital systems shower and uses less energy to heat the water. Connected to the cabin's grey water system would be Ensavetec heat recovery device that would serve two cabins. Wasenco system would be in use at special locations such as the laundry. Service intervals of the water filters in the shower and Ensavetec system are quite short and this might be an issue on a ship as maintenance personal is kept to a minimum.

The Ensavetec system has potential in most climates to serve two cabins simultaneously. In colder climates such as the Baltic Sea one cabin can utilize the whole capacity of the heat exchanger. If one system is installed for two cabins weight can be saved and most of the energy saving potential can be used, as the two showers are not likely to be used at the same time.

The faucet of the washbasin can be a large water consumer and some ways to reduce its water consumption should be installed. The faucet has the same water flow as the cabin shower, but it has nothing to control it. Touchless faucet or a similar solution could reduce the water consumption, but the passengers often feel that these are difficult to use and the ship owners hesitate to implement them to the cabins.

Switching the lighting to LEDs has already happened and this thesis proves the change was beneficial. The change was not only beneficial in means of energy savings but also savings in the maintenance costs as LEDs have a longer lifetime than compact fluorescent lamps. LEDs also enable weight savings in the cabins, as luminaires can be smaller as the lights themselves are smaller. Switching to LED lighting also reduces the heat load in the cabin and reduces the need for cooling.

The ventilation systems run around the clock and consume roughly one third of the ship's energy. Implementing changes to the system such as variable air volume system or clock automation can cause large savings. Improving the specific fan power of the air handling units would also save energy.

The ventilation system currently uses steam as its main energy source for heating. Implementing colder heat flows such as LT water or grey water to preheating can reduce the energy used in serving the cabins.

Active shading of the balcony door can provide large savings in the cabin's fan coil unit's energy usage, as the need to cool the cabin will be reduced. Some additional need to heat the cabins may occur at current ventilation settings. This can be balanced with the air handling unit's settings by adjusting supply air to warmer setting for the shaded time to reduce the need for heating. Shading system would be a new technology for cabins and quite challenging to produce, as the system should be light, elegant and robust against wind and salt spray. If such a system can be build, large savings would be achieved from the energy consumption of air handling.

Parans lighting system has potential to reduce the energy consumption in the center parts of the ship. Bringing the sunlight to the inside cabins without a view outside will not only enhance the customer experience, but also reduce energy consumption as lesser electricity is needed for the lighting. Head units of the system, meaning the luminaires, should be the hybrid LED model that provides constant lighting not depending on the sunshine outside.

Improving the energy efficiency of a cruise ship passenger cabin is possible and there are many ways to improve it. The largest savings are achievable from ventilation and water systems. These systems have the largest energy flows of any cabin system and thus even a small reduction can result to a large improvement. Replacing old systems with new ones results in largest savings, for example changing the current shower to a water recycling one. Installing new systems can also bring great savings, for example the active shading of the balcony door.

During this research, new research topics arouse. Direct current network and DC capability of the current cabin area is probably the biggest topic as DC networks are currently making their breakthrough. Adding renewable energy sources to a ship would be a subject to study along the DC network. DC network makes the integration easier and the devices needed to connect the energy sources to the network are lighter in weight than those required with the AC network. Another new topic is the use of an active chilled beam to replace the cabin fan coil. On land the active beams have surpassed the fan coils in many applications hence it would be interesting to see how they work on a cruise ship. Solar lighting and its possibilities is the final topic. Lighting the cabins consumes electricity and heats the air. If solar lighting can be used then lighting would need less energy and the system would not heat the cabin as much.

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List of Appendices

Appendix 1. Weather data. 1 page.

Appendix 1. Weather data

Temperatures and operating months

Area	Outside air temperature [°C]	Temperature of the sea water [°C]	Months
Baltic Sea	5,80	9,80	7-9
Caribbean	22,50	27,70	12-2
Canary Islands	19,20	21,40	3,10-11
Mediterranean	16,70	18,20	4-6

Sun's altitude angle [°]

Area	Month 1	Month 2	Month 3
Baltic Sea	53,60	46,00	35,30
Caribbean	48,10	50,30	58,90
Canary Islands	60,10	53,00	43,50
Mediterranean	61,70	70,80	75,20

Sun's radiation on a vertical surface [kWh/m2/day]

	Facing south			Facing east			Facing west		
Area	**Month 1**	**Month 2**	**Month 3**	**Month 1**	**Month 2**	**Month 3**	**Month 1**	**Month 2**	**Month 3**
Baltic Sea	3,20	3,19	2,85	2,56	2,55	2,28	2,56	2,55	2,28
Caribbean	4,57	4,60	3,86	3,66	3,68	3,09	3,66	3,68	3,09
Canary Islands	3,63	4,06	4,33	2,90	3,25	3,46	2,90	3,25	3,46
Mediterranean	3,38	2,87	2,63	2,70	2,30	2,10	2,70	2,30	2,10

Sunshine hours and shading of the cabin [h]

	Month 1								
Area	**Sunrise**	**30 %**	**60 %**	**100 %**	**100 %**	**60 %**	**30 %**	**Sunset**	**Length**
Baltic Sea	4:37	8:20	10:06	11:27	15:10	16:31	18:17	22:00	17:23
Caribbean	6:14	8:28	9:53	-	-	13:39	15:03	17:16	11:02
Canary Islands	7:40	9:43	10:50	11:37	15:41	16:28	17:36	19:39	11:59
Mediterranean	6:32	8:50	10:02	10:51	15:23	16:13	17:25	19:43	13:11

	Month 2								
Area	**Sunrise**	**30 %**	**60 %**	**100 %**	**100 %**	**60 %**	**30 %**	**Sunset**	**Length**
Baltic Sea	5:40	9:07	11:08	-	-	15:25	17:27	20:55	15:15
Caribbean	6:25	8:35	9:53	11:06	12:54	14:06	15:25	17:33	11:08
Canary Islands	7:31	9:40	10:55	11:57	14:34	15:36	16:51	19:01	11:30
Mediterranean	5:57	8:18	9:23	10:12	15:55	16:39	17:49	20:11	14:14

	Month 3								
Area	**Sunrise**	**30 %**	**60 %**	**100 %**	**100 %**	**60 %**	**30 %**	**Sunset**	**Length**
Baltic Sea	6:43	10:19	-	-	-	-	15:56	19:33	12:50
Caribbean	6:18	8:19	9:26	10:41	13:54	14:43	15:50	17:50	11:32
Canary Islands	6:52	9:14	10:57	-	-	13:32	15:16	17:38	10:46
Mediterranean	5:44	8:10	9:20	10:04	16:11	16:55	18:05	20:32	14:48