Bachelor's thesis

NTNU
Norwegian University of Science and Technology
Department of Ocean Operations and Civil Engineering

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Energy efficient hot water production, storage and recovery of heat on a RoPax- vessel

Bachelor's thesis in Renewable Energy Engineering
Supervisor: Ann Rigmor Nerheim
Co-supervisor: Lene Æsøy
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Kunnskap for en bedre verden

Abstract

The maritime industry is obligated to emit less greenhouse gases in order to meet the requirements and demands of more sustainable solutions. One of the solutions involves improving the existing propulsion and auxiliary systems on ships. Given these challenges, the strive for energy efficiency have introduced new technologies. Some of these are based on recovering and storing waste energy.

Ulmatec Pyros Waste Energy Management System reduces fuel consumption and emissions by active recovery of existing energy losses. The system utilizes as much of the waste heat as possible and ensures distribution to all relevant consumers on board. Typical consumers are tank and room heating, air conditioning and other hot water consumers. The heat recovery is performed by exhaust gas economizers, which are placed on top of the main engines. The economizers extracts the heat from the exhaust gas and uses it to heat up water.

When there's excess recovered heat, the heat can be stored in thermal energy storage systems, using encapsulated phase changing materials as a storage medium. Calculations on recovered heat, energy demand and surplus energy was completed in Excel, using operational data given by Ulmatec Pyro. The results made it possible to simulate how integrating thermal energy storage affects Ulmatec Pyros System. Ideally, the idea is to store energy similarly to how we store electrical energy in batteries.

In phase changing materials, latent heat storage can be utilized through changes in the state of matter from liquid to solid, and solid to liquid. During these transitions, heat can be added or extracted. The five compounds investigated as storage mediums were Acetamide, Xylitol, ATP 78, ATS 84 and ATS 89. These were chosen as suitable options based on heat of fusion and melting temperature, because the system has a specific operating temperature. On a vessel, where there's often weight restrictions and limited space, the size and weight of each components are crucial. Therefore, the weight and the volume of each compound is compared. In the system that was examined, Xylitol proved to be the most suitable compound.

By calculating the CO_2 emissions and fuel related costs, each storage capacity and corresponding weight and volume was discussed. The results indicates that the storage capacities that were investigated proved to be both environmentally and economically profitable when integrated on a RoPax-vessel. However, practical limitations makes it inconvenient to install large storage systems in the engine room of a vessel. Despite being incapable of storing all of the surplus energy, the smallest storage capacity examined is still able to reduce the usage of the fuel fired heater drastically.

Sammendrag

Den maritime næringen er forpliktet til å slippe ut mindre klimagasser for å møte etterspørselen og kravene til bærekraftige løsninger. En av løsningene innebærer å forbedre de allerede eksisterende fremdrifts- og hjelpesystemene ombord. Gitt disse utfordringene, har ønsket om energieffektivisering introdusert ny teknologi. Noen av disse er basert på gjenvinning og lagring av spillvarme.

Ulmatec Pyros Waste Energy Management System reduserer drivstofforbruket og utslipp ved aktiv utvinning av eksisterende energitap. Systemet utnytter mest mulig av spillvarmen og sikrer distribusjon til alle aktuelle forbrukere ombord. Typiske forbrukere er tank- og romoppvarming, klimaanlegg og andre varmtvannsforbrukere. Varmegjenvinningen utføres av eksosgassgjenvinnere, som er plassert på toppen av hovedmotorene. Gjenvinnerene henter varmen fra eksosgassen og bruker den til å varme opp vann.

Når det er overskudd av gjenvunnet varme, kan varmen lagres i termiske energilagringssystemer ved å bruke innkapslede faseendrende materialer som lagringsmedium. Beregninger på gjenvunnet varme, energibehov og overskuddsenergi ble gjennomført i Excel, ved å bruke driftsdata gitt av Ulmatec Pyro. Resultatene gjorde det mulig å simulere hvordan integrering av termisk energilagring påvirker Ulmatec Pyros system. Ideelt sett er ideen å lagre energi på samme måte som vi lagrer elektrisk energi i batterier.

I faseendrende materialer kan latent varmelagring utnyttes gjennom endringer i stoffets tilstand fra flytende til fast, og fast til flytende. Under disse overgangene kan varme tilføres eller trekkes ut. De fem materialene som ble undersøkt som lagringsmedier var Acetamid, Xylitol, ATP 78, ATS 84 og ATS 89. Disse ble valgt som passende alternativer basert på fusjonsvarme og smeltetemperatur, fordi systemet har en spesifikk driftstemperatur. På et fartøy, hvor det ofte er vektbegrensninger og begrenset plass, er størrelsen og vekten på hver enkelt komponent avgjørende. Derfor sammenlignes vekten og volumet av hvert materiale. I systemet som ble undersøkt, viste Xylitol seg å være det best egnede materialet. Ved å beregne CO_2 utslipp og drivstoffrelaterte kostnader, ble hver lagringskapasitet med

tilsvarende vekt og volum diskutert. Resultatene indikerte at lagringskapasitetene som ble undersøkt viste seg å være både miljømessig og økonomisk lønnsomt, ved integrering på et RoPax-fartøy. Imidlertid gjør praktiske begrensninger det upraktisk å installere store lagringssystemer i maskinrommet på et fartøy. Til tross for at den ikke er i stand til å lagre all overskuddsenergien, er den minste lagringskapasiteten som er undersøkt i stand til å redusere drivstofforbruket drastisk.

Preface

This bachelor thesis is submitted to the Norwegian University of Science and Technology (NTNU). The bachelor project has been performed at the Department of Ocean Operations and Civil Engineering, with associate professor Ann Rigmor Nerheim as main supervisor. PhD Candidate Lene Æsøy and Professor Vilmar Æsøy were co-supervisors. The scope of work was defined in collaboration with Lars-Erik Helland from Ulmatec Pyro, who also provided us with information and data on their equipment and system.

We would like to express our gratitude to our supervisor and co-supervisors for guidance through this project. We will also thank Lars-Erik Helland from Ulmatec Pyro for the opportunity to work on this bachelor thesis.

Ålesund, 16. May 2022

William Haugland   Victoria Myklebust   Mathias Herø Ulla

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Nomenclature

List of Abbreviations

Abbrev.	Definition
DNV	Det Norske Veritas
EH	Electrical Heater
EGE	Exhaust Gas Economizer
FFH	Fuel Fired Heater
FCU	Flow Control Unit
HVAC	Heating, Ventilation, and Air Conditioning
HT	High Temperature
IMO	International Maritime Organization
LT	Low Temperature
ME	Main Engine
MDO	Marine Diesel Oil
MGO	Marine Gas Oil
NTNU	Norges Teknisk-Naturvitenskapelige Universitet
NOK	Norwegian Kroner
PCM	Phase Changing Material
TES	Thermal Energy Storage
WEMS	Waste Energy Management System

List of symbols

Symbol	Definition	Unit
C_A	Costs thermal storage capacity 6134kWh	[NOK]
C_B	Costs thermal storage capacity 10632kWh	[NOK]
C_C	Costs thermal storage capacity 15189kWh	[NOK]
C_{NT}	Cost without thermal storage	[NOK]
ρ	Density	$[kg/m^3]$
E	Energy	$[kWh]$
E_S	Energy from surplus recovered thermal heat	$[kWh]$
TES_A	Energy in thermal storage with capacity 6134kWh	$[m^3]$
TES_B	Energy in thermal storage with capacity 10632kWh	$[m^3]$
TES_C	Energy in thermal storage with capacity 15189kWh	$[m^3]$
E_{FFH}	Energy produced by the fuel fired heater	$[kWh]$
E_{TES}	Energy stored in the thermal energy storage	$[kWh]$
T_f	Final temperature	[°C]
E_A	Fuel fired heater CO_2-emissions with capacity 6134kWh	$[10^3 kg]$
E_B	Fuel fired heater CO_2-emissions with capacity 10632kWh	$[10^3 kg]$
E_C	Fuel fired heater CO_2-emissions with capacity 15189kWh	$[10^3 kg]$
E_{NT}	Fuel fired heater CO_2-emissions without thermal energy storage	$[10^3 kg]$
FFH_A	Fuel fired heater production with capacity 6134kWh	$[kWh]$
FFH_B	Fuel fired heater production with capacity 10632kWh	$[kWh]$
FFH_C	Fuel fired heater production with capacity 15189kWh	$[kWh]$
FFH_{NT}	Fuel fired heater production without thermal storage	$[kWh]$
Q	Heat	$[J]$
C_p	Heat capacity	$[kJ/kg \cdot K]$
T_i	Initial temperature	[°C]
m	Mass	$[kg]$
m_A	Mass of the phase change material for the volume V_A	$[10^3 kg]$
m_B	Mass of the phase change material for the volume V_B	$[10^3 kg]$
m_C	Mass of the phase change material for the volume V_C	$[10^3 kg]$
T_m	Melting temperature	[°C]
e	Specific energy	$[kWh]$
V	Volume	$[m^3]$
u	Volumetric energy density	$[kW/m^3]$
V_A	Volume with thermal storage capacity 6134kWh	$[m^3]$
V_B	Volume with thermal storage capacity 10632kWh	$[m^3]$
V_C	Volume with thermal storage capacity 15189kWh	$[m^3]$

1 Introduction

The climate is changing because more greenhouse gases are emitted into the atmosphere. Humans are increasingly influencing the climate and the earth's temperature by burning fossil fuels, among other reasons. This adds enormous amounts of greenhouse gases to those naturally occurring in the atmosphere, increasing the greenhouse effect and global warming [16]. Climate change has serious consequences. The warmer it gets, the greater the effect of climate change. Poor people get affected the most because they are least equipped to handle the changes [45]. According to the UN Climate Panel, climate change will lead to health problems, less access to food and water, economical inequality, conflicts and refugees, damage to nature, infrastructure and buildings, and loss of biodiversity. Global warming increases the risk of extreme weather, more rain, floods and acidification of the ocean. The only way to stop climate change is to emit much less greenhouse gases than we do today [44].

Through the EEA agreement, The Paris Agreement and as a member of the UN, Norway is obligated to reduce their greenhouse gas emissions. The Paris Agreement is a legally binding international treaty surrounding climate change. According to the Paris Agreement, all countries must report new or updated emission targets every five years [29]. Norway's additional climate target is to reduce emissions by at least 50% by 2030 compared with the 1990 level. Through the climate agreement with the EU, Norway has already committed to reduce emissions by at least 40% by 2030 compared to levels in 1990 [40]. In addition, Norway is a part of the UN. The UN's sustainability goals consist of 17 goals, with 169 sub-goals. These describe the way to ensure global sustainable development by 2030 [43].

Shipping and fishing accounted for 7.5% of Norwegian greenhouse gas emissions in 2020 [28]. According to the Norwegian climate report in 2017, the Norwegian government has a goal for Norway to reduce emissions in the transport sector by 35-40% by 2030 compared to the levels in 2005 [41]. The maritime industry is obligated to emit less climate gases in order to meet the requirements and demands of more sustainable solutions. One of these changes will involve optimizing the already existing propulsion- and auxiliary-systems on ships. Most diesel engines operates within an efficiency range between 30-60%, producing more losses than usable rotating power. Majority of the losses can be recovered, and contained within Ulmatec Pyro's Waste Energy Management System. The system distributes recovered heat to relevant consumers on board. Reducing additional use of energy for heat production [38].

The strive for energy efficiency have introduced new technologies in the maritime industry. Some of them are based on recovering waste energy and storing it. This means that the recovered heat can also be used for producing electricity and as an energy source, for example water heating and air conditioning systems. Heat recovery is mainly from engine exhaust and high temperature cooling system, but low temperature and auxiliary systems are also candidates for recovery [38].

Ulmatec Pyros Waste Energy Management System reduces fuel consumption and emissions by recovering waste heat. The system utilizes as much of the waste heat as possible and ensures distribution to all relevant consumers on board. Typical consumers consists of the HVAC system, heating of bathrooms, cabins and living rooms, producing hot potable water, tank heating, preheating and heating water for the fresh-water generator and for the pool. The heat recovery is performed by exhaust gas economizers, which are placed on top of the main engines. The economizers extracts the heat from the exhaust gas and uses it to heat up water when surplus heat is available, instead of running a fuel fired heater. Optimally, the fuel fired heater only functions as a back up, or for peak shaving, and will very rarely be in operation [38]. A fuel fired heater usage reduction offers savings in fuel consumption and CO_2 emissions. The more on board consumers that can be added to the system, the more energy efficient the vessel will be. Naturally, the easiest way is to utilise the heat for other heat consumers on board [36].

The waste energy management system extracts heat and balances energy between various consumers. The system automatically detects energy available, and balances the recovery against consumer demand. Newer technology can store surplus energy in thermal storage systems, using phase changing materials. The storage of energy can provide heat when vessel is idle, at dock or not operational for other reasons. If the ship is operating in colder climates, the surplus energy can be used for anti-icing on railings, decks, stairs, etc. All these functions would otherwise require additional use of fuel, burned in an engine, with associated carbon emissions [38]. Thermal energy storage appears to be an appropriate method for correcting the mismatch that sometimes occurs between the supply of energy and demand of energy. It is therefore a very attractive technology for meeting society's needs and desires for more efficient and environmentally friendly energy use. TES are providing uninterrupted use of renewable energy for heating and cooling, flexibility options for power generation and secure and long-life use of electronics that are becoming more and more important in the digitized world [31].

Today, thermal energy storage is used to store energy from solar and wind energy production. The stored energy is then used at peak hours, and at night and when there isn't any sun. An example for thermal energy storage is a solar tower plant. A solar power system converts energy from the sunlight into electricity. The tower has mirrors that focuses the sunlight into an area where there is a heat transfer fluid. Newer solar power towers often uses molten salt because of increased heat transfer and energy storage abilities. The molten salt gets heated up by the sun, and then transported to a reservoir of water where it turns to steam. The salt can be stored in the reservoir and used when desired. The steam gets transported to a conventional turbine where the steam is being used to produce electricity [23]. This will be the same principle for thermal storage on ships.

In this thesis three students from the Norwegian University of Science and Technology are researching the amount of excess energy that can be stored by integrating thermal energy storage into the waste energy management system. The problem formulation is written in collaboration with Ulmatec Pyro AS. Ulmatec Pyro is a part of the maritime cluster on the north-western coast of Norway. In 2021, they set out to mobilize what they call "Green shipping". The company specialize in heating systems for ships based on waterborne heat. Pyro develops and sells systems and products for energy efficiency on ships [34].The market for their products includes, among others, research ships, offshore rigs, fisheries and offshore wind.

Problem formulation

To optimize the Waste Energy Management System (WEMS), Ulmatec Pyro wants to look at the possibility of integrating Thermal Energy Storage (TES) into the system. This is to be able to store the recovered heat, and reduce emissions from a diesel-fired boiler, which is used for heating water. The task was given in connection with a bachelor thesis in Renewable Energy Engineering at the Norwegian University of Science and Technology (NTNU).

Objectives

The main objective of this bachelor thesis project is to complete calculations and simulations to investigate if it is environmentally and economically profitable to optimize Ulmatec Pyros Waste Energy Management System on a RoPax-vessel by integrating thermal energy storage. The goal is to reduce emissions and save fuel related costs by optimizing the system.

Scope of work

The thesis is planned to cover:

- Description of the Waste Energy Management System.
- Description of Thermal Energy Storage systems for ships.
- Simulation of thermos tank and PCM-based storage unit.
- Requirements and prerequisites for the Water Heating system to be located in the engine room.
- Economic and environmental factors that play a role in the dimensioning of the TES system.

2 Theory

Ulmatec Pyros Waste Energy Management System (WEMS) reduces emissions and fuel consumptions by active recovery of energy losses. The focus is on how much energy can be utilized, and to ensure an optional distribution of recovered energy. The method is to use as much excess engine heat as possible. A exhaust gas economizer makes it possible to re-use heat from the exhaust for use in the auxiliary systems. A fuel-fired heater is, ideally, not used so often, but purposes is back up and for peak shaving. In the system, energy is balanced around in the ship so that rooms, tanks and water are being held at the required temperature. Other consumers for the waste energy that is recovered is the fresh water generator, cookers, tank heating, hot water consumers and HVAC. The WEMS is illustrated in figure 2.1, with the main components labeled [38] [25].

Surplus energy from the system can be stored in thermal energy storage tanks so that the ship can save the energy for heating when the boat is docked, running at battery mode or anti-icing in colder climates [37]. In Appendix A, the complete technical drawing of the the system with integrated thermal storage is shown [25].

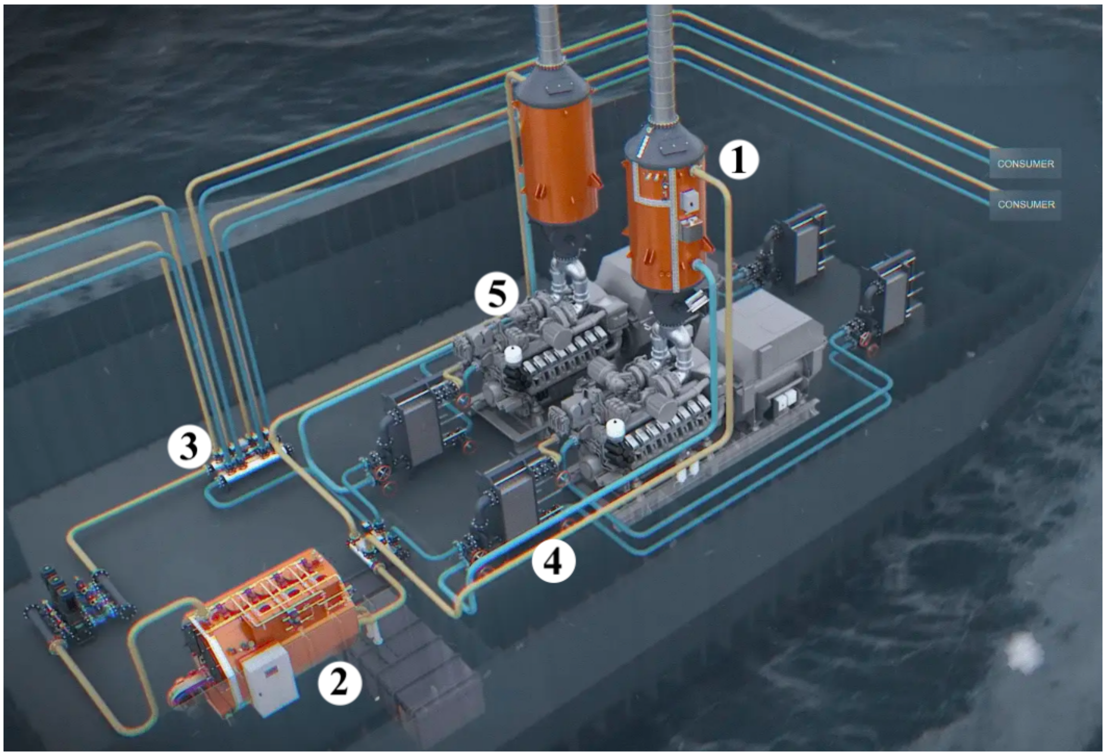

Figure 2.1: *Ulmatec Pyro's Waste Energy Management System: (1) Exhaust Gas Economizer; (2) Fuel Fired Heater; (3) Flow Control Unit; (4) Heat Exhangers; (5) Main Engines [38].*

2.1 Exhaust Gas Economizer (EGE)

The Exhaust Gas Economizer (EGE) is a waste heat recovery unit which recovers heat from exhaust of main or auxiliary engines and therefore does not use fuel. Instead of releasing exhaust gas immediately, the EGEs are placed on top of the main engines. The exhaust gas goes through the EGEs before it's released. The gas is captured in a tank and makes it possible for the economizer to re-use the heat from the exhaust to heat up water [25]. An illustration of the EGE is shown in Figure 2.1, labeled 1. The system is working on a temperature from 95°C to 120°C.

According to DNVs requirement, the exhaust gas economizer shall have manholes for inspection openings at the intake and outlet exhaust gas. In addition, it's required to have one stand-by pump when it is necessary with forced circulation for the exhaust gas economizer to operate. To prevent steam from being generated e.g. when feed water flow is being stopped suddenly, the economizer shall be installed with suitable equipment. DNVs requirements also states that in case the economizer is designed in a way that soot deposit may create a problem with fire hazard for example exhaust gas boilers with surface tubes that are extended, shall have soot-cleaning [20].

Flue gases along with some un-burned carbon particles, get deposited on the EGEs. Normally dry soot deposits have a very high ignition temperature. At low temperatures, or when the soot gets wet with hydrocarbon vapours, their ignition temperature comes down to approximately 150°C. This may result in boiler soot fire or boiler uptake fire [21]. Ulmatec Pyro delivers an additional soot cleaning tank for maintenance of the economizer [35].

2.2 Fuel Fired Heater (FFH) and Electrical Heater (EH)

For an auxiliary system that uses hot water to run consumers it's essential to have available energy in the system when it's needed. The FFH is a heat generation unit consisting of oil fired duct furnaces. A FFH is one solution to generate thermal energy on demand. It is used to generate heat from burning fuels to heat water for costumers on board. Ulmatec Pyro's™ Fuel Fired Heater uses marine gas oil (MGO) and marine diesel oil (MDO) to heat water in a closed system where water-pipes goes through to exchange heat. The heater also has electrical heating elements for back up. The water pipes has a pressure of 6bar. Ulmatec Pyro delivers FFHs that range from 25kW in use for small systems to 3500kW for high output systems, with working temperatures from 95°C to 120°C [38].

Unlike the FFH, electrical heaters uses electricity to heat water to the required temperature. For this to happen, the electric heater has to be connected to a power supply. The water is being heated by heating elements in the water that provides production of heat. When a ship is out in the ocean, a heat exchanger circuit is sending water that is used to cool the engine to the electrical heater to heat up the water inside the system [22]. Even though it's heating the water by using electricity, it is not particularly energy efficient, since the electrical power is generated by diesel generators at around 30-60% efficiency [38].

2.3 Flow control unit (FCU)

The flow control unit controls the flow of the system. A flow control unit has a motor controlled valve that is operating from open at 100% to closed at 0%. These valves are regulated by measuring the temperature of the water in the return line from the heat exchangers. When the valve is closed, there is a small flow that always run through the circuit. If the temperature goes over the preset temperature, the flow will increase in a attempt to retain the temperature. If the temperature sinks, the flow will decrease to keep the temperature that was preset. To keep the needed pressure over time at any flow, there is installed a motor controlled valve to regulate pressure between the pressure pipe to the recovery units and the return pipe on the fuel fired heater. The pipes that are used in the fuel fired heater system are insulated with mineral wool [25].

2.4 Heat exchanger

An heat exchanger exchanges heat between two thermal fluids. The heat exchanger has a cold fluid and a warm fluid and gives the opportunity to exchange heat without the two fluids mixing. Heat exchangers are used inn all types of systems including air conditioners, engine cooling systems and is an essential part of heat recovery. In the exhaust gas economizer an heat exchanger is used to recover heat from the warm exhaust air and transfers the heat by convection through metal to the water. The heated water can then be used to run consumers [25].

In the WEMS, a heat exchanger is installed in the high temperature cooling system of the engine. The normal inlet temperature for the heat recovery heat exchanger is 85°C to 96°C on the engine side. The outlet temperature is between 65°C to 75°C. The heating system side has normally 65-70°C in and 85°C out. The heat exchanger for heat recovery can also be used for pre-heating the engine when the ship stands still. For this to work, the pre-heated pump on the engine has to be started and circulate the high temperature cooling water through the heat exchanger. The preferred direction is the opposite of the normal flow [25].

2.5 Requirements and prerequisites for the water heater system

The water heater system that is installed has a thermostat that is sensing the temperature of the water and maintain the set temperature. Using these thermostats is a requirement from DNV regarding water heaters. There is also requirements when temperatures rises. Equipment that is used for controlling the heating system such as switches, handles and knobs has maximum temperatures attainable. Metal parts has a maximum attain temperature at 55°C and parts that is made of porcelain, glass, moulded plastic or wood can not have temperatures higher then 65°C [19].

While dimensioning is done for a water heater system, Table 2.1 shall be used when the output of the heater is known to figure out dimensions of expansion, overflow, drainage and pipes for venting. This requirement is given by DNV's rule 3.3.2 [20].

2.6 Phase Changing Materials (PCM)

A phase changing material is often a chemical compound that changes states depending on the temperature of the material. It can be defined as: "An organic or inorganic compound,

Table 2.1: *DNVs Requirement 3.3.2 about regarding diameter of expansion, overflow, drainage and venting pipes for different outputs of the heater [20].*

Heater Output [kW]	Expansion and overflow pipes Nominal diameter DN	Drainage and venting pipes Nominal diameter DN
$\leq$600	25	32
$\leq$900	32	40
$\leq$1200	40	50
$\leq$2400	50	65
$\leq$6000	65	80

able to store and release the thermal energy under latent form when it changes from one physical state to another at a nearly constant temperature" [12]. PCMs are ideal for use in any application where a storage and release of thermal energy is desired. The best known and used PCM is water, used as ice for cold storage since early times. Many materials have been studied as PCM, but only a few of them have been commercialized, mainly due to problems such as phase separation, subcooling, corrosion, long-term stability, and low heat conductivity. Usually PCM are selected based on the appropriate melting enthalpy and temperature, availability and cost [13].

Encapsulation of PCM

Successful utilization of PCM and heat transfer fluid depends on the containment of the material. The PCM encapsulation with different geometries of capsules has its own advantages and disadvantages. PCM containment should meet the requirements of strength, flexibility, corrosion resistance and thermal stability. The containment should also act as barrier to protect the PCM from harmful interaction with the environment, provide sufficient surface for heat transfer, provide structural stability and easy handling [39].

Three alternatives for encapsulation is illustrated in Figure 2.2. Multiple-pipe configuration (A) separate the PCM in tubes, with the water flowing outside of the tubes, e.g. In a tank. The flat-plate encapsulation (B) works by flow of the heat transfer fluid, in this case water, by plates encapsulated with PCM. The cross flow shell and tube encapsulation (C) is a two layer tube, where the PCM is in the outer shell, and water flows through the middle in a separate tube.

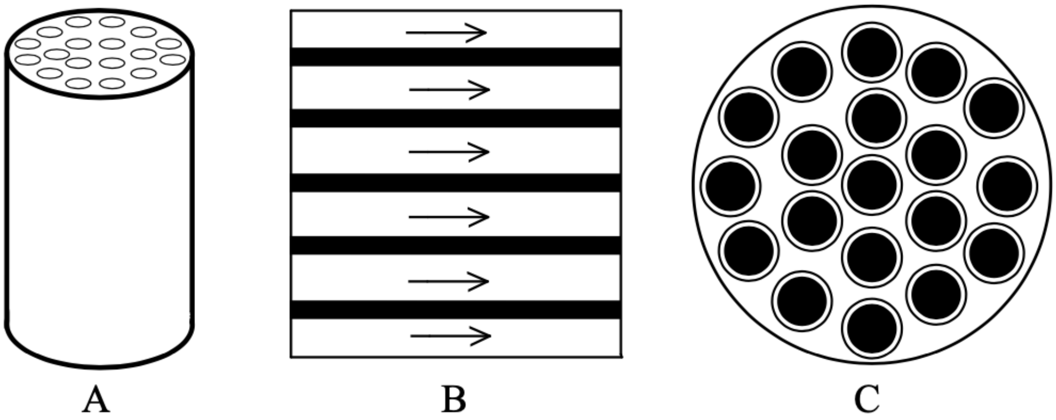

Figure 2.2: Three different types of encapsulation of phase changing material:(A) multiple pipe configuration, (B) flat-plate and (C) shell and tube with cross flow.

It is essential that the material that's used has a low volume change during phase changing. Although liquid to gas transitions have a higher transformation heat than solid–liquid transitions, liquid to gas phase changes are more expensive and impractical for thermal storage because larger volumes and high pressures are required to store the materials in their gas phase. For the material to change state from a solid to a liquid, it absorbs heat. The temperature of the material does not change until the whole material has changed form. After everything has changed form, the temperature rises and the stored thermal energy is determined by its energy capacity. When thermal energy is taken out of the material, it releases its stored energy and changes back to solid form [33].

There are several different compounds to explore for PCM in any required temperature range from −5°C up to 190°C. The system that's investigated in this thesis operates at between 80°C and 95°C. Acetamide, Xylitol, ATP 78, ATS 84 and ATS 89 are some of the PCMs that are relevant for these operational temperatures. All of the properties of the PCMs used in the calculations in this project is listed in Table 2.2.

Table 2.2: Properties of 6 different Phase Change Materials [10], [8], [5], [46], [47]

Class of compounds	**Compound**	**Melting temp.** $[°C]$	**Heat of fusion** $[J/g]$	**Thermal conductivity** $[w/mK]$	**Heat capacity** $[kJ/kgK]$	**Density** $[kg/m^3]$
Amides	Acetamide	82-86	263	0,43	1,13	1160
Sugars	Xylitol	92-96	280	0,4	2,36	1520
Organic	ATP 78	75-79	225	0,2	2	800
Inorganic	ATS 84	81-85	145	0,6	2	1650
Inorganic	ATS 89	88-91	145	0,6	2	1580
Inorganic	Water	0	0	0,6	4,2	1000

2.6.1 Acetamide

Acetamide is a organic fatty acid with 97% purity. Acetamide has a melting temperature from 108°C to 112°C. Stainless steel and aluminium are suggested to be compatible with

Acetamide. In a study testing Acetamide as a PCM, the conclusion that PCM is best used for mid-range (80-120°C) [11]. There has been limited knowledge about the corrosion behavior of Acetamide with different metals. Acetamide has a melting point at around 80°C-82°C. The latent heat of fusion is 241kJ/kg - 264,2kJ/kg. The density of Acetamide is 1159kg/m^3 [14]. Thermal conductivity at 0,43 W/mK at 60°C solid and 0,25W/mK at 90°C liquid. The specific heat of Acetamide is 1,13kJ/kgK (LG) [10]. Acetamide is slightly flammable, and poisonous gases are produced in fire. It has a moderate health hazard, as it can affect you when inhaling and by passing through the skin [24].

2.6.2 Xylitol

Xylitol is an organic compound which can be used in PCM based TES. Xylitol is an sugar alcohol with density of 1520kg/m^3 and melting point between 92°C and 96°C, with peak heat capacity at 95.89°C [50]. Sugar alcohols are non corrosive and shown to be stable over repetitive cycling. One downside to sugar alcohols is their low thermal heat transfer. They are sustainable and extracted from plants which makes them both cheap and accessible. Xylitol having a melting point higher then the operating temperature would diminish its capabilities for latent heat storage as the material haven't all melted at operating temperature. Its heat of fusion is 280kJ/kg and has a specific heat capacity of 2.36kJ/kgK Xylitol is not regarded as dangerous for the environment. Dust may irritate the eyes and the respiratory system. Fire or excessive heat may produce hazardous decomposition products [17] [5] [33] [9].

2.6.3 ATP 78

ATP 78 is a organic compound designed by a German company, Axiotherm GmbH, who specialize in TES and PCM. Their PCM is designed to absorb and release large quantities of thermal energy and deliver high heat storage capacities. ATP 78 is a organic compound. ATP 78 has a density as liquid to 800kg/m^3. The melting temperature of the compound is from 75°C to 79°C. Heat of fusion for ATP 78 is 225kJ/kg at a optimum temperature range of 70°C to 85°C. ATP 78 has a volume expansion at $> 10\%$. ATP 78 is a simple PCM and safe to handle. Raw materials in use are renewable, non-toxic and biodegradable. Axiotherm GmbH sells these materials in what they call Heatsel®s and Heatplates which are sealed containers for optimizing surface to mass ration for faster energy transfers [7]. ATP78 is simple and safe to handle. It is based on renewable raw materials, nontoxic and biodegradable [8].

2.6.4 ATS 84 and ATS 89

ATS 84 and ATS 89 is an inorganic compound also designed by Axiotherm GmbH. ATS 84 and 89 are two similar compounds are shown to be consistent. They are made from renewable raw material which are non toxic and biodegradable. Both have shown capable performance over thousands of thermal cycles. On the other hand they do have a corrosive effect on metals which provide a challenge to containing the compounds. They also comes in Axiotherm's Heatsel®s and Heatplates [7]. ATS 84 has a melting range between 81°C-85°C while ATS 89 has a melting range of 88°C-91°C. Both has latent heat of fusion

145kJ/kg, specific heat capacity of 2kJ/kgK and a volume change under 6%. ATS 84 has a density of 1650kg/m^3 while ATS 89's density is at 1580kg/m^3. ATS 84 and 89 has great operation temperatures for the systems temperature range, but their latent heat of fusion is low [8].

2.7 Principle of Thermal energy storage (TES)

Ali H. Abedin and Marc A. Rosen defines thermal energy storage as "the temporary holding of thermal energy in the form of hot or cold substances for later utilization" [3]. TES is an advanced energy technology that is attracting increasing interest for thermal applications such as space and water heating, cooling, and air conditioning. TES systems have enormous potential to facilitate more effective use of thermal equipment and large-scale energy substitutions that are economic. TES appears to be the most appropriate method for correcting the mismatch that sometimes occurs between the supply and demand of thermal energy [18].

Surplus energy from the system can be stored in thermal energy storage system, using Phase changing materials (PCM) encapsulated in some form as a storage medium. As shown in Figure 2.3, hot water runs through the system, which heats the PCM-material to the desired temperature. The energy is stored in the PCM-material at liquid phase, until it's needed. To release the stored energy, colder water runs through the tank. The water is heated up by the PCM-material, before it's distributed to the costumer. When using TES on maritime environments, one of the main challenges include the size of the TES. On a ship, the weight and size of a TES can't be too high for the specific ship. TES systems are divided into three types; Sensible, latent and thermochemical thermal energy storage. All three with their own advantages and disadvantages depending on the area of use.

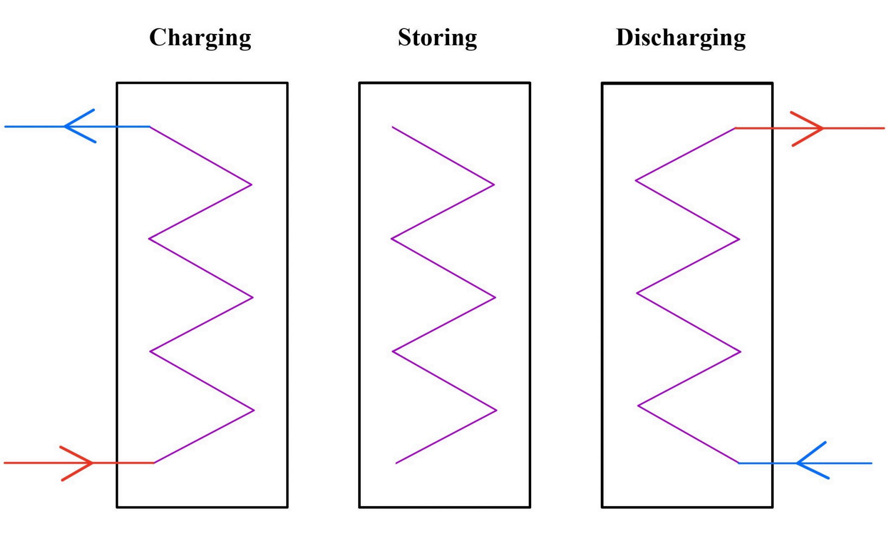

Figure 2.3: *Illustation of the principle behind thermal energy storage.*

Sensible- and thermochemical thermal energy storage

Sensible TES stores energy by heating or cooling a solid or liquid material. Examples of materials typically used as a storage medium are water, air, oil, rocks, concrete, sand and soil. Normally it is used for a volumetric air or compressed-air system [52]. In Equation 2.1 [33], the stored thermal heat Q is dependent on the material's heat capacity C_p, it's mass m, and temperature differential $T_f - T_i$.

$$Q = \int_{T_i}^{T_f} mC_p dT = mC_p(T_f - T_i) \tag{2.1}$$

Thermochemical TES is produced when a chemical reaction, with high energy involved in the reaction, is used to store energy. Thermochemical TES systems are especially suitable for long-term energy storage, and often have minimal losses. Thermochemical heat storage is rather complex, and generally the technology is not available, but undergoing research and pilot project tests [3].

Latent thermal energy storage

Latent thermal energy storage is more relevant for this application than sensible and Thermochemical energy storage. Latent heat storage can be achieved through changes in the state of matter from liquid to solid, solid to liquid, solid to gas and liquid to gas. During these transitions, heat can be absorbed or released. However, only solid to liquid and liquid to solid phase changes are practical when using PCM because of the large expansion of gasses. Latent heat is more effective because it can store energy in two separate stages. The first stage is in form of sensible energy storage from thermal energy, and the second stage is from the latent heat storage, where energy needed to change phase is stored. This makes it possible to store more energy with the same amount of material [33].

Equation 2.2 [33] for latent energy storage uses two integrals and an addition for the melting of material to calculate the stored thermal energy. The first integral is based on initial temperature T_i to the melting point T_m. Then we can add on a segment for the energy stored during phase changing where a_m is fraction melted and ΔH_m is heat of fusion. After this we can add on the integral for the molten material from the temperature T_m to the final temperature T_f.

$$Q = \int_{T_i}^{T_m} mC_p dT + ma_m \Delta H_m + \int_{T_m}^{T_f} mC_p dT \tag{2.2}$$

Equation 2.3 for latent energy storage uses two integrals and an addition for the melting of material to calculate the stored energy. The first integral is based on initial temperature T_i to the melting point T_m. Then we can add on a segment for the energy stored during melting where a_m is fraction melted and ΔH_m is heat of melting per unit mass [J/kg]. After this we can add on the integral for the molten material from the temperature T_m to the final temperature T_f.

Volumetric energy density u for a compound can be calculated as shown in Equation 2.3 where specific energy e is multiplied with its density ρ [32].

$$u = e\rho \tag{2.3}$$

The volume V of the different PCM can be calculated as shown in Equation 2.4 where energy E is divided by volumetric energy density u [32].

$$V = \frac{E}{u} \tag{2.4}$$

The mass of the different PCMs can be calculated using Equation 2.5 , where m is mass of a compound, V is volume of a compound and its density ρ [32].

$$m = V\rho \tag{2.5}$$

The stored energy in a TES can be calculated using Equation 2.6, where E_{TES_n} is the current energy stored, $E_{TES_{n-1}}$ is the energy of the previous step, E_{S_n} is the Surplus energy for the current step and n is the current step

$$E_{TES_n} = E_{TES_{n-1}} + E_{S_n} \tag{2.6}$$

Equation 2.7 [32] is a modified version of 2.6 where E_{FFH_n} is the energy usage of the FFH.

$$E_{FFH_n} = E_{TES_{n-1}} + E_{S_n} \tag{2.7}$$

3 Methods

It was straightforward and manageable to carry out the calculations and simulation in excel. The data which is used in calculations and simulations of the TES was provided by Ulmatec Pyro. The data includes operating profile for existing ships. In addition to the data given, other material was collected online from different scientific papers and peer reviewed publications. Individual references will be given when it's relevant.

Ulmatec Pyro provided operational profiles for one vessel, including hours of operation and distances for each profile. The heat recovery data Ulmatec Pyro gave was from an other vessel. During calculations on energy flow, it was assumed that these two ships had similar operational hours and distance. The energy balance was multiplied by its corresponding operational hours to calculate the energy use and excess energy for each operation, as presented in Appendix B. These were then added together, resulting in a total energy balance for each trip, using both 14kn and 20kn sailing speed, with and without energy storage. The excess recovered heat was taken in to the calculation for energy storage. For the calculations without energy storage, all excess production was set to zero to simulate disposal of excess heat to sea water heat sinks, as it is practiced without the thermal storage.

3.1 Comparing phase changing materials

To calculate the values for specific energy in Figure 4.2, Equation 2.1 and Equation 2.2 was used. Before the material is melting, Equation 2.1 is used to calculate the storage potential of each material, with a starting temperature of 80°C. and T_f is its current temperature. At the melting point of each material, Equation 2.1 is still used, as it's assumed that the material has done little to no melting. This makes the $a_m \approx 0$ and there's no energy from the latent heat or the last integral in Equation 2.2, since the T_m and T_f are the same.

When the material has stated to melt, Equation 2.2 was used. Each material has a 4 degree melting range, where a_m increased in increments of 0,25 each degree of melting, until it reaches 1 on the 4th degree. This is determined on the basis that Xylitol, ATP 78 and ATS 84 has a melting range of 4 degree. From this we get an accurate calculation for how the latent heat of each material affects its performance. The three terms of Equation 2.2 are used to calculate stored thermal energy in each compound, except water. The first term is calculated using the first integral, and responds to the sensible energy storage of the solid material. The second term responds to the latent heat stored while melting. The final term uses the last integral to calculate the sensible energy storage of the liquid material. By adding these together we get the stored energy of the each material at a given temperature, as shown in Figure 4.2.

To calculate the energy density for Xylitol, ATS 89 and Acetamide in Table 4.2 is converted from kJ to kWh by dividing kJ on 3600, which is the conversion factor between kWh and KJ. This conversion was done to match the energy units used in the documentation provided by Ulmatec Pyro. Then the stored energy of each material at 95°C is multiplied by their density to get their energy density using Equation 2.3. The storage capacities was divided by the energy density using Equation 2.4, resulting in minimum required volume for each compound.

To check that the calculations are realistic along the way, the energy density calculated in Table 4.2 was compared to a general density storage of latent thermal energy storage, which the range of 0,3 - 0,5 GJ/m^3 [3]. This was done by multiplying the energy density with 3600.

The calculated data and information from Ulmatec Pyro was reviewed. A minimal, repetative and maximum recovered energy was set as the thermal storage capacity. These are presented in Table 4.1. These three capacities where suggested based on calculations for main engine heat recovery at 20kn. The required material volume in Table 4.2 was then calculated by using Equation 2.4, where the energy is divided by the energy density. The material weight in Table 4.3 was then calculated by multiplying each of the material's density by the volume in Table 4.2 using Equation 2.5. The corresponding mass for each storage capacity is calculated by using the volume from Table 4.2 and multiplying it by each compound's density, as shown in Equation 2.5.

3.2 Simulation of thermal energy storage and fuel fired heater

The vessel is traveling between three ports A, B and C. During trip 1, Route A-B shown in Appendix B, it was assumed that all three TES system from Table 4.1 is fully charged. For the next trip the energy remaining was carried over from the previous route. This was done for all trips on the assumption that the TES can't be charged in port. Ulmatec Pyro didn't provide any data on heat recovery at port from the main engines EGEs, so this was not taken in to consideration in the calculations.

The simulation comprehends how much energy is flowing in and out of the TES system, and when the FFH needs to provide extra energy. The calculations on each trip includes the three TES systems and their corresponding FFH, where TES_A is connected to FFH_A A etc. FFH_{NT} represents how the system is today with no thermal storage. Ulmatec Pyro provided operational profiles for 42 trips for a RoPax-vessel. Our simulation is based on this data. Each operation uses different amounts of time, and therefore it was decided to break every operation into increments of 0-1 hour. Hours for each operation was set up. This was necessary to get an accurate status for energy demand, energy production and surplus energy.

The auxiliary heat consumption is calculated by multiplying consumer demand, and operational hours to get the auxiliary heat consumption. Consumer demand is constant, but auxiliary heat consumption varies depending on time. Recovered heat from the EGE is calculated by multiplying recovered power by its operational hours for its corresponding operation. Each operation has its own recovered power, shown in Figure 4.1. The surplus is calculated by subtracting auxiliary heat consumption from the recovered heat. This gives an energy balance for each operating hour. A positive surplus means there is a excess of energy and a negative surplus means a lack of energy. When there is a lack of energy, the TES or the FFH has to provide it. Energy stored in the TES was calculated using Equation 2.6 where the surplus was added to the TES in the previous step. When the energy in the TES goes negative it is set to zero until it gets charged. When the stored energy is higher then the storage capacity, it is set to its maximum value. When there isn't enough energy in the TES, the FFH is starts energy production. The energy production is calculated using Equation 2.7. In Appendix B, the FFH production values are negative. In hindsight, maintaining the values positive might be advantageous to avoid confusion.

3.3 Calculations on emissions and costs

Ulmatec Pyro provided data showing the most demanding month for a RoPax-vessel. To calculate the economic and environmental savings, the FFH fuel consumption is necessary for each storage capacity. The fuel consumption for each storage capacity is compared to the usage without TES. Only six of the routes provided by Ulmatec Pyro was used for further calculations, due to a large amount of calculation with a limited amount of time. A ratio between sailing time and distance was calculated to check if the ratio could be representative for for all trips. A ratio between sailing time and distance was calculated for six routes and for the whole month. Sailing time was divided by distance and the division gave an average speed. This was done to see if they were comparable, which they were. In that way, the calculations that was already completed for the six routes could be used as an approach for all trips, with 5% insecurity. The calculations for the six selected trips, as shown in Appendix B, were then multiplied by seven for it to be representative for the 42 routes of one month.

Specific fuel oil consumption for the FFH was given by Ulmatec Pyro [25]. Energy production from the FFH was multiplied with specific fuel consumption and then divided by 1000 to convert specific fuel from g to kg. The price of the fuel consumption was calculated by multiplying fuel consumption and MGO global average bunker price given by ship and bunker [48]. This price is in dollars per kg. It was converted to NOK per kg by multiplying the currency exchange from dollars to NOK , using the currency exchange rate at 9,83 NOK/dollar [51].

CO_2 emission is needed to calculate economic and environmental savings. The CO_2 emission is calculated by multiplying fuel consumption in kg with MGO CO_2 emissions. The MGO emissions are tank to wake values and is in ton/ton fuel [15]. The calculation is divided by 1000 to get the CO_2 emission in ton. To calculate the cost of the Norwegian CO_2 tax, the CO_2 emission was multiplied with the CO_2 tax [42]. Since the CO_2 emission only included six trips, it was multiplied by seven to get CO_2 emission per month. Fuel cost for the FFH with different storage capacities was calculated by summarizing the fuel consumption cost of each FFH, and then multiply it with seven to get the fuel cost for one month. The total fuel related costs was calculated by summarizing the calculated CO_2 tax and fuel cost. Savings was calculated by subtracting the costs including TES from the the costs without TES. Calculating the environmental savings was done by summarizing the CO_2 emissions from each of the FFH, and then multiplying them by seven.

The material costs have not been included in the economical calculations due to challenges related to available comprehensive information. To create a more realistic picture of how large the savings will be, the cost of the materials also has to be included in the calculations.

4 Results and discussion

The power balance for each operational profile of the vessel is shown in Figure 4.1. The blue pillar represent recovered by the EGE. The orange is the maximum consumer demand. The grey is the surplus power that's recovered, and can be stored. When the power balance is positive, the system is producing excess power. When it's negative, it needs extra power from the FFH. These results are for the specific motor and loads from the data provided by Ulmatec Pyro. In Appendix B, it's shown that the ship operates with one motor at 50% load at 14kn and two motors at 80% load at 20kn. These results are mainly representative for this specific vessel with the assumptions stated in the Methods in section 3.

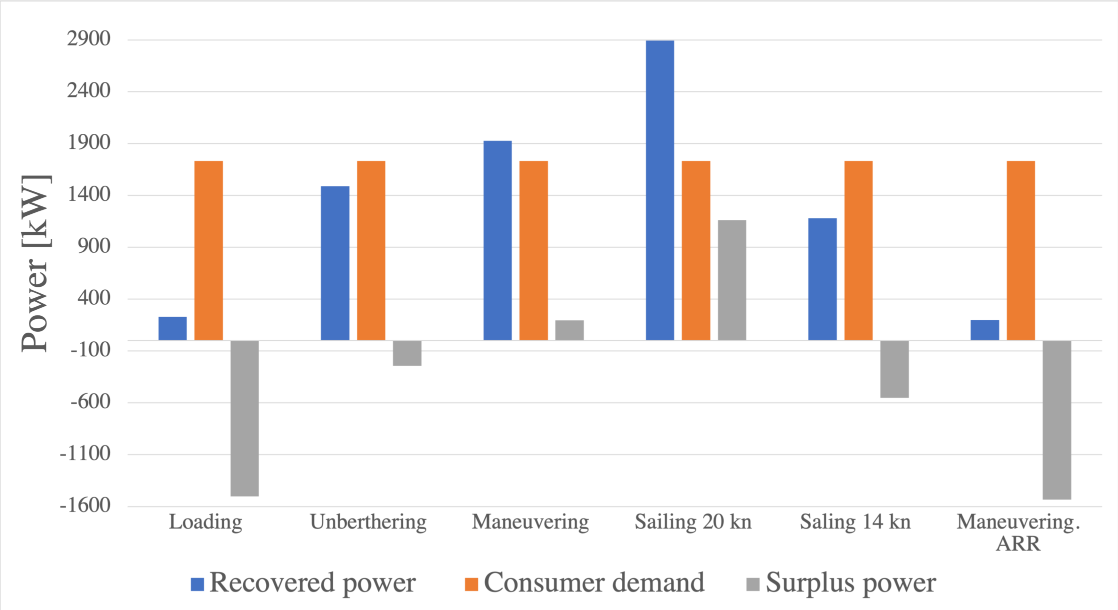

Figure 4.1: *Energy balance for the exhaust gas economizer with different operation profiles.*

As shown in Figure 4.1, the EGE only recovered power when the ship is sailing at 20kn and when maneuvering. This vessel often sailing at 20kn, and has the potential to recover and store a certain amount of energy when it does. However, if the ship was to mainly sail at 14kn, it would not recover enough heat to supply the consumers.

4.1 Performance of different phase changing materials

The operating temperature in the system is 95°C. However, the simulation presented in Figure 4.2 shows how one kg of each material stores energy with rising temperature up to 99°C. This is shown because ATS 84 and ATS 89 is at their maximum operating temperature at 99°C. At temperatures higher than max operating temp, the materials might become unstable. In addition, Xylitol shows a performance increase after the operating temperature of the system. Xylitol has a peak energy storage capacity for latent heat at 95,89°C, and has a higher energy density than the other compounds. Therefore, it is relevant to look at how much space that could be saved by increasing the system temperature by 1°C [50].

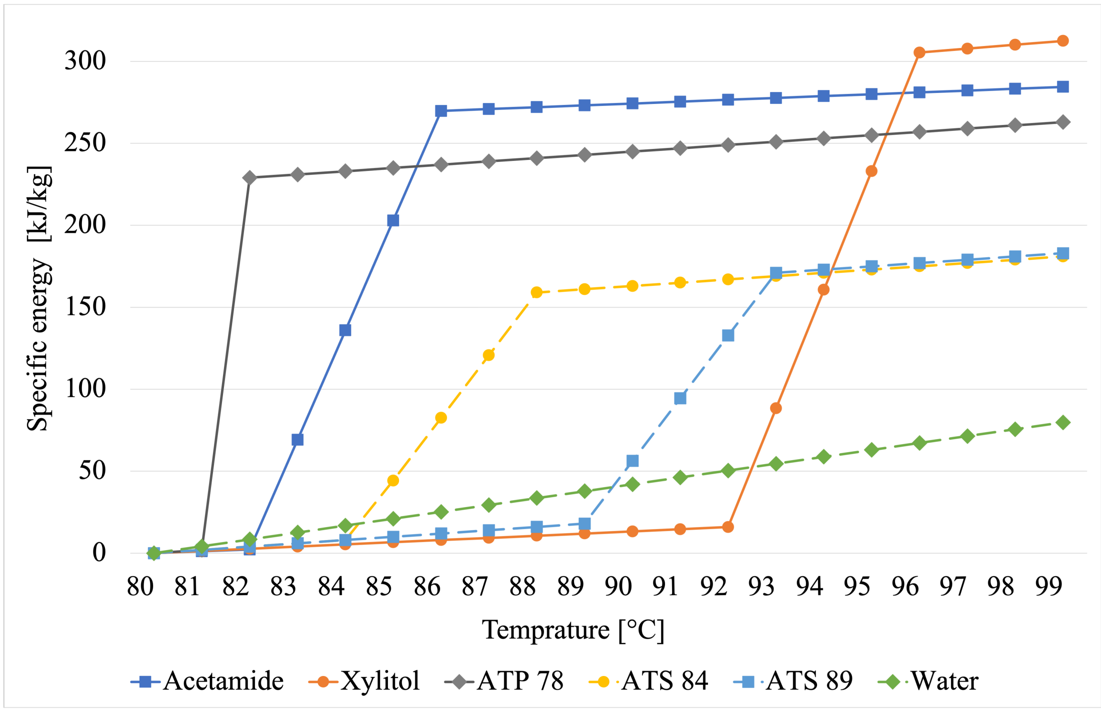

Figure 4.2: *Specific energy for different phase changing materials up to 99 °C.*

Figure 4.2 shown that there are three compounds that provide superior specific energy. ATP 78 has the highest specific energy in the beginning, and ends with the third highest value. ATP 78 is already completely melted at the starting temperature and wouldn't release any latent heat. Meaning that it's less effective in this temperature range. The next material to melt is Acetamide at 82°C. It surpasses ATP 78 at 86°C. It then reaches a peak of 280kJ/kg. At 95°C Xylitol is still melting and reaches its specific energy is at 233kJ/kg, which is lower than Acetamide and ATP 78. Xylitol shows great potential to deliver much of its energy at a high temperature, but lacks in specific energy. At 96°C, Xylitol reaches over 300kJ/kg, and has the highest specific energy. Acetamide is still rising, but not at the rate that Xylitol does. By increasing the operating temperature 1°C , Xylitol can provide a higher specific energy at a lower weight compared to the other compounds. ATS 84 and ATS 89 melts at different temperatures but reach similar specific energy values, which are significantly lower than Xylitol, Acetamide and ATP 78. Water, which only have sensible thermal energy storage has a consistent and steady rise but get outcompeted by all others at 93°C.

4.2 Dimensioning the thermal energy storage

The three storage capacities shown in Table 4.1 are based on looking at minimum, repetitive and maximum heat recovery data calculated. The energy production from sailing at 14kn and 20kn was calculated by multiplying the energy balance in Figure 4.2 by its operational hours, as mentioned in Section 3.1.

Table 4.1: *Three thermal storage capacities for each thermal energy storage system.*

Storage Capacity	A	B	C
Energy Storage [kWh]	6134	10632	15189

When the goal is to optimize the efficiency, it can be challenging to insert a TES system at the size needed for the PCM. Especially on a vessel with weight and volume limitations. Inserting a heavy system to optimize a system on a vessel might not be profitable, because the vessel might use more fuel for propulsion, even though it's saving fuel in the auxiliary system. Table 4.2 describes the different energy densities and volume for each compound that's investigated in these calculations at different storage capacities and temperatures.

Table 4.2: *Energy density and minimum required volume of each material for the different storage capacities given in Table 4.1, for 95°C and 96°C.*

Temperature $[°C]$	Compound	Energy density $[kWh/m^3]$	V_A $[m^3]$	V_B $[m^3]$	V_C $[m^3]$
95	Xylitol	98,39	62,34	108,05	154,37
	ATS 89	76,81	79,86	138,43	197,76
	Acetamide	90,21	68,00	117,86	168,38
96	Xylitol	128,95	47,57	82,45	117,79
	ATS 89	77,68	78,96	136,86	195,52
	Acetamide	90,57	67,73	117,39	167,70

At 96°C Xylitol has a 29,8% less volume than Acetamide for all volumes. However, the volume of Xylitol is still unrealisticly large. V_C corresponds to the size of approximately 5,5 average swimming pools on cruise ships, which is around 3x6x1,5m [26]. The comparison is based on the PCM size alone, without encapsulation. It's unlikely that a vessel has the capability to integrate a thermal energy storage system at this size, given that space is limited on these types of vessels. V_A and V_B can compare to the size of 1,7 and 2,9 average swimming pools on vessels, respectively. These are more likely to be able to fit on a vessel, given that this is a large vessel, but it depends on the amount of free space available.

Xylitol has the highest volumetric energy density of all three compounds at 95°C and gets an increase off 31% at 96°C. It also has the lowest volume requirements out of the three compounds at 95°C. ATS 89 has the highest density of the three, as shown in Table 2.2, which impacts its volumetric energy density and making it comparable despite its low specific energy. Its energy density is the lowest, requiring the highest volume out of the three. The difference between operating at 95 and 96°C for ATS 89 is minimal. Acetamide is a close runner up to Xylitol with a high volumetric energy density and low volume for every storage capacity. Acetamide has a small change from 95°C and 96°C.

The required weight for each TES capacity is calculated by using the volume from Table 4.2 and multiplying it by each compound's density, as shown in Equation 2.5. Table 4.3 presents how much weight is needed for each storage capacity. Xylitol is the second heaviest compound at 95°C, but becomes the lightest at 96°C. ATS 89 has the heaviest weight at at 95°C, which is 25% higher then the second heaviest, Xylitol. Acetamide is the lightest compound at 95°C, but Xylitol becomes 8% lighter than Acetamide at 96°C.

To choose a suitable PCM, it's useful to compare each compounds strengths and disadvantages. Xylitol, with its higher energy density uses the least amount of space but is the second heaviest compound at 95°C. Choosing Acetamide at 95°C would reduce the weight, but there is a small size increase compared to Xylitol. ATS 89 has a significantly larger volume than Xylitol and Acetamide.

Increasing the temperature with 1°C reduces weight and volume for every compound,

Table 4.3: Material weight for each compound at 95°C and 96°C.

Temperature [°C]	Compound	m_A [$10^3 kg$]	m_B [$10^3 kg$]	m_C [$10^3 kg$]
95	Xylitol	94,76	164,24	234,64
	ATS 89	126,19	218,72	312,46
	Acetamide	78,88	136,72	195,32
96	Xylitol	72,31	136,05	186,11
	ATS 89	124,76	216,24	308,93
	Acetamide	78,56	136,17	194,54

which would be advantageous. The outlier is Xylitol which gets an 31% increase in its energy density. Using Xylitol at 96°C achieves the smallest system. There's still a challenge regarding that it would be rather large and hard to incorporate, and also regarding weight. ATS 89 having the smallest specific energy, lowest energy density, largest volume and being the heaviest makes it the least suitable compound for this specific system.

An essential part of operation is the temperature of the water. The temperature operates between 80°C and 95°C which means that ATP 78 would never solidify and release heat. This makes ATP 78, in practise, a sensible TES and not latent TES with PCM. To make ATP 78 a suitable compound, the operating temperature would need to be lowered to 75°C. Xylitol delivers most of its latent heat between 92°C and 96°C, which helps to maintain a stable high temperature. Acetamide has a low melting point, which means that most of its latent energy is delivered between 82°C and 85°C. This could potentially impact the performance of consumers that might be temperature sensitive. ATS 89 delievers latent heat at temperatures between 88°C and 91°C, which makes it easier to maintain a stable high temperature, comparable to Xylitol.

Xylitol is the compound that appears to be most suitable for the system. Increasing the operating temperature would reduces both the required weight and volume. However, even by choosing the smallest storage system at 96°C, which is 47,57m^3, the storage medium alone can compare to a fuel tanker trailer with a capacity of 45m^3 [27]. A storage system of this size is likely not possible to incorporate in an engine room on a vessel. Further research on examining available space in the specific vessel is suggested, given that it's an essential part when considering integrating a thermal storage system.

4.3 Simulation results

The simulation comprehends how the auxiliary systems consumes and produces energy, with and without TES for six consecutive trips. The simulation was performed in Excel to represent the energy flow during operation and show the capabilities of the different TES capacities. The simulation incorporates four systems where TES$_A$ corresponds with FFH$_A$ and similarly for TES$_B$ and TES$_C$, while FFH$_{NT}$ is how the system operates without TES. The simulation is in Appendix B, and shows the different consecutive trips preformed by a RoPax-vessel. The starting condition for the first trip in the simulation is that every TES is fully charged, corresponding with their storage capacities from Table 4.1. The second condition is that there isn't any consumption or charging while the vessel is at port.

The speed of trip 1, Route A-B in Appendix B is 20kn. The simulation shows that every TES is discharging during loading and unberthing. TES$_A$ still has 26% charge, while

TES_B and TES_C still has 58% and 70% charge, respectively. During sailing every TES reaches its maximum storage capacity and remains at maximum until maneuvering arrival and Unloading operations begin to draining energy. The simulation shows that TES_A, TES_B and TES_C can deliver enough energy, provided the starting condition and charging during sailing. For trip 2, Route B-C in Appendix B, the charging state of each TES is carried over from the previous trip. Its only FFH_A and FFH_{NT} which has to produce energy during the trip. TES_A gets charged from maneuvering and sailing, and avoids running FFH_A. FFH_{NT} has to produce energy at all operations except maneuvering and sailing. On Trip 3, Route C-B in Appendix B, the vessel is sailing at 14kn and TES_A and TES_B starts with a low state of charge. Before the loading is finished, they both are both empty. TES_C, on the other hand, still has 22% charge left, which lasts another five hours. Here the outlier is TES_C which can deliver energy for a longer period after the others are empty. FFH_A and FFH_B produces a similar amount of energy that FFH_{NT} does.

On trip 4, Route B-C in Appendix B, the sailing speed is 20kn and all the TESs are empty at the start. This means that all the FFHs needs to provide energy until the manoeuvring operation starts. For the later operations its only FFH_{NT} that has to run. TES_A has less stored energy compared to the others, because it reaches its maximum capacity during sailing. On Trip 5, Route C-B in Appendix B, the vessel is sailing at 14kn. TES_A doesn't have enough energy to last through the first hour, while TES_B and TES_C only lasted an hour more. The systems with the TES and without is similar with only small differences in FFH usage. The last trip, Route B-C in Appendix B, is identical to trip 4 Route B-C.

The simulation shows how each TES and FFH set reacts to energy demand and surpluses in the system. To keep a usable charge for TES, it's essential that there is enough 20kn trips, so that the TES has a chance to charge. When the ship is sailing at 14kn, the sailing time are longer and there isn't any surplus energy to charge the TES. One or two consecutive trips with a speed of 14kn depletes every TES, depending on starting energy. The outlier is TES_A which seems to either be empty or at a low charge at the end of every trip. This is because even if its fully charged during sailing at 20kn it needs to deliver at least 4506kWh during Unloading. This makes the maximum remaining energy 1628kWh, and it gets even lower if manoeuvring arrival is taken in to consideration. The carry over energy is never enough to deliver energy for loading and unberthing operations, but it still saves usage of FFH_A.

TES_B and TES_C has the capacity to deliver energy over consecutive trips, provided that there are enough 20kn trips to charge them. If TES_B and TES_C are emptied and there isn't enough, or the 20kn trips are short, the energy stored in both of them remain the same. As seen in Appendix B, when both systems have been discharged, they are essentially the same until TES_B fully charge. On this basis TES_B is the most optimal, having adequate capacity and using a wider state of charge range then TES_C.

Being able to charge the TES at port could result in a smaller system which with a more consistent ability to deliver power. A further study should investigate the possibility for land based power to charge the TES at port.

4.4 Emission reductions

The goal of integrating a TES in the WEMS is that the FFH will reduce fuel consumption, resulting in a reduction in greenhouse gas emissions. In this thesis, the main greenhouse gas that is focused on is CO_2, due to relatability. A potential reduction of emissions for NOx and SOx are relevant because these emissions can be significant in areas with heavy ship traffic. Marine fuels normally has a high sulphur content compared to fuels used on land. In Europe, shipping contributes to approximately 20% of the SOx emitted. In Norway, shipping and fishing accounts for approximately a third of the total NOx emissions. However, it is not only Norwegian emissions that threatens Norwegian nature. This kind of pollution can be carried across national borders and long distances[49]. NOx and SOx emissions and strictly regulated by IMO and should be included in further studies [1], [2].

By integrating a TES-system in the WEMS, the monthly CO_2 emissions from the FFH can be significantly reduced. With storage capacity C, the system is able to reduce the CO_2-emissions by approximately 64% compared to the emissions without the TES. With Storage Capacity A and B, the CO_2-emissions are reduced by 52% and 56%, respectively. The CO_2 emission for each storage capacity and without TES is presented in Figure 4.3.

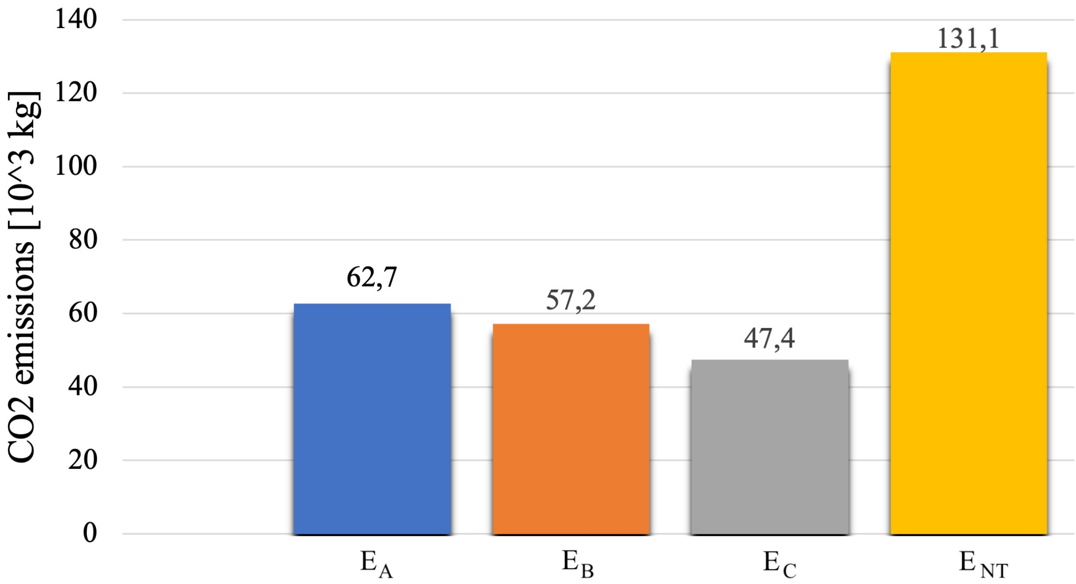

Figure 4.3: *Approximated monthly CO_2 emissions from the fuel fired heater with three different thermal energy storage capacities and (E_{NT}) without TES: (E_A) 6134kWh, (E_B) 10632kWh, (E_C) 15189kWh.*

The storage capacity that provides the largest amount of reduction is E_C. E_C's reductions are comparable to the emissions released by 218 average passenger vehicles per year in the United States. E_B and E_A has emission reductions comparable to 193 and 178 average passenger vehicles per year, respectively. These reductions indicates that integrating the TES is environmentally profitable [4].

4.5 Economical savings

By integrating the TES in the WEMS, the usage of the FFH is reduced, considering that it's only used when there's not enough stored energy to supply the energy demand. These results are based on the economical calculations on fuel related costs. Specific costs and savings should include material and installation costs. It's suggested to do a economical study of accurate investment costs related to materials and cost of installation of the thermal energy storage system.

Table 4.4 shows fuel related costs and savings for the four different fuel fired heaters. The results shows the costs associated with the CO_2-tax for each of the FFHs and the fuel costs for the most demanding month, as seen in Table 4.4. These two added together makes the total cost. The results has a 5% insecurity because the calculations are approximated based on a relation between operating hours and distance.

Table 4.4: *Approximated monthly costs and savings of fuel for the fuel fired heater for each of the three thermal storage capacities, and (C_{NT}) without thermal storage. (C_A) 6134kWh storage capacity; (C_B) 10632kWh storage capacity; (C_C) 15189kWh storage capacity.*

	CO_2 tax [NOK]	Fuel cost [NOK]	Total cost[NOK]	Savings [NOK]
C_A	36 986	244 392	281 378	307 183
C_B	33 724	222 838	256 562	331 998
C_C	27 992	184 962	212 953	375 607
C_{NT}	77 363	511 197	588 560	0

The total cost of C_A is higher than capacity C_B and C_C. All of the storage capacities have proved to be economically profitable, given the assumptions. Since the cost is based on the most demanding month, this will be maximum possible costs and savings. C_C will reduce total costs by approximately 64%. C_B and C_A will reduce total costs by 56% and 52%, respectively. Even though C_C has 2,5 times larger storage capacity, it only saves 12% more of the total costs. This means that C_A, with a significantly smaller TES system, can save a comparable amount of costs. C_C, which is a significantly larger system, will likely have larger investment costs in addition to taking up space on the vessel, which again can reduce profits.

5 Conclusions

The main objective of this bachelor thesis project was to complete calculations and simulations to investigate if it is environmentally and economically profitable to optimize Ulmatec Pyros Waste Energy Management System on a RoPax-vessel by integrating thermal energy storage.

Based on the calculations on recovered heat, the minimum, repetitive and extreme energy surplus is applied as the storage capacities for the thermal energy storage system. The compounds that was investigated as a storage medium in the thermal storage system is Acetamide, Xylitol, ATP 78, ATS 84 and ATS 89. The five compounds was compared to find the most suitable material in terms of melting temperature, energy capacity, weight and volume. For both 95°C and 96°C, Xylitol proved to be the most suitable phase changing compound for the thermal energy storage.

With 6134kWh, 10632kWh and 15189kWh storage capacity, the volume of Xylitol at operating temperature is $62m^3$, $108m^3$ $154m^3$, respectively. Integrating a thermal energy storage system with a storage capacity of 6134kWh makes it possible to reduce emissions from the fuel fired heater by 68000kg CO_2 per month, and monthly fuel related costs by 307 000 NOK. The most repetitive potential storable surplus energy was 10632kWh. At this storage capacity, it is possible to reduce monthly emissions by 74000kg CO_2 and monthly fuel related costs by approximately 332000 NOK. The largest storage capacity of 15189kWh reduces monthly emissions by 84000kg CO_2 and monthly fuel related costs by approximately 376 000 NOK. Integrating a thermal energy storage system proved to be both environmentally and economically profitable for all three capacities. However, according to the results, the volume and weight limitations makes it practically inconvenient to install systems of such great volumes in the engine room on a vessel.

For each of the storage capacities used for calculations in this thesis, every volume that's required is large. By increasing the operational temperature by 1°C, the volume of Xylitol will decrease by 31%, which is advantageous. Even by choosing the smallest storage system at 96°C, which is $48m^3$, the storage medium alone can be compared to the size of a tanking trailer. A system of this size is more likely to fit in an engine room. An assessment should be made as to whether or not there is room for a storage system at this size, as it depends on the available space on the specific vessel.

Despite having 2,5 times greater storage capacity, the largest system only saves a modest 12% more than the smallest system in regards of total costs and reduced emissions. This implies that the significantly smaller system can save a comparable amount of costs. Even if the smallest system is incapable of storing all of the surplus energy, it will still be able to reduce the usage of the fuel fired heater drastically.

6 Suggestions for further work

The results from calculations and simulations are based on numerous assumptions. Based on the results and conclusions in this thesis, the work suggested in the following list should be completed in further work:

- Experiments and performance simulation on the thermal behavior of each system with the different type of encapsulations with the relevant PCMs and water as the heat transfer fluid.
- Corrosion of contact materials by PCM has remained as a practical challenge despite its several advantages. Looking at each PCMs corrosion behaviour with different types of metals might be an interesting task for further theoretical studies and experiments.
- According to a comparative life cycle assessment study of TES systems for solar power plants [30], TES system can last up to 20 years. However, this is depending on the PCM that's used for storage. A suggestion for further work would be to simulate or asses on the life cycle of each of the PCMs listed in Table 2.2.
- Specific costs and savings should include material and installation costs. It's suggested to do a economical study of accurate investment costs related to materials and cost of installation of the thermal energy storage system.
- In these calculations, it's assumed that the energy stored in the phase change materials are constant in the phase where the compound is liquid. In reality, the temperature in the system will decrease after a certain period. A useful task for further studies will be to conduct experiments and study how long the materials can hold on to the energy.
- Our calculations comprehends specifically the volume and weight of each compound on their own. Further research should look in to the realistic volume and weight of the system including water and materials.
- Its suggested to do further calculations on if the fuel consumption of the main engine will increase by increasing the load of the vessel with the weight of the thermal storage system.
- Being able to charge the TES at port could result in a smaller system and with a more consistent ability to deliver power. Further work should investigate the possibility for land based power to charge the TES at port.
- Specific costs and savings should include material and installation costs. It's suggested to do a comprehensive economical study of accurate investment costs related to materials and cost of installation of the thermal energy storage system.
- A large storage system is likely not possible to incorporate in an engine room on a vessel. Further research on examining available space in the specific vessel is suggested, given that it's an essential part when considering integrating a thermal storage system.

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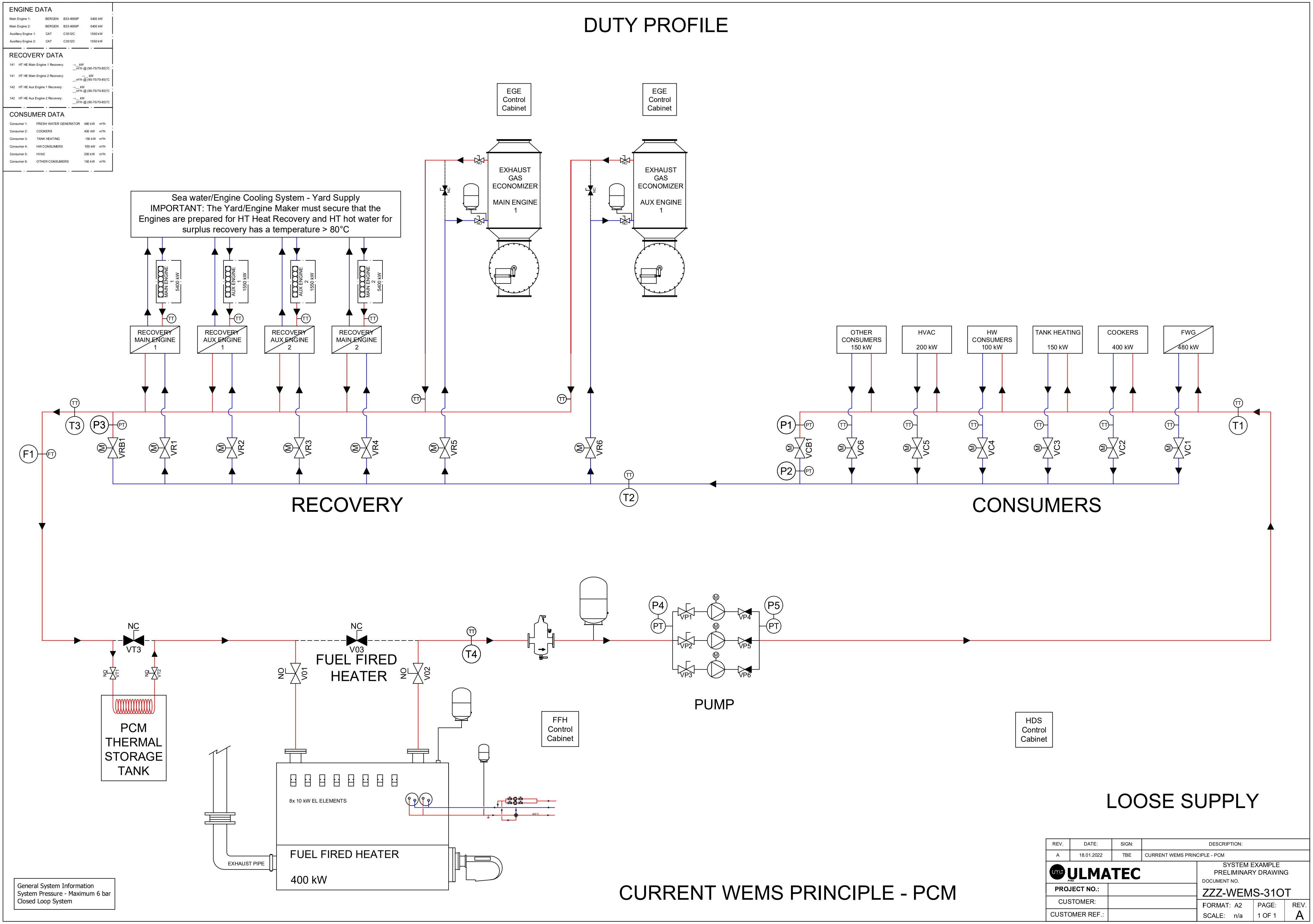
Appendix A: Technical drawing

The technical drawing is given by Ulmatec Pyro. The drawing shows the Waste Energy Management System (WEMS) with thermal energy storage integrated. The component symbols in technical drawings is not representative for actual component sizes.



ENGINE DATA
Main Engine 1: BERGEN B33:4569P 5400 kW
Main Engine 2: BERGEN B33:4569P 5400 kW
Auxillary Engine 1: CAT C3512C 1550 kW
Auxillary Engine 2: CAT C3512C 1550 kW
RECOVERY DATA
141 HT HE Main Engine 1 Recovery: →__kW __m³/h @ (90-75/70-85)°C
141 HT HE Main Engine 2 Recovery: →__ kW __m³/h @ (90-75/70-85)°C
142 HT HE Aux Engine 1 Recovery: →__ kW __m³/h @ (90-75/70-85)°C
142 HT HE Aux Engine 2 Recovery: →__ kW __m³/h @ (90-75/70-85)°C
CONSUMER DATA
Consumer 1: FRESH WATER GENERATOR 480 kW m³/h
Consumer 2: COOKERS 400 kW m³/h
Consumer 3: TANK HEATING 150 kW m³/h
Consumer 4: HW CONSUMERS 100 kW m³/h
Consumer 5: HVAC 200 kW m³/h
Consumer 6: OTHER CONSUMERS 150 kW m³/h
DUTY PROFILE
EGE Control Cabinet
EGE Control Cabinet
EXHAUST GAS ECONOMIZER MAIN ENGINE 1
EXHAUST GAS ECONOMIZER AUX ENGINE 1
Sea water/Engine Cooling System - Yard Supply
IMPORTANT: The Yard/Engine Maker must secure that the Engines are prepared for HT Heat Recovery and HT hot water for surplus recovery has a temperature > 80°C
MAIN ENGINE 1 5400 kW
AUX ENGINE 1 1550 kW
AUX ENGINE 2 1550 kW
MAIN ENGINE 2 5400 kW
RECOVERY MAIN ENGINE 1
RECOVERY AUX ENGINE 1
RECOVERY AUX ENGINE 2
RECOVERY MAIN ENGINE 2
OTHER CONSUMERS 150 kW
HVAC 200 kW
HW CONSUMERS 100 kW
TANK HEATING 150 kW
COOKERS 400 kW
FWG 480 kW
TT
T3
P3
PT
F1
FT
VRB1
VR1
VR2
VR3
VR4
VR5
VR6
T2
P1
P2
VCB1
VC6
VC5
VC4
VC3
VC2
VC1
T1
RECOVERY
CONSUMERS
NC
VT3
NO
VT1
VT2
NC
V03
NO
V01
NO
V02
FUEL FIRED HEATER
T4
P4
P5
VP1
VP2
VP3
VP4
VP5
VP6
PUMP
PCM THERMAL STORAGE TANK
FFH Control Cabinet
HDS Control Cabinet
8x 10 kW EL ELEMENTS
EXHAUST PIPE
FUEL FIRED HEATER
400 kW
LOOSE SUPPLY
CURRENT WEMS PRINCIPLE - PCM
General System Information
System Pressure - Maximum 6 bar
Closed Loop System
REV. DATE: SIGN: DESCRIPTION:
A 18.01.2022 TBE CURRENT WEMS PRINCIPLE - PCM
ULMATEC
SYSTEM EXAMPLE
PRELIMINARY DRAWING
DOCUMENT NO.
ZZZ-WEMS-31OT
PROJECT NO.:
CUSTOMER:
CUSTOMER REF.:
FORMAT: A2
SCALE: n/a
PAGE: 1 OF 1
REV. A

Appendix B: Simulation results

The following tables are the results from the Excel simulation. The operational routes and hours was given by Ulmatec Pyro, and used for further calculations. Each trip and route are labeled on the top of each table. Only the first six days of the month are appended, as they were used for the calculations. The rest of the calculations are based on the ratio between operating hours and distance, as explained in Section 3.3.

1	Route A-B												
Operation	Time [h]	Operating hours [h]	Aux. heat consumtion [kWh]	Recovered heat from EGE [kWh]	Surplus [kWh]	Energy balance [kWh]	TES_A [kWh]	TES_B [kWh]	TES_C [kWh]	Production FFH_A [kWh]	Production FFH_B [kWh]	Production FFH_C [kWh]	Production FFH_{NT} [kWh]
Port	0	0	0	0	0	0	6134	10632	15189	0	0	0	0
Loading	1	1	1732	230	-1502	-1502	4632	9130	13687	0	0	0	-1502
Loading	2	1	1732	230	-1502	-3004	3130	7628	12185	0	0	0	-1502
Loading	3	1	1732	230	-1502	-4506	1628	6126	10683	0	0	0	-1502
Unbethering	3,04	0,04	69	60	-10	-4516	1618	6116	10673	0	0	0	-10
Manoeuvring	3,165	0,125	217	241	25	-4491	1643	6141	10698	0	0	0	0
Sailing	4,165	1	1732	2894	1162	-3329	2805	7303	11860	0	0	0	0
Sailing	5,165	1	1732	2894	1162	-2167	3967	8465	13022	0	0	0	0
Sailing	6,165	1	1732	2894	1162	-1005	5129	9627	14184	0	0	0	0
Sailing	7,165	1	1732	2894	1162	157	6134	10632	15189	0	0	0	0
Sailing	7,665	0,5	866	1447	581	738	6134	10632	15189	0	0	0	0
Manoeuvring arr.	8,04	0,375	650	75	-575	163	5560	10058	14615	0	0	0	-575
Unloading	9,04	1	1732	230	-1502	-1339	4058	8556	13113	0	0	0	-1502
Unloading	10,04	1	1732	230	-1502	-2841	2556	7054	11611	0	0	0	-1502
Unloading	11,04	1	1732	230	-1502	-4343	1054	5552	10109	0	0	0	-1502

2	Route B-C											
	Time	Operating hours	Aux. heat consumtion	Recovered heat from EGE	Surplus	Energy balance	TESA	TESB	TESC	Production FFHA	Production FFHB	Production FFHC	Production FFHNT
Operation	[h]	[h]	[kWh]	[kWh]	[kWh]	[kWh]	[kWh]	[kWh]	[kWh]	[kWh]	[kWh]	[kWh]	[kWh]
Port	0	0	0	0	0	0	1054	5552	10109	0	0	0	0
Loading	1	1	1732	230	-1502	-1502	0	4050	8607	-449	0	0	-1502
Loading	2	1	1732	230	-1502	-3004	0	2548	7105	-1502	0	0	-1502
Loading	3	1	1732	230	-1502	-4506	0	1046	5603	-1502	0	0	-1502
Unbethering	3,04	0,04	69	60	-10	-4516	0	1036	5593	-10	0	0	-10
Manoeuvring	3,25	0,21	364	405	41	-4475	41	1077	5634	0	0	0	0
Sailing	4,25	1	1732	2894	1162	-3313	1203	2239	6796	0	0	0	0
Sailing	5,25	1	1732	2894	1162	-2151	2365	3401	7958	0	0	0	0
Sailing	6,25	1	1732	2894	1162	-989	3527	4563	9120	0	0	0	0
Sailing	7,25	1	1732	2894	1162	173	4689	5725	10282	0	0	0	0
Sailing	8,25	1	1732	2894	1162	1335	5851	6887	11444	0	0	0	0
Sailing	9,25	1	1732	2894	1162	2497	6134	8049	12606	0	0	0	0
Sailing	9,5	0,25	433	724	291	2788	6134	8339	12896	0	0	0	0
Manoeuvring arr.	9,875	0,375	650	75	-575	2213	5560	7765	12322	0	0	0	-575
Unloading	10,88	1	1732	230	-1502	711	4058	6263	10820	0	0	0	-1502
Unloading	11,88	1	1732	230	-1502	-791	2556	4761	9318	0	0	0	-1502
Unloading	12,88	1	1732	230	-1502	-2293	1054	3259	7816	0	0	0	-1502

3	Route C-B												
Operation	Time [h]	Operating hours [h]	Aux. heat consumtion [kWh]	Recovered heat from EGE [kWh]	Surplus [kWh]	Energy balance [kWh]	TESA [kWh]	TESB [kWh]	TESC [kWh]	Production FFHA [kWh]	Production FFHB [kWh]	Production FFHC [kWh]	Production FFHNT [kWh]
Port	0	0	0	0	0	0	1054	3259	7816	0	0	0	0
Loading	1	1	1732	230	-1502	-1502	0	1757	6314	-449	0	0	-1502
Loading	2	1	1732	230	-1502	-3004	0	255	4812	-1502	0	0	-1502
Loading	3	1	1732	230	-1502	-4506	0	0	3310	-1502	-1247	0	-1502
Unbethering	3,04	0,04	69	60	-10	-4516	0	0	3300	-10	-10	0	-10
Manoeuvring	3,165	0,125	217	241	25	-4491	25	25	3325	0	0	0	0
Sailing	4,165	1	1732	1180	-552	-5043	0	0	2773	-528	-528	0	-552
Sailing	5,165	1	1732	1180	-552	-5595	0	0	2221	-552	-552	0	-552
Sailing	6,165	1	1732	1180	-552	-6147	0	0	1669	-552	-552	0	-552
Sailing	7,165	1	1732	1180	-552	-6699	0	0	1117	-552	-552	0	-552
Sailing	8,165	1	1732	1180	-552	-7251	0	0	565	-552	-552	0	-552
Sailing	9,165	1	1732	1180	-552	-7803	0	0	13	-552	-552	0	-552
Sailing	10,165	1	1732	1180	-552	-8355	0	0	0	-552	-552	-539	-552
Sailing	11,165	1	1732	1180	-552	-8907	0	0	0	-552	-552	-552	-552
Sailing	12,095	0,93	1611	1097	-513	-9421	0	0	0	-513	-513	-513	-513
Manoeuvring arr.	12,47	0,375	650	75	-575	-9995	0	0	0	-575	-575	-575	-575
Unloading	13,47	1	1732	230	-1502	-11497	0	0	0	-1502	-1502	-1502	-1502
Unloading	14,47	1	1732	230	-1502	-12999	0	0	0	-1502	-1502	-1502	-1502
Unloading	15,47	1	1732	230	-1502	-14501	0	0	0	-1502	-1502	-1502	-1502

4	Route B-C												
Operation	**Time [h]**	**Operating hours [h]**	**Aux. heat consumtion [kWh]**	**Recovered heat from EGE [kWh]**	**Surplus [kWh]**	**Energy balance [kWh]**	**TESA [kWh]**	**TESB [kWh]**	**TESC [kWh]**	**Production FFHA [kWh]**	**Production FFHB [kWh]**	**Production FFHC [kWh]**	**Production FFHNT [kWh]**
Port	0	0	0	0	0	0	0	0	0	0	0	0	0
Loading	1	1	1732	230	-1502	-1502	0	0	0	-1502	-1502	-1502	-1502
Loading	2	1	1732	230	-1502	-3004	0	0	0	-1502	-1502	-1502	-1502
Loading	3	1	1732	230	-1502	-4506	0	0	0	-1502	-1502	-1502	-1502
Unbethering	3,04	0,04	69	60	-10	-4516	0	0	0	-10	-10	-10	-10
Manoeuvring	3,25	0,21	364	405	41	-4475	41	41	41	0	0	0	0
Sailing	4,25	1	1732	2894	1162	-3313	1203	1203	1203	0	0	0	0
Sailing	5,25	1	1732	2894	1162	-2151	2365	2365	2365	0	0	0	0
Sailing	6,25	1	1732	2894	1162	-989	3527	3527	3527	0	0	0	0
Sailing	7,25	1	1732	2894	1162	173	4689	4689	4689	0	0	0	0
Sailing	8,25	1	1732	2894	1162	1335	5851	5851	5851	0	0	0	0
Sailing	9,25	1	1732	2894	1162	2497	6134	7013	7013	0	0	0	0
Sailing	9,5	0,25	433	724	291	2788	6134	7304	7304	0	0	0	0
Manoeuvring arr.	9,75	0,25	433	50	-383	2405	5751	6921	6921	0	0	0	-383
Unloading	10,75	1	1732	230	-1502	903	4249	5419	5419	0	0	0	-1502
Unloading	11,75	1	1732	230	-1502	-599	2747	3917	3917	0	0	0	-1502
Unloading	12,75	1	1732	230	-1502	-2101	1245	2415	2415	0	0	0	-1502

5	Route C-B												
	Time	Operating hours	Aux. heat consumtion	Recovered heat from EGE	Surplus	Energy balance	TESA	TESB	TESC	Production FFHA	Production FFHB	Production FFHC	Production FFHNT
Operation	[h]	[h]	[kWh]	[kWh]	[kWh]	[kWh]	[kWh]	[kWh]	[kWh]	[kWh]	[kWh]	[kWh]	[kWh]
Port	0	0	0	0	0	0	1245	2415	2415	0	0	0	0
Loading	1	1	1732	230	-1502	-1502	0	913	913	-257	0	0	-1502
Loading	2	1	1732	230	-1502	-3004	0	0	0	-1502	-589	-589	-1502
Loading	3	1	1732	230	-1502	-4506	0	0	0	-1502	-1502	-1502	-1502
Unbethering	3,04	0,04	69	60	-10	-4516	0	0	0	-10	-10	-10	-10
Manoeuvring	3,165	0,125	217	241	25	-4491	25	25	25	0	0	0	0
Sailing	4,165	1	1732	1180	-552	-5043	0	0	0	-528	-528	-528	-552
Sailing	5,165	1	1732	1180	-552	-5595	0	0	0	-552	-552	-552	-552
Sailing	6,165	1	1732	1180	-552	-6147	0	0	0	-552	-552	-552	-552
Sailing	7,165	1	1732	1180	-552	-6699	0	0	0	-552	-552	-552	-552
Sailing	8,165	1	1732	1180	-552	-7251	0	0	0	-552	-552	-552	-552
Sailing	9,165	1	1732	1180	-552	-7803	0	0	0	-552	-552	-552	-552
Sailing	10,17	1	1732	1180	-552	-8355	0	0	0	-552	-552	-552	-552
Sailing	11,17	1	1732	1180	-552	-8907	0	0	0	-552	-552	-552	-552
Manoeuvring arr.	11,25	0,08	139	94	-44	-8951	0	0	0	-44	-44	-44	-44

6	Route B-C											
	Time	Operating hours	Aux. heat consumtion	Recovered heat from EGE	Surplus	Energy balance	TESA	TESB	TESC	Production FFHA	Production FFHB	Production FFHC	Production FFHNT
Operation	[h]	[h]	[kWh]	[kWh]	[kWh]	[kWh]	[kWh]	[kWh]	[kWh]	[kWh]	[kWh]	[kWh]	[kWh]
Port	0	0	0	0	0	0	0	0	0	0	0	0	0
Loading	1	1	1732	230	-1502	-1502	0	0	0	-1502	-1502	-1502	-1502
Loading	2	1	1732	230	-1502	-3004	0	0	0	-1502	-1502	-1502	-1502
Loading	3	1	1732	230	-1502	-4506	0	0	0	-1502	-1502	-1502	-1502
Unbethering	3,04	0,04	69	60	-10	-4516	0	0	0	-10	-10	-10	-10
Manoeuvring	3,25	0,21	364	405	41	-4475	41	41	41	0	0	0	0
Sailing	4,25	1	1732	2894	1162	-3313	1203	1203	1203	0	0	0	0
Sailing	5,25	1	1732	2894	1162	-2151	2365	2365	2365	0	0	0	0
Sailing	6,25	1	1732	2894	1162	-989	3527	3527	3527	0	0	0	0
Sailing	7,25	1	1732	2894	1162	173	4689	4689	4689	0	0	0	0
Sailing	8,25	1	1732	2894	1162	1335	5851	5851	5851	0	0	0	0
Sailing	9,25	1	1732	2894	1162	2497	6134	7013	7013	0	0	0	0
Sailing	9,5	0,25	433	724	291	2788	6134	7304	7304	0	0	0	0
Manoeuvring arr.	9,75	0,25	433	50	-383	2405	5751	6921	6921	0	0	0	-383
Unloading	10,75	1	1732	230	-1502	903	4249	5419	5419	0	0	0	-1502
Unloading	11,75	1	1732	230	-1502	-599	2747	3917	3917	0	0	0	-1502
Unloading	12,75	1	1732	230	-1502	-2101	1245	2415	2415	0	0	0	-1502

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