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Design and assessment of a PCM-based Thermal Energy Storage system

Application to Waste Heat Recovery on cruise ships

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Abstract

The maritime sector is facing increasing pressure to improve energy efficiency and reduce greenhouse gas emissions under the International Maritime Organization (IMO) strategy and, in parallel, regional regulatory frameworks. A significant share of the fuel energy converted onboard ships is rejected as waste heat through exhaust gases and cooling circuits. Waste Heat Recovery Systems (WHRS) represent an effective pathway to reduce fuel consumption; however, their potential is often limited by the temporal mismatch between waste heat availability and onboard thermal demand.
In this context, Thermal Energy Storage (TES) can act as a buffer to decouple heat recovery from heat utilization. Among TES technologies, Phase Change Materials (PCMs) are particularly attractive for marine applications due to their high energy density and quasi-isothermal behavior during phase transition. This thesis investigates the integration of a PCM-based TES system within a cruise ship WHR framework, with the specific goal of reducing the reliance on oil-fired boilers during hoteling conditions.
A representative cruise vessel case study is analyzed using operational profiles, engine configuration data, and seasonal thermal demand. The selected PCM is the commercial organic material *A95*, integrated in a shell-and-tube storage configuration. A lumped-parameter dynamic model is developed in MATLAB to simulate charging and discharging transients and to evaluate key performance indicators, including stored and released energy, state of charge/discharge, and effectiveness. In addition, long-term simulations over a 25-year horizon are performed to assess the impact of PCM degradation on the storage capacity and discharge performance.
Overall, the results indicate that PCM-based TES can effectively mitigate the mismatch between recovered heat and thermal demand, improving WHRS utilization and reducing fuel consumption and associated emissions during port stays. The analysis also highlights the importance of long-term material stability and heat transfer enhancement to support durable and scalable shipboard implementation.

Abbreviations

EGB : Exhaust Gas Boiler
ETS : Emissions Trading System
GHG : Greenhouse Gas
IMO : International Maritime Organization
LHS : Latent Heat storage
OFB : Oil-Fired Boiler
PCM : Phase Change Material
SHS : Sensible Heat Storage
SoC : State of Charge
SoD : State of Discharge
TCS : Thermochemical Storage
TES: Thermal Energy Storage
WHR : Waste Heat Recovery
WHRS : Waste Heat Recovery System

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Introduction

The maritime industry is under increasing pressure to reduce greenhouse gas (GHG) emissions. The International Maritime Organization (IMO) has established ambitious decarbonization targets,requiring a 20-30% reduction in GHG emissions by 2030 and the achievement of net-zero emissions by 2050 [10]. These global objectives are further reinforced by regional regulation such as the European Union Emissions Trading System (EU ETS) and the FuelEU Maritime regulation, as well as long-term outlooks including the *DNV Maritime Forecast to 2050*, which introduce direct carbon pricing mechanisms and increasingly strict energy intensity thresholds for marine fuels [11, 12]. Meeting these targets requires a combination of technological innovation and improvements in operational efficiency. Within this context, Waste Heat Recovery Systems (WHRS) represent a key strategy, enabling ship to capture and reuse thermal energy that would otherwise dissipated [1, 13, 14].

WHRS offer significant potential; however, their effectiveness is often constrained by a temporal mismatch between waste heat availability and onboard thermal demand [2]. During navigation phases, marine engines typically operate at high load, producing large amounts of recoverable heat while the demand for thermal energy remains relatively low. Conversely, during low-load operation or port stays, thermal demand persist whereas waste heat availability decreases, leading to increased reliance on auxiliary oil-fired boilers.

Thermal Energy Storage (TES) provides a viable solution to this mismatch by enabling surplus thermal energy to be stored when available and released during periods of deficit [15].
Among the various TES technologies, Phase Change Materials (PCMs) are particularly promising, as they can store and release large amounts of thermal energy at nearly constant temperature during the phase transition [4, 16, 17]. Their high energy density and compactness make PCM-based systems well-suited for shipboard applications, where space limitations and variable operating profiles represent critical constraints [15, 18].

The aim of this thesis is to investigate the integration of PCM-based TES within waste heat recovery frameworks onboard cruise vessels, with the objective of increasing overall energy efficiency, reducing reliance on auxiliary boilers, and supporting compliance with environmental regulations. The study combines a comprehensive state-of-the-art review with the design and numerical simulation of a PCM-based thermal storage system, placing particular emphasis on its technical feasibility and long-term performance.

The thesis is structured as follows. *Chapter 1* presents the state of the art, reviewing the main WHRS technologies, the different TES concepts, and the fundamental properties of PCMs. *Chapter 2* introduces the case study, drawing on operational and technical data from Ponant cruise vessels to describe engine configurations, thermal demand profiles, and the proposed integration strategy for the PCM storage unit. *Chapter 3* develops the numerical model, detailing the selection of the PCM material, the shell-and-tube configuration, and the lumped-parameter dynamic approach implemented in MATLAB. *Chapter 4* discusses the simulation results, analyzing charging and discharging behavior under seasonal operating scenarios, evaluating key performance indicators such as the state of the charge and discharge, and system effectiveness, extending the analysis over a period of 25 years to capture material degradation effects. Finally, the *Conclusions* summarize the main findings, highlights the benefits and limitations of PCM-based TES for maritime WHRS, and outline possible directions for future research.

Chapter 1
State of the art

1.1 Waste Heat Recovery Systems

Marine propulsion systems are inherently constrained by the thermodynamic limits of internal combustion engines, which inhibit the complete conversion of the chemical energy contained in fuel into useful mechanical work. Despite the significant technological improvements achieved in recent decades through advanced turbocharging, optimized fuel injection systems, and improved combustion control, large two-stroke and four-stroke marine diesel engines still exhibit overall efficiencies typically ranging between 35% and 50%. As a consequence, a substantial fraction of the fuel energy input, approximately 50-65%, is rejected as waste heat through various onboard streams, including exhaust gases, jacket cooling water, lubricating oil cooling and change air cooling [1, 13, 14].

The distribution of this rejected energy among the different heat sources is not uniform and depends strongly on engine size, design, and operating conditions. Exhaust gases represent the highest-temperature heat source and therefore offer the largest potential for energy recovery, while cooling circuits provide lower-grade thermal energy that can still be effectively exploited for heating applications and auxiliary services [1, 13]. Moreover, the availability of waste heat varies continuously with engine load, resulting in a highly dynamic thermal profile during ship operation. This variability is particularly relevant for vessels characterized by alternating operational modes, such as cruise ships, where sailing and port phases are associated with markedly different engine loads and thermal requirements [19].

From an energy system perspective, the recovery and reuse of waste heat represents a significant opportunity to improve the overall efficiency of marine propulsion plants. Historically, however, a large share of this thermal energy was simply discharged to the environment, as fuel costs and environmental constraints did not justify the additional complexity and investment associated with recovery systems. This approach has progressively changed in recent years due to the combined effect of rising fuel prices, stricter environmental regulations and the increasing pressure on the maritime sector to reduce greenhouse gas emissions [20].

In this evolving context, Waste Heat Recovery Systems (WHRS) have emerged as a key enabling technology for improving the energy efficiency of ships. By capturing part of the thermal energy otherwise lost, WHRS allow a reduction in fuel consumption and associated emissions, contributing to both economic and environmental benefits. Their importance has been further reinforced by international regulatory frameworks such as the *Energy Efficiency Design Index (EEDI* and the *Carbon Intensity Indicator (CII)*, as well as regional measures including the *European Union Emissions Trading System (ETS)*, which impose increasingly stringent limits on ship energy performance [1, 10].

Several WHRS configurations have been developed and applied in the maritime sector, depending on the type of recovered heat and the intended end use. Common solutions include exhaust gas economizers for steam or hot water production, space heating systems and power generation technologies. These systems are generally mature and widely adopted, and in many cases they represent a standard design choice for large vessels [13, 14].

Nevertheless, the effectiveness of conventional WHRS is not solely determined by the amount of recoverable heat, but also by the ability of the ship energy system to utilize it when it becomes available. A fundamental limitation arises from the temporal mismatch between waste heat generation and onboard thermal demand. Waste heat availability is closely linked to engine load and operational mode, while thermal demand depends on auxiliary systems, hotel services, and operational phases. This mismatch becomes particularly evident during port stays or low-load operation, when the reduced thermal output of the main engines is often insufficient to cover auxiliary heat demand [19, 20].

As a result, auxiliary boilers are frequently required to operate at partial load to compensate for the lack of recovered heat, reducing the overall efficiency of the energy system and partially offsetting the benefits achieved through WHRS. This operational limitation highlights that, although waste heat recovery represents a necessary step toward more efficient ship energy systems, it is not sufficient on its own to fully exploit the available thermal potential [21].

For these reasons, increasing attention has been devoted in recent years to system-level solutions capable of decoupling heat recovery from heat utilization. Thermal Energy Storage (TES) technologies have been proposed as a complementary approach to WHRS, enabling the storage of excess thermal energy during high-load operation and its subsequent release during periods of low waste heat availability. The integration of TES within waste heat recovery frameworks therefore represents a natural evolution of conventional WHRS, aiming to enhance operational flexibility, improve overall system efficiency, and reduce reliance on auxiliary boilers [19, 22].

1.1.1 Sources of waste heat onboard

The principal sources of waste heat available onboard ships originate from the operation of the main and auxiliary engines and are characterized by different temperature levels, thermal power and operational stability. The main waste heat stream can be summarized as follows:

- *Exhaust gases*, generated during the combustion process and discharged through the exhaust manifold, represent the highest-temperature waste heat source available onboard. Due to their elevated temperature, exhaust gases offer the greatest recovery potential and the highest thermodynamic quality among all waste heat streams. They are commonly exploited through exhaust gas economizers for steam or hot water production and, in more advanced configurations, for electricity generation via bottoming cycles such as organic Rankine cycles. Their high temperature level enables efficient heat transfer and flexible integration within waste heat recovery architectures [1, 13, 14].

- *Scavenge air*, typical of turbocharged marine engines, constitutes an intermediate-temperature waste heat source. After compression, intake air is cooled before entering the cylinders in order to increase air density and improve combustion efficiency, releasing thermal energy in the process. Although scavenge air heat recovery is less commonly implemented than exhaust gas recovery, it can provide a meaningful contribution when integrated into combined heat recovery systems, particularly by supplementing exhaust-based solutions and improving the overall thermal balance of the engine [1].

- *Jacket cooling water*, which circulates around cylinder liners and cylinder heads to remove excess heat and maintain safe operating temperatures, represents a lower-temperature but relatively stable waste heat source. While its temperature level generally limits its applicability to direct thermal uses, such as space heating and domestic hot water preparation, its operational stability makes it a reliable source for continuous auxiliary heat supply during steady sailing conditions [19, 20].

- *Lubricating oil cooling*, which removes heat from engine components such as bearings, pistons, and moving parts, provides waste heat at temperature levels comparable to or slightly lower than those of jacket water [13].

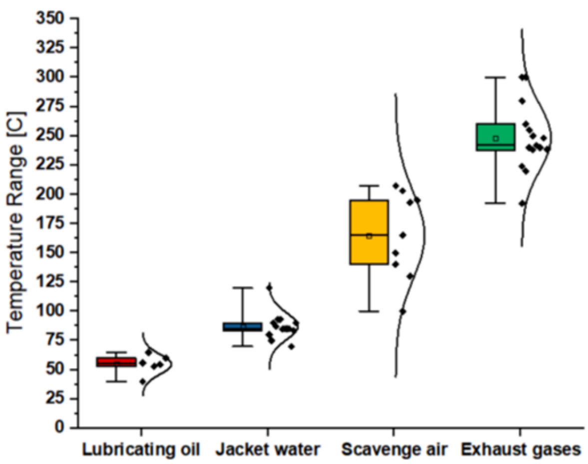


Figure 1.1: *Temperature levels of various waste heat streams [1]*

The temperature level of each waste heat stream strongly affects its recovery potential, as illustrated in **Figure 1.1**. High-temperature sources allow for more efficient and versatile recovery solutions, while lower-temperature streams are generally restricted to direct thermal applications [1].

1.1.2 Main WHRS technologies

Waste Heat Recovery Systems (WHRS) are technologies designed to capture and reuse thermal energy that would otherwise be dissipated during fuel combustion, converting it into useful thermal, mechanical or electrical power. By exploiting waste heat stream at different temperature levels, WHRS contribute to improving the overall energy efficiency of marine propulsion plants and reducing fuel consumption and operating costs, while supporting compliance with increasingly stringent international regulations on emissions [1, 2, 14].

Over the years, a wide range of WHRS technologies has been developed to address the diversity of waste heat sources available onboard ships and the variety of onboard energy demands. The selection of a suitable recovery technology does not depend solely on the temperature level and thermal power of the available waste heat streams, but also on the operational profile of the vessel, the balance between thermal and electrical demand, and the space, weight and integration constraints imposed by ship design. These aspects are particularly relevant in the maritime sector, where available volume and installation flexibility are often limited [19].

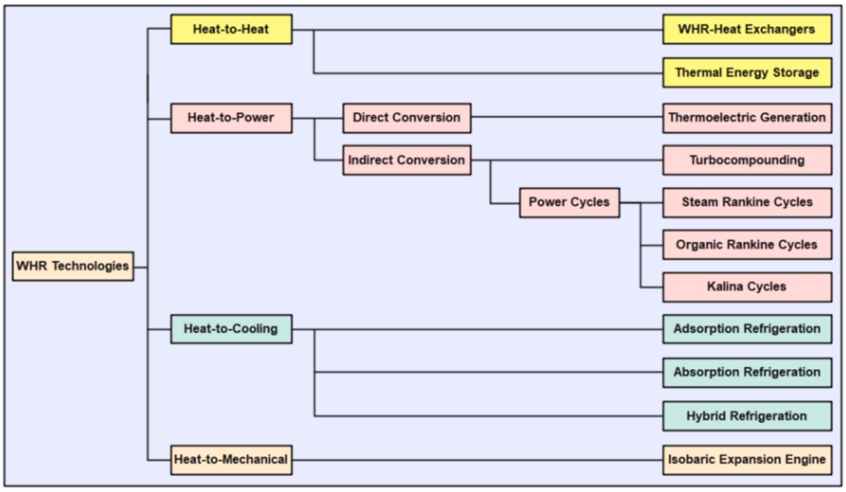


Figure 1.2: *Classification of onboard WHRS technologies [1]*

As illustrated in **Figure 1.2**, WHRS technologies can be broadly classified into four main categories according to the form of useful energy delivered [1]:

1. *Heat-to-Heat*
   Heat-to-heat systems directly reuse recovered thermal energy to satisfy onboard heat demands through heat exchangers, without intermediate energy conversion. These systems are generally characterized by high efficiency, low complexity, and high technological maturity, making them widely adopted in marine applications. Common configurations include:

   - *Economisers*, typically finned-tube heat exchangers installed in the exhaust gas path to preheat boiler feedwater and reduce fuel consumption in auxiliary boilers;
   - *Exhaust gas boilers*, which generate steam directly from hot exhaust gases and are commonly used to supply heating and process steam onboard;

- *Recuperators*, employed to preheat scavenge or combustion air, thereby improving overall engine efficiency;
- *Regenerators*, which use a solid storage medium to alternately absorb and release heat in cyclic operation;
- *Heat Recovery Steam Generators (HRSGs)*, more complex multi-pressure systems generally adopted in large combined or hybrid plants, capable of producing high-pressure steam for power generation or process applications.

2. *Heat-to-Power*
Heat-to-power systems convert recovered thermal energy into electrical power and are particularly attractive for vessels with high electrical demand or hybrid propulsion architectures. These systems enable a direct reduction in fuel consumption for electricity generation and can enhance the flexibility of the onboard energy system. The main technologies include:

    - *Steam Rankine Cycle (SRC)*, the most established heat-to-power solution, based on the conventional water-steam cycle and typically applied to high-temperature exhaust gas recovery;
    - *Organic Rankine Cycle (ORC)*, in which water is replaced by an organic working fluid with a lower boiling temperature, allowing effective recovery from medium and low-temperature heat sources;
    - *Kalina Cycle*, which employs a water-ammonia mixture as the working fluid and offers improved thermal matching at the expense of higher system complexity;
    - *Supercritical CO_2 Cycle*, operating with carbon dioxide at high pressure and temperature in a dense supercritical state, offering compactness and high efficiency potential but still limited industrial maturity;
    - *Thermoelectric Generators (TEGs)*, which directly convert heat into electricity via the Seebeck effect and are characterized by simplicity and reliability, albeit with relatively low conversion efficiency.

3. *Heat-to-Cooling*
Heat-to-cooling systems exploit waste heat to meet onboard cooling and refrigeration demands, typically through adsorption or absorption refrigeration cycles. These technologies are particularly relevant in applications where cooling demand is significant, such as air conditioning and refrigeration on passenger ships, allowing a reduction in electrical load and auxiliary fuel consumption.

4. *Heat-to-Mechanical*
Heat-to-mechanical systems convert waste heat directly into additional mechanical power, generally through isobaric expansion devices. Although less widespread than other WHRS technologies, these systems offer a direct means of enhancing propulsion efficiency by supplementing shaft power under suitable operating conditions.

Overall, each WHRS category presents specific advantages and limitations in terms of efficiency, complexity, and integration requirements. Consequently, modern ship energy systems increasingly rely on a combination of different WHRS technologies, selected according to the characteristics of the available waste heat sources and the operational needs of the vessel [1, 13, 19].

1.2 Thermal Energy Storage

Thermal Energy Storage (TES) systems enable the decoupling of energy production from energy use in both time and space, allowing thermal energy to be stored when it is available and released when required. This capability represents a key enabler for improving the flexibility and efficiency of energy systems characterized by variable generation and demand profiles [15, 16, 23].

In order to properly frame the role of TES within ship energy systems, it is useful to consider the broader landscape of energy storage technologies. As illustrated in **Figure 1.3**, energy storage solutions can be classified according to the form in which energy is stored, including mechanical, electrical, thermal, chemical, and electrochemical technologies . While mechanical, electrical, and electrochemical storage systems are mainly designed to store energy in a form that can be readily converted into electricity or mechanical power, thermal energy storage systems allow the direct storage of heat, without the need for intermediate energy conversion steps [15, 16].

This characteristic makes TES particularly well suited for waste heat recovery applications, where energy is already available in thermal form. In such contexts, converting heat into another energy carrier may introduce additional complexity and efficiency losses, while direct thermal storage enables a simpler and more efficient utilization of the recovered energy. For this reason, TES represents a natural complement to Waste Heat Recovery Systems, allowing excess thermal energy to be buffered during periods of high availability and subsequently released when demand exceeds instantaneous recovery potential [4, 15].

From a system-level perspective, one of the main limitations of conventional WHRS is the temporal mismatch between waste heat generation and onboard energy demand. During navigation at moderate to high engine load, marine engines generate large amounts of recoverable heat, while onboard thermal demand may remain relatively limited. Conversely, during port stays or low-load operation, thermal demand remains significant, whereas waste heat availability is substantially reduced. In these conditions, auxiliary boilers are commonly required to supply thermal and electrical power, leading to increased fuel consumption and emissions [19, 20].

By buffering excess thermal energy when available and releasing it when required, TES systems directly address this structural mismatch, improving overall system efficiency, operational flexibility, and the utilization factor of WHRS [15, 20]. For these reasons, TES technologies are increasingly recognized as a key element in advanced marine energy systems, particularly for vessels characterized by highly variable operating profiles [19].

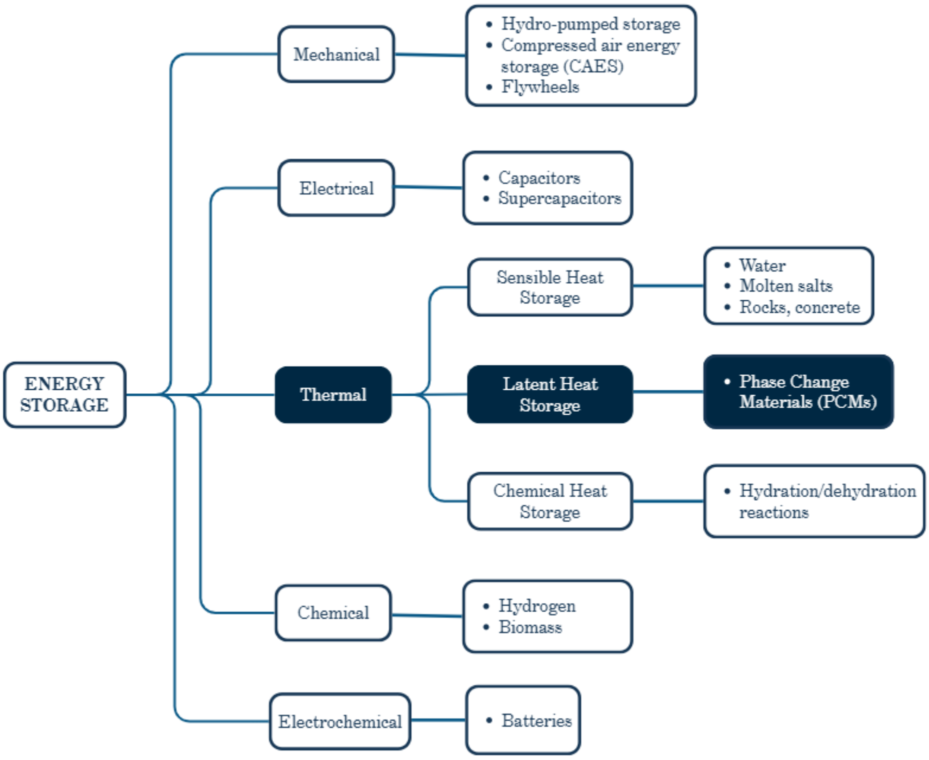


Figure 1.3: *Different energy storage technologies*

1.2.1 Sensible heat storage

Sensible Heat Storage (SHS) represents the most established and widely implemented form of thermal energy storage. In sensible storage systems, thermal energy is stored by increasing or decreasing the temperature of a storage medium without inducing any phase change. The storage and release processes are therefore governed solely by temperature variations, making SHS conceptually simple and technologically mature [2, 15].

The amount of thermal energy that can be stored in a sensible heat storage system is directly proportional to the mass of the storage medium, its specific heat capacity, and the temperature difference between the charging and discharging phases. This relationship is commonly expressed as [2, 15]:

$$Q = m \cdot c_\mathrm{p} \cdot \Delta T \tag{1.1}$$

As illustrated in **Figure 1.4**, the energy stored in a sensible TES increases linearly with temperature. As a consequence, achieving large storage capacities requires either large temperature swings or a significant amount of storage material. In practical applications, the allowable temperature range is often limited by material properties, system design constraints, and safety considerations, which in turn restrict the maximum achievable energy density of sensible storage systems [2].

A wide range of materials can be employed for sensible heat storage, including both solids and liquids such as rocks, concrete, ceramics, water, thermal oils, and molten salts. The choice of the storage medium depends on the required operating temperature range, thermal capacity, cost, availability, and compatibility with heat transfer fluid [23]. Among these materials, water is by far the most commonly used sensible storage medium in low and medium temperature applications due to its high specific heat capacity, low cost and non-toxicity, while molten salts are typically adopted for high-temperature applications such as concentrated solar power plants [15, 23].

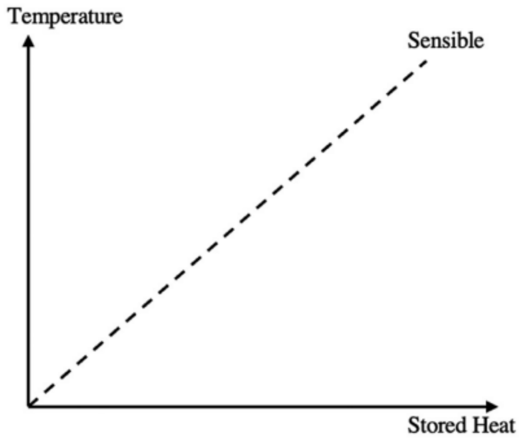


Figure 1.4: *Relation between temperature and stored energy in sensible TES [2]*

Sensible heat storage systems are generally characterized by technological simplicity, high reliability, and well-established design and operating practices. These features make SHS attractive from an implementation and maintenance perspective, particularly in applications where space availability is not a critical constraint. However, a major limitation of sensible heat storage lies in its relatively low energy storage density. Because energy is stored only through temperature changes, large storage volumes are often required to meet significant thermal capacity requirements, especially when the allowable temperature difference is limited [15, 16].

This drawback becomes particularly relevant in applications with strict space and weight constraints, such as marine systems, where the volumetric requirements of sensible heat storage may significantly limit its feasibility [19, 20] In such contexts, the adoption of alternative storage technologies with higher energy density is often required to ensure adequate integration flexibility onboard. For this reason, while sensible heat storage represents a robust and proven solution, it may not always be the most suitable option for shipboard waste heat recovery applications, where compactness and modular integration are key design drivers [15, 19].

1.2.2 Latent heat storage

Latent Heat Storage (LHS) is based on the use of Phase Change Materials (PCMs), which are capable of absorbing and releasing significant amount of thermal energy during a phase transition, most commonly between the solid and liquid states [4, 16, 17]. During the phase change process, energy is stored or released in the form of latent heat, while the temperature of the material remains nearly constant. This characteristic represents the fundamental difference between latent and sensible heat storage systems and constitutes one of the main advantages of LHS [5, 15].

Unlike sensible heat storage, where energy accumulation is associated with a temperature variation of the storage medium, latent heat storage occurs within a narrow temperature range close to the phase change temperature of the PCM. As a result, latent storage systems can achieve significantly higher energy storage density for a given temperature range, enabling more compact storage solutions compared to sensible systems operating under similar conditions [5, 15].

The amount of thermal energy that can be stored in a latent heat storage system is primarily determined by the mass of the PCM and its latent heat of fusion, according to the following relationship [2, 15]:

$$Q = m \cdot \Delta h \tag{1.2}$$

where Δh represents the specific latent heat associated with the phase transition.

As illustrated in **Figure 1.5**, the energy stored in a latent TES increases sharply during the phase change process, while the temperature remains approximately constant. Outside the phase change interval, additional energy can be stored in sensible form, although the dominant contribution to the storage capacity is provided by the latent heat [2].

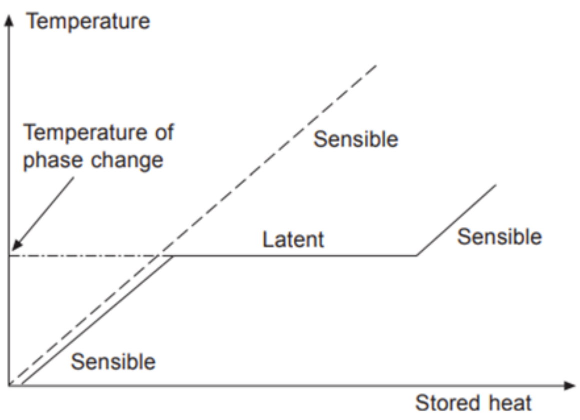


Figure 1.5: *Relation between temperature and stored energy in latent TES [2]*

Latent heat storage systems offers several advantages over sensible storage solutions, including higher energy storage density, reduced storage volume, and quasi-isothermal operation. The latter is particularly beneficial in applications requiring a stable temperature supply, as it allows thermal energy to be delivered at nearly constant temperature during both charging and discharging phases [15]. These characteristics make LHS particularly suitable for integration with waste heat recovery systems, where the temperature of the recovered heat can be effectively matched with the phase change temperature of selected PCMs, enabling efficient and stable thermal energy utilization [4, 15, 16].

Despite these advantages, the practical implementation of latent heat storage systems presents several technical challenges. One of the main limitations of PCMs is their relatively low thermal conductivity, which can significantly restrict heat transfer rates during charging and discharging, leading to longer response times and incomplete utilization of the storage capacity [15, 18]. In addition, issues related to material stability, supercooling, phase segregation, and long-term reliability under repeated thermal cycling must be carefully addressed to ensure durable and predictable performance over the system lifetime [4, 17].

1.2.3 Thermochemical storage

Thermochemical Storage (TCS) is based on the use of reversible chemical reactions to store and release thermal energy. During the charging phase, thermal energy supplied to the system drives an endothermic reaction, converting heat into chemical potential energy. During discharge, the reverse exothermic reaction occurs, releasing the stored energy in the form of heat. Unlike sensible and latent heat storage, thermochemical storage relies on changes in chemical composition rather than temperature variation or phase transition, which fundamentally alters the storage mechanism and its performance characteristics [15].

One of the main advantages of thermochemical storage lies in its very high theoretical energy density, which can significantly exceed that of sensible and latent heat storage systems. In addition, since the stored energy is bound in chemical form, thermal losses during the storage period are theoretically negligible, allowing long-term energy storage without continuous insulation requirements. These features make TCS particularly attractive for applications requiring seasonal storage or long-duration energy buffering [4, 15].

Despite these promising characteristics, thermochemical storage systems are still affected by several technological and practical limitations. Challenges related to reaction kinetics, material stability, reversibility over repeated cycles, system complexity, and reactor design currently limit their large-scale deployment. Moreover, the integration of thermochemical storage systems often requires precise control of operating conditions and additional auxiliary components, increasing system complexity and reducing overall technological readiness [15].

As a result, the technological maturity of thermochemical storage remains relatively low compared to sensible and latent heat storage solutions. While TCS has been extensively investigated at laboratory and pilot scale, its application in marine energy systems is currently limited to research and demonstration activities. The complexity of shipboard integration, combined with the stringent requirements in terms of reliability, safety and operational robustness, further constrains its adoption in the maritime sector at present [4].

1.3 Phase Change Materials

Phase Change Materials (PCMs) are substances capable of storing and releasing significant amounts of thermal energy during a phase transition, most commonly between solid and liquid states. During this process, energy is absorbed or released in the form of latent heat, while the temperature of the material remains nearly constant. Owing to this characteristic, PCMs have been extensively investigated for latent heat thermal energy storage application, particularly in systems where compactness and stable temperature control are required [4, 5, 15, 16, 17].

Different types of phase transitions can be exploited for thermal energy storage, including solid-solid, solid-liquid, solid-gas, and liquid-gas transitions. Each of these mechanisms exhibits distinct characteristics in terms of latent heat, volume change, operating conditions, and practical feasibility, which directly affect their suitability for engineered storage systems [4, 16]:

- *Solid-solid phase change*, involving transitions between different crystalline structures, is typically characterized by relatively low latent heat values. However, these materials exhibit minimal volume change and good cycling stability, which can be advantageous from a mechanical and containment perspective.

- *Solid-liquid phase change* is the most widely applied mechanism in thermal energy storage systems. It offers comparatively high latent heat, moderate and manageable volume change, and good reversibility over repeated charging and discharging cycles. These features make solid-liquid PCMs particularly suitable for practical TES applications.

- *Solid-gas liquid-gas phase changes* can theoretically provide very high latent heat values. Nevertheless, their application in thermal energy storage is generally impractical due to the extremely large volume changes involved and the need for pressurized containment systems, which significantly increase system complexity and safety requirements.

Among these options, solid-liquid PCMs represent by far the most widely adopted solution in practical latent heat storage systems. They provide a favorable balance between high latent energy storage density, acceptable volume change, and feasible containment, making them suitable for a wide range of thermal energy storage applications, including waste heat recovery systems [4, 16].

Unlike sensible heat storage media, which store energy through temperature variation over a relatively wide range, PCMs operate within a narrow temperature interval during the phase change process. This quasi-isothermal behavior enables higher energy storage density and a more stable thermal output during charging and discharging. As a result, PCM-based storage systems are particularly attractive for compact thermal energy storage solutions and for applications requiring controlled temperature levels, such as those encountered in marine waste heat recovery systems [5, 15].

1.3.1 Phase change behavior of PCMs

The distinctive feature of Phase Change Materials lies in their ability to store and release thermal energy through a combination of sensible and latent heat mechanisms. Unlike conventional sensible storage media, in which energy accumulation is solely associated with temperature variation, the total heat stored in a PCM results from two distinct contributions: sensible heat, related to temperature changes of the material, and latent heat, associated with the phase transition process itself [5, 15].

The overall thermal energy storage in a PCM-based system can therefore be expressed as the sum of sensible and latent contributions, as follows [5, 15]:

$$Q_{\text{total}} = Q_{\text{sensible}} + Q_{\text{latent}}. \tag{1.3}$$

During the heating process, a PCM initially stores energy in sensible form as its temperature increases. Once the phase change temperature is reached, the material undergoes a phase transition, typically from solid to liquid, during which additional thermal energy is absorbed as latent heat while the temperature remains nearly constant. After completion of the phase change, further heat input again results in sensible heat storage in the liquid phase. During cooling, the reverse process occurs, with latent heat released during solidification followed by sensible heat release as the temperature decreases [5, 17].

This phase change behavior is schematically illustrated in **Figure 1.6**, which highlights the characteristic plateau in the temperature-energy relationship during the phase transition. The presence of this quasi-isothermal region represents a defining feature of PCM-based thermal energy storage and distinguishes latent heat storage from purely sensible systems [5, 17].

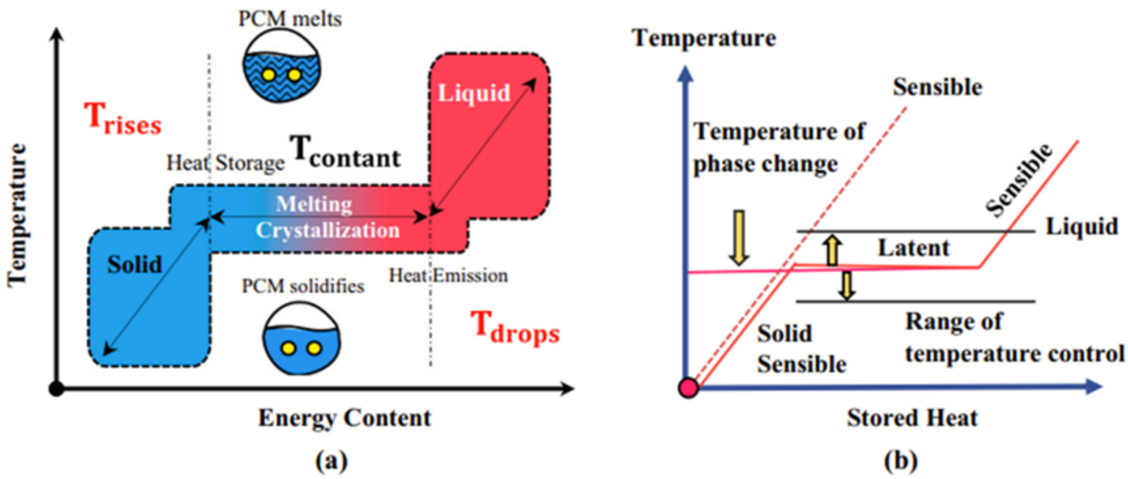


Figure 1.6: (a) Principle of phase change behavior of PCM; (b) Graphical representation of phase change for PCM [3]

1.3.2 Classification of PCMs

Phase Change Materials are commonly classified into three main categories according to their chemical nature: organic PCMs, inorganic PCMs, and eutectic mixtures. This classification is widely adopted in the literature, as it reflects not only fundamental chemical differences but also distinct thermophysical properties, performance characteristics, and practical implications for thermal energy storage system design. Each category exhibits specific advantages and drawbacks in terms of latent heat, thermal conductivity, stability under thermal cycling, cost and compatibility with containment materials, which must be carefully considered when selecting a PCM for a given application [17, 24, 25].

Figure 1.7 provides an overview of the main PCM categories and highlights the broad diversity of materials available for latent heat storage applications. This diversity allows PCMs to be tailored to specific operating temperature ranges and system requirements, but it also introduces trade-offs that influence their suitability for practical implementation [15, 17, 24].

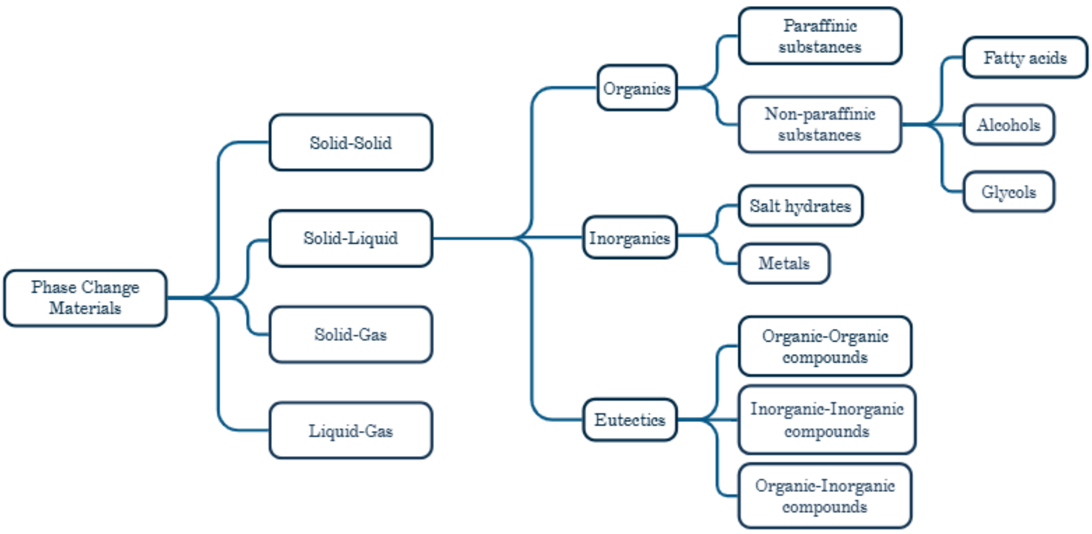


Figure 1.7: *Classification of phase change materials*

1.3.2.1 Organic PCMs

Organic PCMs mainly include paraffins and fatty acids. These materials are among the most extensively investigated and applied PCMs due to their favorable thermophysical and chemical properties. Organic PCMs are characterized by a wide range of melting temperatures, relatively high latent heat of fusion, negligible supercooling, and good chemical stability over repeated thermal cycles. In addition, they generally exhibit good compatibility with a wide range of container and encapsulation materials, which contributes to their reliability and ease of integration in practical storage systems [4, 16].

Despite these advantages, organic PCMs also present some limitations. Their thermal conductivity is typically low, which can restrict heat transfer rates during charging and discharging. Moreover, they often exhibit moderate volumetric energy density and noticeable volume expansion during melting. In some cases, issues related to flammability and relatively low operating temperatures limits may further constrain their application, particularly in environments with strict safety requirements or elevated temperature conditions [4, 16].

1.3.2.2 Inorganic PCMs

Inorganic PCMs comprise salt hydrates, molten salts, and metallic alloys. Compared to organic materials, inorganic PCMs generally offer higher volumetric energy density and higher thermal conductivity, making them attractive for applications where compactness and enhanced heat transfer are required. In addition, many inorganic PCMs exhibit higher melting temperatures, which makes them suitable for medium and high-temperature thermal energy storage applications [24, 26].

However, the practical use of inorganic PCMs is often challenged by several drawbacks. Common issues include supercooling, phase segregation during repeated melting and solidification cycles, and potential corrosion of containment materials. These phenomena can lead to degradation of thermal performance and reduced long-term reliability, particularly in applications requiring frequent cycling and extended service life. As a result, careful material selection and appropriate system design are required to mitigate these limitations [24, 26].

1.3.2.3 Eutectic mixtures

Eutectic PCMs are formed by combining two or more components that melt and solidify simultaneously at a specific and well-defined temperature. This characteristic allows eutectic mixtures to provide sharp melting points and relatively high energy storage density, which can be advantageous in applications requiring precise temperature control and stable thermal output [17, 25].

Despite their potential benefits, the application of eutectic PCMs in practical thermal energy storage systems remains relatively limited. One of the main constraints is the scarcity of comprehensive experimental data on their long-term thermophysical behavior, including stability under repeated cycling and compatibility with containment materials. In addition, eutectic mixtures often involve higher material and processing costs compared to single-component PCMs, which can limit their economic attractiveness [17, 25].

Classification	Advantages	Disadvantages
Organic PCMs	Versatility over a wide temperature range High latent heat of phase change Absence of subcooling Physical/chemical stability and recyclability High compatibility with various materials	Low thermal conductivity Significant volume change Low volumetric heat storage density Susceptibility to flammability
Inorganic PCMs	High melting point Excellent thermal conductivity Low volume change High volumetric heat storage density (compared to organic PCMs) Low-cost access	Supercooling Corrosion
Eutectics PCMs	Distinct phase change temperature High volumetric heat storage capacity	Insufficient data available on thermophysical properties

Figure 1.8: *Advantages and disadvantages of different categories (classes) of phase change materials [4]*

The main advantages and disadvantages associated with the different PCM categories are summarized in **Figure 1.8**. This comparison highlights that no single PCM category is universally optimal, and that the selection of an appropriate PCM must be based on a careful balance between thermal performance, material stability, safety considerations, and integration constraints.

1.3.3 Criteria for PCM selection

The selection of a suitable Phase Change Material represents a critical step in the design of latent heat thermal energy storage systems, as the overall performance, reliability and feasibility of the storage unit depend on the properties of the chosen material. A PCM must satisfy a set of requirements spanning thermophysical, kinetic, chemical, economic, and environmental aspects, which are often interrelated and may involve significant trade-offs [27, 28].

Figure 1.9 provides an overview of PCMs classified according to their melting temperature and latent heat of fusion, highlighting the wide range of materials available for thermal energy storage applications. This diversity enables the selection of PCMs tailored to specific operating temperature ranges, but also requires a careful and systemic evaluation of multiple criteria to ensure suitability for the intended application [3].

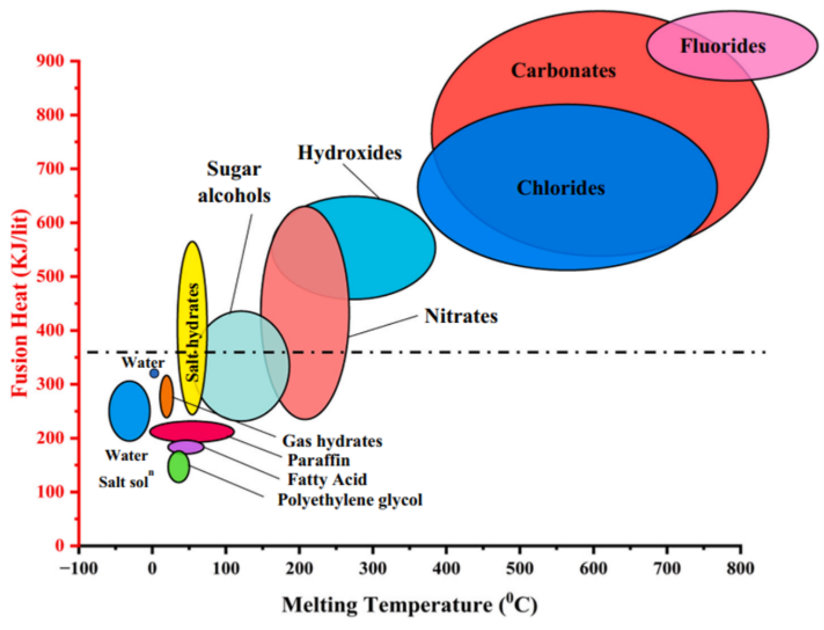


Figure 1.9: Classification of PCMs according to melting temperatures and fusion heat [3]

1.3.3.1 Thermophysical properties

From a thermophysical perspective, an ideal PCM should exhibit a melting temperature closely matching the operating temperature range of the target application, in order to maximize the utilization of latent heat. A high latent heat of fusion is desirable to achieve elevated energy storage density, while adequate thermal conductivity is required to ensure effective heat transfer during both charging and discharging phases [15, 16, 27].

Additional desirable thermophysical characteristics also play an important role in PCM selection. These include sufficiently high specific heat capacity, appropriate density to limit storage volume, minimal volume change during phase change transition, and low vapor pressure to avoid containment issues. Furthermore, consistent and repeatable melting and solidification behavior over multiple thermal cycles is essential to guarantee predictable long-term performance [4, 27].

1.3.3.2 Kinetic properties

Beyond equilibrium thermophysical properties, the kinetic behavior of a PCM strongly influences the dynamic performance of a thermal energy storage system. The effectiveness of latent heat storage depends not only on how much energy can be stored, but also on how rapidly the PCM can absorb and release heat during operation [5].

To ensure efficient charging and discharging, the PCM should exhibit fast nucleation and crystallization rates, minimizing the occurrence of supercooling, and enabling timely heat release during solidification. Similarly, rapid melting behavior is required to fully exploit the available heat input during the charging phase. Materials with slow phase transition kinetics may lead to incomplete utilization of the storage capacity and reduced system responsiveness [17, 27].

1.3.3.3 Chemical properties

Chemical stability and safety considerations are essential for the practical deployment of PCM-based storage systems, particularly in applications involving long service life and frequent thermal cycling. The PCM should exhibit fully reversible phase transitions over repeated melting and solidification cycles, without degradation of its thermophysical properties [27].

In addition, the material must be chemically stable within the operating temperature range and compatible with container and encapsulation materials, avoiding corrosion or chemical reactions that could compromise system integrity. Safety-related aspects, such as non-toxicity, non-flammability, and non-explosiveness, are particularly important for applications in confined or regulated environments, including marine systems [16, 27].

1.3.3.4 Economic and sustainability considerations

In addition to technical suitability, economic and environmental aspects play a decisive role in the selection of PCMs for real-world applications. The material should be cost-effective, readily available at industrial scale, and associated with reasonable processing and encapsulation costs. High material costs or limited availability can significantly hinder large-scale deployment, even for PCMs with excellent thermophysical properties [4, 28].

From a suitability perspective, increasing attention is being devoted to the environment impact of PCM production, use and end-of-life management. Preference is therefore given to materials with low environmental footprint, recyclability potential, and limited health and safety risks, in line with broader objectives of sustainable energy system design [4].

The main criteria governing PCM selection and their interrelations are summarized in **Figure 1.10**, which highlights the need for a balanced approach that accounts for both performance-driven and practical considerations.

Thermophysical properties	Ideal melting point range High value of latent heat of phase change excellent thermal conductivity Significant specific heat Good density Minimal volume fluctuations and low vapor pressure Consistent melting
Kinetic properties	Fast nucleation rate to avoid supercooling Rapid crystallization rate which leads to optimal heat release Fast melting rate which leads to optimal heat storage capacity
Chemical properties	Full reversibility of solidification and melting Chemical stability and resilience Integrity maintained through numerous solidification/melting cycles No-corrosive No-toxic, no-flammable, and no-explosive
Sustainability, profitability, and economic efficiency	Reasonable cost Immediately accessible and widely available

Figure 1.10: *Criteria for selecting phase change materials [4]*

1.3.4 Problems associated with PCM types

Despite their attractive thermophysical properties and high energy storage density, the practical implementation of Phase Change Materials is affected by several technical challenges that can limit system performance, reliability, and long-term applicability. These issues are associated both with the intrinsic properties of the materials and with the operating conditions of the thermal energy storage system, and they must be carefully addressed during the design phase to ensure effective and durable operation [16, 17].

1.3.4.1 Thermal conductivity

One of the most critical limitations of many PCMs is their inherently low thermal conductivity, a drawback that is particularly pronounced in organic materials. Low thermal conductivity restricts heat transfer within the storage medium, leading to reduced charging and discharging rates and the developments of significant temperature gradients inside the storage unit [29].
As a consequence, the PCM may not melt or solidify uniformly throughout the storage volume, resulting in incomplete utilization of the available latent heat capacity. This effect can significantly extend the overall cycle time and reduce the effective performance of the storage system, especially in applications requiring rapid thermal response or frequent cycling [29, 17].

1.3.4.2 Supercooling

Supercooling represent another relevant limitation, particularly for inorganic PCMs and salt hydrates. In this phenomenon, the material remains in the liquid state even when cooled below its equilibrium solidification temperature, delaying the onset of crystallization and preventing the timely release of stored latent heat[5].
Supercooling is commonly associated with insufficient nucleation during the solidification process and can result in unpredictable system behavior, reduced thermal output, and poor temperature control during discharge. In practical applications, severe supercooling can

compromise the reliability of the storage system and limit its suitability for applications requiring stable and repeatable thermal performance [5, 16].

The effect of supercooling on heat storage behavior is illustrated in **Figure 1.11**, which highlights the differences between systems with adequate nucleation and those affected by severe sub-cooling.

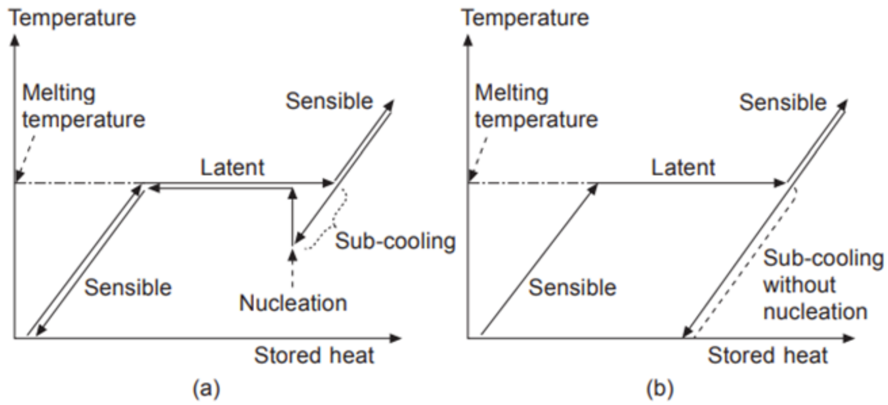


Figure 1.11: *Effect of sub-cooling on heat storage: (a) with little sub-cooling and nucleation; (b) severe sub-cooling without nucleation [5]*

1.3.4.3 Phase segregation

Phase segregation mainly affects salt hydrate PCMs and occurs when different components of the material separate during melting due to differences in density or solubility. During solidification, only part of the mixture recrystallizes, while the remaining fraction remains inactive and no longer contributes to latent heat storage [30, 31].
Repeated thermal cycling can therefore lead to a progressive reduction in effective storage capacity, as the active fraction of the PCM decreases over time. This degradation mechanism represents a major challenge for the long-term stability and reliability of salt hydrate-based storage systems [30, 31].

1.3.4.4 Corrosion

Corrosion constitutes a further challenge, particularly for inorganic PCMs such as molten salts and salt hydrates. Many of these materials exhibit corrosive behavior toward commonly used metallic containment and heat exchanger materials, potentially compromising mechanical integrity and system durability over prolonged operation [26, 32]. To mitigate corrosion-related issues, careful selection of construction materials, protective coatings or corrosion-resistant alloys is required. However, these measures may increase system complexity and cost, influencing the overall feasibility of PCM-based storage solutions [26, 32].

1.3.4.5 Chemical instability and safety aspects

Chemical instability under repeated melting and solidification cycles may lead to degradation of PCM properties, including shifts in melting temperature, reduction in latent heat capacity, and changes in phase change behavior. Such degradation phenomena can adversely affect long-term system performance and reliability, particularly in applications involving frequent thermal cycling [33, 34, 35].

In addition to material stability, safety aspects must be carefully considered. Organic PCMs may pose fire hazards due to their flammability, while some high-performance inorganic materials may raise concerns related to toxicity, handling complexity or environmental impact. These issues are especially relevant in confined or regulated environments, such as marine applications, where safety and operational robustness are critical design requirements [16, 27].

1.3.5 Technical improvements

To overcome the limitations associated with PCMs and enhance their practical applicability, several technological strategies have been proposed in the literature. These approaches primarily aim to improve heat transfer performance, material stability, and operational reliability, addressing the main drawbacks discussed in the previous section. The most widely investigated solutions include encapsulation techniques and heat transfer enhancement strategies, which can be adopted individually or in combination depending on system requirements [36].

1.3.5.1 Encapsulation technologies

Encapsulation consists of enclosing the PCM within a protective shell in order to prevent leakage during the liquid phase, improve mechanical stability, and mitigate material degradation over repeated thermal cycles. By physically separating the PCM from the surrounding environment, encapsulation can also enhance safety and compatibility with containment materials, facilitating system integration [36].

Depending on capsule size and manufacturing approach, encapsulation techniques can be classified into three main categories [37, 38]:

- *Macro-encapsulation*, involving relatively large containers such as tubes, spheres, pouches or panels filled with PCM. This approach is characterized by simple fabrication, ease of handling, and straightforward integration into thermal energy storage units, making it particularly suitable for large-scale applications.

- *Micro-encapsulation*, where PCM particles with typical diameters ranging from 1 to 1000 μm are coated with a polymeric or inorganic shell. Micro-encapsulation significantly increases the effective heat exchange surface area and improves thermal response, while also reducing leakage and phase segregation issues.

- *Nano-encapsulation*, in which the PCM is enclosed at the nanometer scale using polymeric, inorganic, or hybrid shells. This approach offers very high surface-to-volume ratios and enhanced thermal performance, although it is generally associated with higher production complexity and cost.

An example of macro-encapsulated PCM system is shown in **Figure 1.12**. In addition to containment and protection, encapsulation can contribute to improved heat transfer by increasing the effective contact area between the PCM and the heat transfer fluid, while also simplifying material handling and system integration [36, 37]

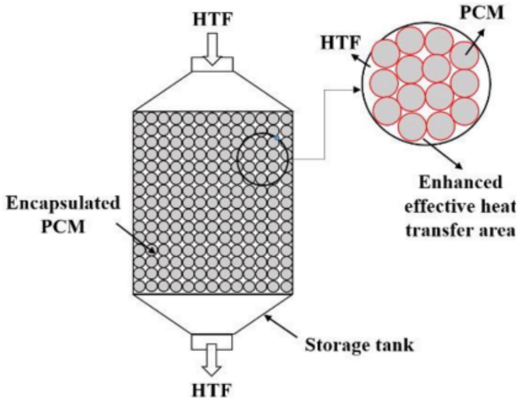


Figure 1.12: *Example of a macro-encapsulated PCM system [6]*

1.3.5.2 Heat transfer enhancement

In parallel with encapsulation strategies, extensive research has focused on improving the inherently low thermal conductivity of many PCMs. Enhanced heat transfer is essential to reduce charging and discharging times and to ensure uniform phase change throughout the storage volume. Several heat transfer enhancement techniques have been investigated, particularly those based on the integration of conductive structures or additives within the PCM matrix [3, 39].

Common approach include [3, 17, 39, 40]:

- *Extended surfaces (fins)*, where metallic fins are embedded within the storage unit to increase heat transfer surface area and accelerate melting and solidification processes.
- *Metallic foams and porous matrices*, typically made of aluminium, copper or graphite, which create continuous conductive networks that significantly enhance heat transfer while maintaining acceptable storage density.
- *Conductive additives*, such as metal nanoparticles, graphene or carbon-based materials, dispersed within the PCM to form conductive pathways that improve effective thermal conductivity.
- *Composite PCMs*, in which the phase change material is combined with conductive fillers or supporting matrices, allowing a balance between improved heat transfer, material stability and energy storage capacity.

Examples of heat transfer enhancement configurations are illustrated in **Figure 1.13**. While these techniques can substantially improve thermal performance, they often introduce additional complexity, cost, and potential reductions in effective latent heat due to the presence of non-storage materials. As a result, the selection of heat transfer enhancement strategies requires a careful trade-off between performance improvement and system feasibility [7, 40].

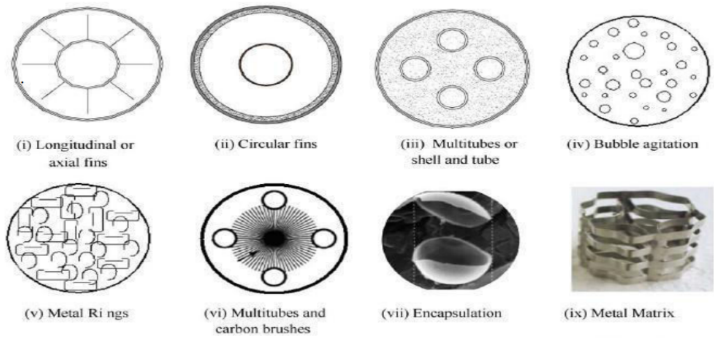


Figure 1.13: *Example of different kind of heat transfer improvements fins [7]*

1.4 Sensible thermal energy storage using water tanks

Sensible thermal energy storage based on water tanks represents one of the most mature and widely implemented solutions for thermal energy systems. This is primarily due to the favorable thermophysical properties of water, including high specific heat capacity, wide availability, and low cost, as well as its non-toxicity and ease of handling [7, 15, 41]. In water-based sensible storage systems, thermal energy is stored by increasing the temperature of the storage medium, and the achievable storage capacity is governed by the mass of water and the admissible operating temperature range.

Thanks to their simplicity and robustness, water tank storage systems are widely adopted in waste heat recovery applications to mitigate temporal mismatches between heat availability and demand. By buffering excess thermal energy when available and releasing it during periods of reduced heat production, these systems improve the overall utilization of recovered waste heat and contribute to more stable operation of the thermal energy system[13]. Their technological simplicity, combined with well-established design methodologies and extensive operational experience, makes water-based storage particularly attractive from a reliability and safety perspective.

In the maritime sector, several studies have investigated the integration of sensible thermal energy storage using water tanks within ship energy systems. In these configurations, waste heat recovered from main engines and auxiliary machinery during navigation is stored and subsequently used to supply onboard thermal demands during port stays or low-load operation, when waste heat availability is limited [42, 20, 21]. The results of these studies consistently indicate that sensible thermal storage can reduce the operating hours of auxiliary boilers, leading to lower fuel consumption and associated emissions.

Despite these advantages, the main limitation of water-based sensible thermal energy storage lies in its relatively low energy density. Since energy is stored solely through temperature variation, significant thermal capacities can only be achieved by either large water masses or wide operating temperature ranges. In practical applications, the allowable temperature difference is often constrained by system design, safety considerations and compatibility with onboard heat users. As a result, large storage volumes may be required, which can represent a critical drawback in marine applications where space availability and mass distribution are key design parameters [15, 41]. Furthermore, operation at elevated temperatures may require pressurized tanks and reinforced structures, increasing system complexity and introducing additional safety and integration constraints onboard ships. These aspects can negatively affect the feasibility of water-based sensible storage in applications with stringent volumetric and weight limitations, motivating the investigation of alternative storage technologies with higher energy density, such as latent heat storage based on Phase Change Materials [19].

Chapter 2
Case study

The maritime sector is currently facing increasing pressure to improve energy efficiency and reduce greenhouse gas emissions, driven by both international and regional regulatory frameworks aimed at decarbonizing maritime transport. At the global level, the International Maritime Organization (IMO) has defined ambitious targets requiring a reduction of greenhouse gas (GHG) emissions by 20-30% by 2030 and the achievement of net-zero emissions by 2050. These objectives reflect the growing urgency to address the environmental impact of shipping and impose increasingly stringent constraints on ship energy performance [10].

In parallel with global initiatives, regional regulations further reinforce these requirements. In particular, the European Union Emissions Trading System (EU ETS) and the FuelEU Maritime regulation introduce direct carbon pricing mechanisms and stricter limits on the greenhouse gas intensity of marine fuels. These measurements directly affect ship operating costs and incentivize the adoption of energy-efficient technologies capable of reducing fuel consumption and emissions without relying exclusively on alternative fuels, which are currently associated with high costs, limited availability and technological uncertainty [12].

Within this regulatory context, improving onboard energy efficiency emerges as a key and immediately actionable strategy to reduce emissions while mitigating exposure to fuel-related uncertainties. According to *DNV's Maritime Forecast to 2050*, efficiency improvements and operational optimization alone could reduce the global fleet energy demand by up to 16% by 2030, providing a substantial contribution to emissions reduction targets while maintaining the use of conventional fuels [11]. These findings highlight the importance of technologies that enhance the utilization of onboard energy resources and reduce waste.

Among the available technological options, Waste Heat Recovery Systems (WHRS) play a central role by enabling the reuse of residual thermal energy from engine exhaust gases and other onboard heat sources. By converting otherwise wasted heat into useful thermal or electrical energy, WHRS can significantly improve the overall efficiency of marine propulsion plants and reduce auxiliary fuel consumption [1, 13, 14].

However, the effectiveness of WHRS onboard ships, and particularly on cruise vessels, is inherently limited by the temporal mismatch between waste heat availability and onboard thermal demand. During navigation, main engines typically operate at medium to high loads, producing large quantities of recoverable heat, while onboard thermal demand may remain relatively moderate. Conversely, during port stays or low-load operation, thermal demand associated with hotel services, accommodation heating, and auxiliary systems remains significant, whereas waste heat availability is substantially reduced due to the limited operation of the main engines. In these conditions, auxiliary oil-fired boilers are often required to cover the thermal demand, leading to increased fuel consumption and emissions [2, 19, 20, 21].

To address this structural mismatch, Thermal Energy Storage (TES) systems can be integrated with WHR units to decouple heat generation from heat consumption. By storing excess thermal energy during periods of high waste heat availability and releasing it when demand exceeds instantaneous recovery potential, TES systems offer a promising solution to enhance the utilization factor of WHRS, reduce auxiliary boiler operation and improve overall energy efficiency, particularly during port stays [15, 22].

In this context, the present chapter introduces a representative cruise vessel case study aimed at evaluating the integration of Thermal Energy Storage systems within a waste heat recovery framework. The analysis focuses on the definition of the operational scenarios, the formulation of the thermal energy balance, and the methodological sizing of the storage system. Particular attention is devoted to volumetric requirements and integration constraints, which represent key design drivers for shipboard applications where space availability is critical.

2.1 Reference vessels and fleet profile

To provide a realistic and representative framework for the assessment of Thermal Energy Storage integration onboard cruise vessels, a reference case study is defined based on ships belonging to the Ponant fleet [8]. This fleet is characterized by a relatively homogeneous design philosophy across different ship classes, particularly in terms of propulsion architecture, hotel load intensity, and operational patterns, while still covering a wide range of vessel sizes and mission profiles. In addition, the availability of detailed technical and operational data makes the Ponant fleet particularly suitable for a structured analysis, allowing the conclusions of the present study to be extended to a broader class of medium-sized and expedition cruise vessels.

Three vessel categories are considered, selected to capture the diversity of operating conditions encountered in cruise ship applications, while maintaining a consistent technological background:

- *Paul Gauguin*, a larger cruise vessel primarily dedicated to long tropical itineraries in the South Pacific. This operational profile is characterized by extended navigation periods at relatively stable engine loads, combined with continuous hotel service demand. Such conditions provide a representative reference case for evaluating waste heat recovery potential under quasi-steady operating conditions.

- *LSB series* ("The Sisterships"), including vessels such as *Le Boréal, L'Austral, Le Soléal,* and *Le Lyrial.* These ships are designed for expedition and semi-luxury cruises across a wide range of destinations, from temperate regions such as the Mediterranean Sea to polar environments. Their operational profiles are therefore more variable, featuring frequent changes in sailing conditions, engine loads and thermal demand, which directly influence the temporal distribution of waste heat availability.

- *PEX series* ("Explorers"), composed of smaller and more recent expedition vessels such as *Le Lapérouse, Le Champlain, Le Bougainville, Le Dumont d'Urville, Le Bellot,* and *Le Jacques Cartier.* These ships are optimized for operations in remote and environmentally sensitive areas, where stringent environmental constraints, limited port infrastructure, and high hotel load intensity per passenger make onboard energy management particularly relevant.

The main geometric, propulsion, and operational characteristics of the selected reference vessels are summarized in **Table 2.1**. The table highlights both the similarities and the differences among the three vessel categories. While the propulsion layouts and engine technologies are comparable across the fleet, the vessels differ in size, installed power, passenger capacity, and operational mission. These parameters determine the magnitude and temporal distribution of waste heat generation and onboard thermal demand, which are subsequently used to define the representative operating scenarios considered in this study.

Table 2.1: *Key vessels characteristics of Ponant vessels [8]*

	Paul Gauguin	**LSB series**	**PEX series**
Destinations	French Polynesia	Antarctica, Oceania, Mediterranean Sea	Mediterranean Sea, South-West Indian Ocean, Polar regions
Construction	Chantier de l'Atlantique (Saint Nazaire, France)	Fincantieri (Ancona, Italy)	Vard Group (Søvik, Norway)
Classification	Bureau Veritas	Bureau veritas	Bureau Veritas
Lenght (m)	154	142	131
Beam (m)	22	18	18
Draft (m)	5.8	4.7	4.7
Ice class	/	1C	1C
Tonnage (tons)	19 200	10 944	9976
Engines	2 × MAN 6L32 + 2 × MAN 9L32	4 × Wärtsilä 8L20	4 × Wärtsilä 8L20
Power (kW)	13 200	6400	6400
Passenger decks	7	6	5
Passengers	318	264	184
Crew	216	145	118

2.2 Operational profile

A representative operating profile is defined based on real voyage data, onboard logs, and energy performance reports provided by the ship operator as internal technical documentation. The adoption of realistic operational profiles is essential to capture the temporal variability of engine loads, waste heat generation, and onboard energy demand, which directly influence the sizing and operation of Waste Heat Recovery and Thermal Energy Storage systems.

For cruise vessels, operating conditions vary significantly over the course of a voyage, reflecting the alternation between sailing periods, port stays, and transient maneuvers. To represent this variability in a simplified yet meaningful manner, the operating behavior of the vessels considered in this study is schematically divided into three main phases:

- *Navigation at sea*, during which the main engines operate at medium-to-high loads to provide propulsion. In this phase, waste heat availability from exhaust gases, scavenge air, and engine cooling systems reaches its highest levels, while onboard thermal demand is primarily associated with hotel services and auxiliary systems. This phase represents the condition in which surplus recoverable thermal energy may be available.

- *Berth* or *port stay*, characterized by very low or null propulsion demand and consequently reduced main engine operation. Despite the limited availability of waste heat, onboard thermal demand remains significant due to accommodation services, heating, domestic hot water production, and auxiliary systems. This phase typically requires the support of auxiliary boilers to satisfy the thermal demand.

- *Maneuvering*, which includes port approaches and departures and is characterized by transient operating conditions with rapidly varying engine loads. Although this phase is relatively short compared to navigation and berth periods, it introduces dynamic variations in waste heat generation and energy demand that can affect the instantaneous balance between supply and demand.

This simplified operational framework captures the typical variability of cruise ship operation while maintaining a level of abstraction suitable for system-level analysis. It provides a consistent basis for the subsequent formulation of the thermal energy balance, which is used to quantify recoverable heat during navigation and thermal demand during port stays.

The three operational phases considered in the analysis are schematically illustrated in **Figure 2.1**, which highlights the alternation between high-load and low-load conditions that defines the temporal structure of heat availability and demand.

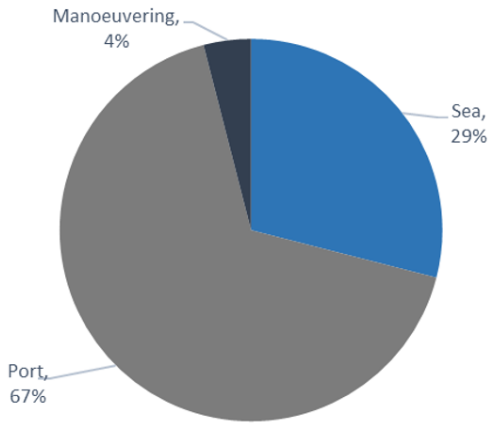


Figure 2.1: *Operational phases of the cruise model*

2.3 Engine configuration

For the purpose of this study, the propulsion system is modeled assuming four main medium-speed diesel engines, all represented as MAN 6L32/40 units. This modeling choice is introduced to ensure consistency in the evaluation of waste heat recovery potential and to provide a representative reference for typical cruise ship machinery layouts. Medium-speed four-stroke engines of this class are widely adopted in cruise and expedition vessels due to their reliability, operational flexibility, and compatibility with waste heat recovery systems based on exhaust gas boilers.

By assuming identical engine units, the analysis focuses on the influence of operational conditions and energy management strategies rather than on differences between engine technologies. This approach allows a clearer assessment of the interaction between waste heat availability and onboard thermal demand under different operating scenarios.

The main thermodynamic and operational characteristics of the engines and the associated exhaust gas boilers (EGBs) are summarized in **Table 2.2**. The reported parameters define the available waste heat level, the steam generation capability, and the temperature range relevant for downstream thermal users and storage systems. In particular, the exhaust gas temperature and mass flow determine the theoretical recoverable thermal power, while the steam conditions at the EGB outlet set the reference level for integration with the ship's thermal distribution network.

Table 2.2: *Key specification of MAN 6L32/40 engine with associated EGB [9]*

Exhaust gas flow rate (kg/s)	2.2
Inlet exhaust temperature (°C)	367
Outlet exhaust temperature (°C)	201.5
Boiler capacity (kW)	400
Steam flow per boiler (kg/h)	590
Steam temperature (°C)	175.5
Steam pressure (bar(g))	8
Feedwater temperature (°C)	90

During navigation at sea, three engines are typically operated simultaneously to meet propulsion and onboard power requirements. Under these conditions, the combined operation of multiple EGBs results in elevated steam production and increased waste heat availability. This operating phase therefore defines the primary time window in which surplus recoverable thermal energy may be present.

Conversely, during port stays and low-load operation, only one engine is generally kept in service to supply essential electrical and auxiliary loads. As a consequence, waste heat availability is reduced and the thermal power provided by the EGBs may become insufficient to fully satisfy onboard thermal demand. In such conditions, auxiliary systems such as Oil-Fired Boilers (OFBs) are typically required to compensate for the reduced recovery potential.

An example of engine operating mode distribution for the *Paul Gauguin* vessel is illustrated in **Figure 2.2**. The figure highlights the predominance of multi-engine operation during navigation and the reduction in active engines during port stays, illustrating the temporal variability of waste heat generation across the voyage. This variability constitutes the basis for the subsequent thermal energy balance analysis presented in the following sections.

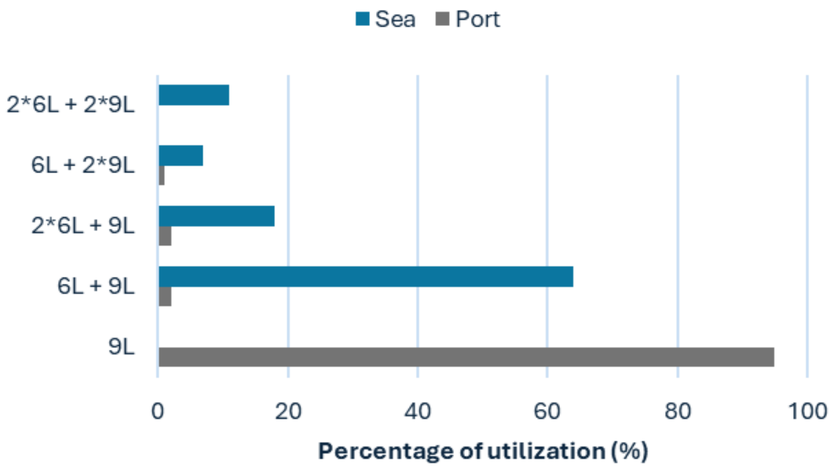


Figure 2.2: *Example engine mode distribution for Paul Gauguin vessel*

2.4 Steam consumers and thermal demand

Steam represents one of the primary energy carriers onboard cruise vessels and is extensively used to supply thermal energy to a wide range of auxiliary systems and hotel services. Owing to the continuous presence of passengers and crew and to the high level of comfort expected onboard, thermal demand remains significant across most operating conditions, including both navigation and port stays. For this reason, steam consumption constitutes a key parameter in the evaluation of waste heat recovery potential and in the formulation of the thermal energy balance.

Based on technical documentation provided by the ship operator, the main steam consumers considered in this study include:

- *Air conditioning (AC) heating*, which represents one of the largest and most continuous thermal loads, particularly in cold climates or during shoulder seasons, and is closely linked to passenger comfort requirements.
- *Domestic hot water (DHW)* production for passenger cabins and crew areas, characterized by a relatively steady baseline demand with additional peaks linked to daily usage patterns.
- *Swimming pool heating*, which requires a stable thermal input to maintain water temperature and represents a non-negligible load during both navigation and port stays.
- *Galley equipment*, including cooking appliances and dishwashing systems, which generate intermittent but high-intensity thermal demand associated with meal preparation cycles.
- *Laundry systems*, comprising dryers and water preheaters, typically characterized by batch operation and pronounced demand peaks.
- *Sanitary water preheating and lube oil separators*, which contribute additional auxiliary thermal loads required for safe and reliable ship operation.

Although the individual contribution of each consumer may vary depending on vessel size, itinerary, and operating mode, the combined effect results in a substantial and relatively continuous thermal demand throughout the voyage. This characteristic becomes particularly relevant during port stays, when propulsion-related waste heat availability is reduced while hotel-related thermal demand remains largely unchanged.

In the vessels considered, these services are typically supplied by steam or hot water at temperatures in range of 85-90°C, with return temperatures between 55 and 60°C. This temperature level defines the operating conditions of the onboard thermal distribution network and directly influences the integration of waste heat recovery units and storage systems. In particular, it establishes the minimum temperature requirements for effective heat delivery and sets the reference temperature level used in the subsequent storage sizing methodology.

2.5 Operational scenarios

To evaluate the performance of Thermal Energy Storage systems under realistic and representative conditions, a set of reference operational scenarios is defined by combining cruise duration and seasonal variability. The definition of multiple scenarios allows the analysis to capture the combined effects of voyage length, climatic conditions, and operational patterns on waste heat availability, thermal demand, and storage operation.

Two cruise durations are considered: a long cruise of 15 days and a short cruise of 8 days. These durations are selected to represent typical operational patterns within the reference fleet, ranging from extended itineraries with repeated navigation and port cycles to shorter cruises characterized by a higher frequency of port calls. Cruise duration influences the cumulative availability of waste heat, the repetition of charging and discharging phases, and the overall energy balance of the system.

Each cruise duration is analyzed under two distinct seasonal conditions, namely summer and winter operation. Seasonal variability plays a key role in determining onboard thermal demand, particularly for air conditioning and space heating, and significantly affects the balance between waste heat production and consumption. In summer conditions, thermal demand is generally lower and navigation periods are typically longer, resulting in different ratios between waste heat availability and demand. Conversely, winter operation is characterized by increased thermal demand and longer port stays, leading yo a different temporal distribution of heat generation and consumption.

The resulting combination of cruise duration and seasonal conditions leads to four reference operational scenarios. For each scenario, representative sailing and port times are defined and summarized in **Table 2.3**. These time allocations reflect typical daily operational patterns and are used as a basis for the subsequent thermal and energy balance formulation.

Table 2.3: *Seasonal and operational scenarios*

	Long cruise (15 days)		**Short cruise (8 days)**	
	Sailing time (h)	Port time (h)	Sailing time (h)	Port time (h)
Summer	20	12	20	12
Winter	11	20	11	20

The four scenarios defined above establish the operational boundary conditions used in the subsequent energy balance and storage sizing methodology. Their quantitative implications in terms of recoverable energy and storage requirements are discussed in **Chapter 4**.

2.6 Steam balance analysis

The steam balance analysis represents a fundamental step in the assessment of waste heat recovery potential and in the formulation of the storage sizing methodology. By quantifying the difference between steam generation and onboard thermal demand under different operating conditions, it is possible to identify periods of surplus recoverable heat and periods of thermal deficit.

Steam production and consumption are analyzed under both summer and winter operating conditions using engine technical specifications and onboard operational reference data. Seasonal differentiation is essential, as thermal demand varies significantly with ambient conditions, particularly for space heating, domestic hot water, and hotel services.

During navigation at sea, steam is recovered from the exhaust gases of the main engines through exhaust gas boilers (EGBs). Each EGB is capable of producing up to 400 kW of thermal power under nominal operating conditions. When multiple engines are operated simultaneously, the resulting steam production may exceeds the instantaneous onboard thermal demand. In such cases, the surplus steam is discharged through dump valves, representing unused recoverable thermal energy.

Conversely, during port stays and low-load operation, the reduced number of operating engines leads to lower waste heat availability. As a result, steam production from EGBs may become insufficient to satisfy onboard thermal demand, which must therefore be supplied by auxiliary oil-fired boilers.

The quantitative steam balance under seasonal conditions is obtained by comparing the generated and required thermal powers during navigation and port stays. The resulting values of steam dumping and auxiliary top-up are reported and discussed in **Chapter 4**.

The thermal power associated with steam dumping during navigation is evaluated as the difference between the thermal power generated by the EGBs and the onboard thermal demand:

$$\dot{Q}_{\text{dump}} = \dot{Q}_{\text{generated}} - \dot{Q}_{\text{demand}}. \tag{2.1}$$

where:

- $\dot{Q}_{\text{generated}}$ represents the total thermal power produced by the engines operating during navigation;
- $\dot{Q}_{\text{demand}}$ denotes the thermal power required by the onboard steam consumers.

Similarly, the auxiliary thermal power required during port stays is calculated as:

$$\dot{Q}_{\text{top-up}} = \dot{Q}_{\text{demand}} - \dot{Q}_{\text{generated}}. \tag{2.2}$$

where:

- $\dot{Q}_{\text{generated}}$ refers to the thermal power produced by the engine operating during port stay;
- $\dot{Q}_{\text{demand}}$ denotes the onboard thermal demand.

2.7 Thermal energy analysis

Based on the steam balance and the previously defined operational profiles, a thermal energy analysis is carried out to quantify both the amount of thermal energy potentially recoverable during navigation and the thermal energy required to satisfy onboard demand during port stay.

The recoverable thermal energy is associated with the steam that is generated in excess of onboard demand during navigation and is normally discharged through dump valves. This quantity represents the maximum theoretical energy that could be stored, assuming adequate storage capacity and suitable charging conditions. It is defined as:

$$E_{\text{recoverable}} = \dot{Q}_{\text{dump}} \cdot t_{\text{sailing}} \tag{2.3}$$

where:

- $\dot{Q}_{dump}$ represents the average thermal power associated with dumped steam during navigation;
- $t_{sailing}$ is the cumulative sailing time over the considered operational scenario.

Conversely, the thermal energy demand during port stays corresponds to the energy deficit arising from insufficient waste heat availability at low engine loads. Under these conditions, the required thermal power is typically supplied by auxiliary oil-fired boilers. The corresponding energy demand is expressed as:

$$E_{\text{demand}} = \dot{Q}_{\text{top-up}} \cdot t_{\text{port}} \tag{2.4}$$

where:

- $\dot{Q}_{top-up}$ is the thermal power required to meet onboard steam demand at berth;
- t_{port} is the cumulative port stay duration.

For each operational scenario, the storage target is defined by comparing the recoverable thermal energy during navigation and the thermal demand during port stays. The quantitative results of this comparison for the different cruise durations and seasonal conditions are presented and discussed in **Chapter 4**.

2.8 System flow diagram

Figure 2.3 illustrates a simplified process flow diagram of the onboard steam system, highlighting the proposed integration of a Thermal Energy Storage unit based on Phase Change Materials within the existing waste heat recovery architecture. The diagram provides a conceptual overview of the steam generation, distribution and storage processes considered in the present study and serves as a reference framework for the subsequent modeling approach.

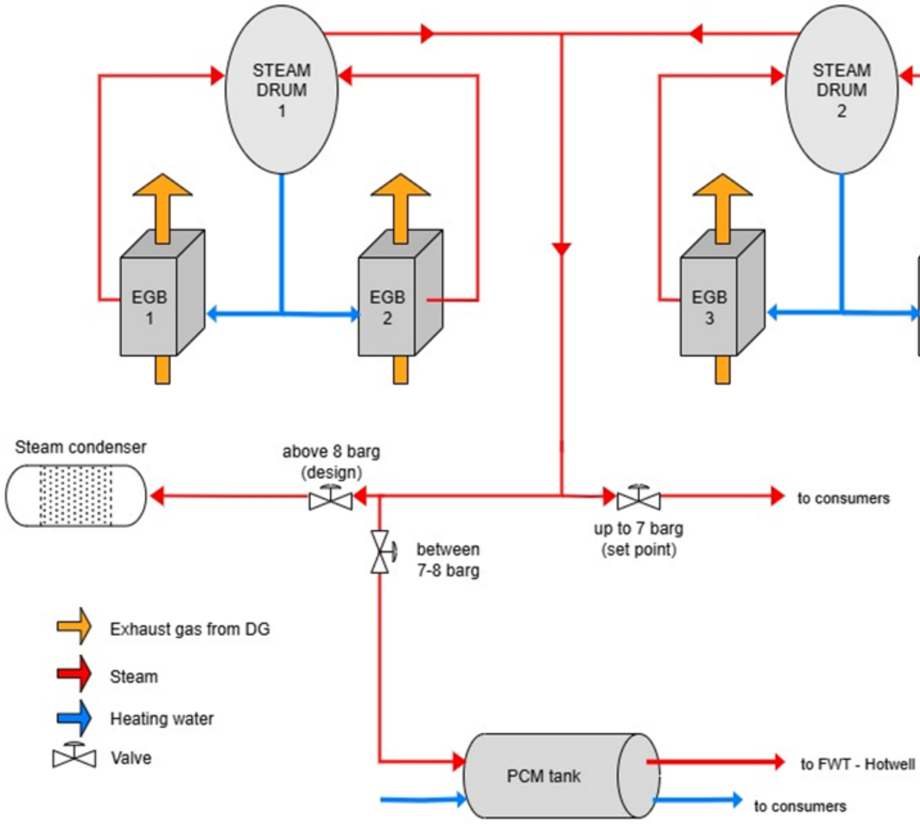


***Figure 2.3:** Steam system process flow diagram based on onboard system data*

The proposed configuration is designed to exploit waste heat recovered during navigation while preserving the original functionality of the onboard steam network. In particular, the TES unit is integrated in parallel with the steam distribution system, allowing surplus thermal energy to be diverted toward storage when available and returned to the thermal network during periods of reduced waste heat generation.

The main components of the system are:

- *Exhaust Gas Boilers (EGBs)*, which recover thermal energy from the exhaust gases of the main engines during navigation. Under medium-to-high engine loads, the EGBs generate saturated steam by transferring heat from the exhaust gases to the water/steam circuit. This represents the primary source of recovered thermal energy within the system.

- *Steam drums*, which act as intermediate storage and distribution nodes within the steam network. The steam drums collect the saturated steam produced by the EGBs and distribute it either to the onboard steam consumers or, when steam production exceeds instantaneous demand, toward the TES unit. Their presence ensures stable pressure control and reliable steam supply under varying operating conditions.

- *PCM storage tank*, which serves as a latent heat accumulator. During navigation, when surplus steam is available, thermal energy can be transferred to the PCM storage tank and stored in the form of latent heat at nearly constant temperature. During port stays or low-load operation, the stored energy can be released and redirected to the steam or hot water network, contributing to the coverage of onboard thermal demand.

2.9 PCM selection and design

The performance of a TES system based on phase change materials is strongly influenced by the thermophysical, chemical, and operational properties of the selected PCM. The choice of the storage material affects the achievable storage density, the operating temperature range, the charging and discharging behavior, and the long-term reliability of the system under real operating conditions [4, 16].

In the context of marine waste heat recovery applications, the PCM must be capable of storing and releasing significant quantities of thermal energy under dynamic and discontinuous operating conditions, characterized by alternating phases of high heat availability during navigation and reduced recovery potential during port stays. In addition to high latent heat, the material must exhibit a phase change temperature compatible with the onboard steam and hot water distribution network, in order to ensure effective heat exchange without requiring additional temperature lifting or complex control strategies.

Chemical stability and long-term durability represent further requirements for marine applications. The selected PCM must maintain its thermophysical properties over repeated melting and solidification cycles, avoiding degradation phenomena such as phase segregation, subcooling amplification or loss of latent heat capacity. Compatibility with containment materials and heat transfer fluids is equally important, as corrosion, leakage or chemical reactions could compromise system safety and operational reliability in the shipboard environment [16].

From a system integration perspective, PCM selection is closely linked to volumetric constraints and installation feasibility. Cruise vessels are characterized by limited available space and strict weight distribution requirements; therefore, materials with high energy density are generally preferred in order to reduce storage volume for a given thermal capacity. At the same time, the PCM must be compatible with compact storage geometries and practical heat exchanger designs suitable for shipboard integration [4, 15, 16].

Based on these considerations, the PCM selection and storage system design in this study are defined according to criteria derived from the operational profiles, steam balance formulation and thermal energy analysis presented in the previous sections. The specific material choice and its quantitative implications in terms of required mass and volume are presented in **Chapter 4**.

2.9.1 Selection criteria

The selection of the Phase Change Material is guided by a set of thermophysical, operational, and safety requirements, derived from the specific characteristics of marine waste heat recovery applications and from the constraints identified in the previous analyses [5, 22]. The PCM must provide high energy storage performance while ensuring long-term reliability and safe operation within the shipboard environment.

The main selection criteria adopted in this study are summarized as follows:

- *High latent heat of fusion*, in order to maximize the amount of thermal energy stored per unit mass and reduce the required quantity of storage material.

- *High volumetric energy storage density*, which is particularly critical in marine applications where available space is limited and the integration of large storage volumes may represent a significant constraint.

- *Stable performance over repeated charging and discharging cycles*, ensuring consistent thermal behavior over the vessel lifetime and avoiding degradation phenomena that could compromise system operation.

- *Long service life*, compatible with the expected operational lifetime of the vessel and minimizing maintenance requirements and material replacement.

- *Non-toxicity*, to ensure safe handling, installation and operation in confined shipboard spaces and to comply with health and safety regulations.

- *Non-flammability*, which represents a key safety requirement in marine environments, where fire risk mitigation is a primary design driver.

In addition to these criteria, the phase change temperature represents a fundamental design parameter. Based on the operating conditions of the onboard thermal distribution network, a target melting temperature range between 90 and 100°C is defined. This range is selected to ensure compatibility with the hot water supply temperature, typically around 90°C, while remaining below the steam generation temperature level of approximately 175°C. Such temperature positioning allows heat exchange between the steam circuit and the storage medium without requiring additional temperature boosting stages.

2.9.2 Candidate materials

A preliminary screening of commercially available organic PCMs is carried out using supplier datasheets and information available in the technical literature. The analysis focuses on organic PCMs operating in the target temperature range identified in the previous section, with particular attention to materials suitable for medium temperature thermal energy storage applications and compatible with shipboard safety requirements.

The screening process is guided by the selection criteria previously defined, namely latent heat of fusion, volumetric energy storage density, thermal stability, and practical feasibility. Organic PCMs are preferred at this stage due to their generally favorable chemical stability, limited supercooling behavior, and compatibility with a wide range of containment materials, which are particularly relevant for marine applications.

The main properties of the candidate materials considered in this study are summarized in **Table 2.4**. The selected candidates include two high-temperature paraffin-based PCMs from the *Rubitherm* product line, namely *RT90HC* and *RT100HC*, and the commercially available *A95* PCM produced by *PCM Products*. All three materials exhibit melting temperatures within or close to the target range and are therefore compatible with the onboard hot water and steam distribution network.

Table 2.4: Organic PCM candidates

	Melting temperature (°C)	Latent heat (kJ/kg)	Density (kg/m^3)	Producer
RT90HC	91-92	170	950	Rubitherm Technologies
RT100HC	99-101	180	1000	Rubitherm Technologies
A95	95	260	900	PCM Products

A preliminary comparison of the candidate materials indicates differences in latent heat and density, which influence the potential storage capacity per unit mass and per unit volume. Among the screened materials, *A95* exhibits the highest latent heat within the target temperature range, while maintaining a density compatible with compact storage configurations.

On the basis of these thermophysical properties and its commercial availability, *A95* is selected as the reference PCM for the numerical modeling and storage sizing analysis developed in the following chapters. The quantitative implications of this choice in terms of required mass, volume, and economic considerations are presented and discussed in **Chapter 4**.

2.9.3 PCM mass and volume estimation

The estimation of the required PCM mass represents a key step in the sizing of the thermal energy storage system, as it directly links the thermal energy analysis to the physical dimensions of the storage unit. The objective of this step is to determine the amount of PCM necessary to ensure that sufficient thermal energy can be released during port stays, while avoiding unrealistic oversizing under constrained operating conditions.

For each operating scenarios, the usable thermal energy for storage, E_{usable}, is defined as the minimum between the recoverable thermal energy during navigation and the thermal energy demand during port stays. This definition ensures that the storage system is sized based on realistically available energy, accounting for both charging and discharging limitations.

The required PCM mass is calculated by considering both sensible and latent heat contributions during a full charging cycle, according to:

$$m = \frac{E_{\mathrm{usable}}}{C_{\mathrm{p}}(T_{\mathrm{m}} - T_{\mathrm{in}}) + L_{\mathrm{s}} + C_{\mathrm{p}}(T_{\mathrm{out}} - T_{\mathrm{m}})} \tag{2.5}$$

This formulation accounts for the complete thermal behavior of the PCM during charging, including sensible heating from the initial temperature T_{in} up to the melting temperature T_m, latent heat absorption during the phase change, and further sensible heating in the liquid phase up to the maximum operating temperature T_{out}.
In this study, the initial PCM temperature before charging is set to 30°C, representing a conservative assumption for the minimum storage temperature under shipboard conditions.

The maximum PCM temperature after full charge is fixed at 160°C, consistent with the temperature level of the recovered steam, and ensuring sufficient temperature difference for effective heat transfer.

The corresponding PCM volume is then calculated as:

$$V = \frac{m}{\rho} \tag{2.6}$$

where ρ is the density of the selected PCM. The quantitative values of PCM mass and volume obtained for each operational scenario are presented and discussed in **Chapter 4**.

2.9.4 Enthalpy behavior

The thermal behavior of the Phase Change Material is governed by enthalpy variations associated with both sensible and latent heat exchanges. An enthalpy-based description is particularly suitable for PCM-based thermal energy storage systems, as it allows the different contributions to the stored energy to be identified and quantified throughout the charging and discharging processes.

During navigation, the PCM undergoes the charging phase, during which thermal energy recovered from the exhaust gas boilers is progressively stored within the material. This process consist of three distinct stages of energy absorption, which are consistent with the typical behavior of solid-liquid phase change materials [22]:

- *Sensible heating of the solid phase*
  In the first stage, the PCM is heated from its initial temperature up to its melting temperature T_{m}. During this phase, thermal energy is stored as sensible heat, with a linear increase in enthalpy as a function of temperature. The corresponding energy contribution is given by:

$$Q_{\mathrm{sensible,solid}} = mC_{\mathrm{p}}(T_{\mathrm{m}} - T_{\mathrm{in}}) \tag{2.7}$$

- *Phase change (latent heat storage)*
  Once the melting temperature is reached, the PCM undergoes the solid-to-liquid phase transition. During this stage, thermal energy is absorbed in the form of latent heat L_s, while the temperature remains nearly constant. This contribution is expressed as:

$$Q_{\mathrm{latent}} = mL_{\mathrm{s}} \tag{2.8}$$

- *Sensible heating of liquid phase*
  After complete melting, the PCM is further heated from the melting temperature to the maximum storage temperature. This additional sensible heat contribution increases the total stored enthalpy:

$$Q_{\mathrm{sensible,liquid}} = mC_{\mathrm{p}}(T_{\mathrm{out}} - T_{\mathrm{m}}) \tag{2.9}$$

During port stays, the PCM undergoes the discharging phase, during which the stored thermal energy is progressively released to the onboard thermal network. The discharging process follow the reverse sequence of the charging phase, involving sensible cooling of the liquid PCM, latent heat release during solidification, and final sensible cooling of the solid phase.

The quantitative distribution of sensible and latent contributions for the different operational scenarios, as well as the corresponding enthalpy evolution during charging and discharging, are presented and discussed in **Chapter 4**.

Chapter 3

Numerical model

This chapter presents the numerical model developed to simulate the transient behavior of a latent heat thermal energy storage (TES) system based on Phase Change Materials. The model is designed to describe the dynamic charging and discharging processes of the storage unit under operating conditions representative of cruise ship applications, as defined in the previous chapter.
The main objectives of the numerical model is to capture the time-dependent thermal response of the PCM during its interaction with the heat transfer fluid, accounting for both sensible and latent heat contributions. In particular, the model is used to quantify the amount of thermal energy that can be effectively stored during navigation and subsequently released during port stays. In addition, it allows the investigation of the influence of key design and operating parameters on system performance. From a system integration perspective, the model also supports the assessment of geometric feasibility by linking thermal requirements to storage size and heat exchanger characteristics.

The modeling approach is based on a dynamic lumped-parameter formulation, following the methodology proposed by Lamnari et al [43]. This approach describes the transient thermal interaction between the phase change material and the heat transfer fluid through global energy balance equations. By adopting a lumped formulation, the storage unit is represented by averaged temperatures, and spatial temperature gradients within the PCM are neglected.

This modeling strategy represents a deliberate trade-off between physical accuracy and computational efficiency. While more detailed distributed or multidimensional models can provide a more accurate description of local heat transfer phenomena, they are generally computationally intensive and less suitable for system-level analyses. The lumped-parameter approach adopted in this work allows rapid simulations and extensive parametric investigations, making it particularly appropriate for preliminary design, optimization studies, and sensitivity analyses.

The numerical model is implemented in MATLAB and applied to the operational scenarios defined in the case study chapter. The structure of the model, governing equations, and the main assumptions adopted are presented in the following sections.

3.1 System description

The thermal energy storage system is modeled as a multi shell-and-tube heat exchanger, in which the phase change material occupies the shell side and acts as the thermal storage medium. This configuration is selected because it allows an effective integration of the PCM within a compact geometry, while ensuring controlled heat exchange with the working fluids and mechanical separation between the storage material and the onboard circuits.

Heat transfer between the PCM and the heat transfer fluids takes place through tube bundles embedded within the PCM volume. The tubes provide the heat transfer surface required to change and discharge the storage unit, while the PCM surrounding the tubes absorbs or releases thermal energy through sensible and latent heat mechanisms. From a modeling perspective, the shell-and-tube arrangement also offers a well-defined heat transfer interface that can be effectively represented using lumped-parameter energy balances.

Two independent heat transfer circuits are considered in the system, corresponding to the two operating modes of the storage unit:

- *Charging phase*, during which saturated steam flows inside a dedicated tube bundle and condenses along the tube walls. The latent heat released during the n is transferred through the tube walls to the surrounding PCM, causing an increase in its temperature and, once the melting point is reached, initiating the phase change process. This configuration reflects typical waste heat recovery conditions during navigation, when excess steam is available from the exhaust gas boilers.

- *Discharging phase*, during which pressurized water flows through a separate tube bundle and extracts thermal energy from the PCM. The recovered heat is then supplied to onboard thermal consumers, such as hot water and heating systems, particularly during port stay when waste heat availability is limited.

The two heat transfer circuits operate alternately and are hydraulically independent. This design choice ensures operational flexibility and prevents any direct contact or contamination between steam and water circuits. In addition, the separation of the charging and discharging circuits simplifies system control and allows the thermal storage unit to be operated under different flow rates and temperatures levels depending on the operating phase.

A schematic representation of the system layout is shown in **Figure 3.1**, which illustrates the arrangement of the shell-and-tube heat exchanger, the PCM storage region, and the tube bundles.

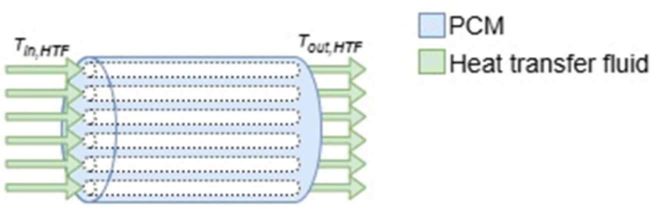


Figure 3.1: *Schematic of a multi shell-and-tube heat exchanger*

3.2 Modeling assumptions

The numerical model is developed within a simplified framework aimed at capturing the dominant thermal phenomena governing the charging and discharging processes of the PCM-based thermal energy storage system, while maintaining low computational cost and suitability for system-level analyses. The adopted assumptions are consistent with the lumped-parameter formulation and with the objective of evaluating the global thermal behavior of the storage unit.

The model is formulated under the following assumptions:

- Uniform temperature within each control volume;
- Unidirectional flow of the heat transfer fluids;
- Constant thermophysical properties of the heat transfer fluids;
- Negligible natural convection within the PCM;
- Negligible radiative heat transfer;
- Perfectly insulated storage tank;
- Negligible thermal interactions between adjacent tubes.

3.3 Governing equations

The numerical model is based on transient energy balances equations applied to the PCM and to the heat transfer fluids during both charging and discharging phases.
The governing equations describe the temporal evolution of PCM temperature and liquid fraction, accounting for sensible and latent heat contributions during the phase change process. In parallel, energy balances are applied to the heat transfer fluids flowing inside the tube bundles in order to evaluate the exchanged thermal power during condensation in the charging phase and during heat extraction in the discharging phase.
By coupling the energy balances of the PCM and of the heat transfer fluids, the model allows the calculation of the instantaneous heat transfer rate between the two domains, as well as the cumulative amount of thermal energy stored and released over time.

The governing equations are presented separately for the charging and discharging phases in the following subsections, reflecting the different heat transfer mechanisms and boundary conditions associated with each operating mode.

3.3.1 Energy balance of the PCM

The PCM stores and releases thermal energy through both sensible and latent heat mechanisms, depending on its temperature relative to the phase change interval. Accordingly, two different formulations of the energy balance are adopted to describe the thermal behavior of the PCM during the charging and discharging processes.

3.3.1.1 Sensible heat exchange

When the PCM temperature lies outside the phase change interval, the material exchanges energy purely through sensible heating or cooling. In this regime, the transient energy balance is formulated by equating the rate of change of internal energy of the PCM to the heat exchanged with the heat transfer fluid through convection.

The corresponding energy balance equation is expressed as [43]:

$$(mC_{\mathrm{p}})_{\mathrm{PCM}}\frac{dT_{\mathrm{PCM}}}{dt} = h_{\mathrm{f}}A(T_{\mathrm{f}} - T_{\mathrm{PCM}}) \tag{3.1}$$

where:

- m is the PCM mass
- C_{p} is the specific heat capacity;
- T_{PCM} is the average PCM temperature;
- T_{f} is the temperature of the heat transfer fluid;
- h_{f} is the convective heat transfer coefficient;
- A is the effective heat transfer area.

3.3.1.2 Latent heat exchange

When the PCM temperature lies within the phase change interval, latent heat effects become dominant and must be explicitly accounted for. In the present model, the phase change process is represented using an effective heat capacity method, which allows the latent heat of fusion to be incorporated into the energy balance through a temperature-dependent apparent heat capacity.

The corresponding transient energy balance is expressed as [43]:

$$m\left(C_{\text{base}}+\frac{\frac{L_{\text{s}}2\gamma}{\Delta T}}{\pi\left(\left((T_{\text{PCM}}-T_{\text{m}})\frac{2\gamma}{\Delta T}\right)^2+1\right)}\right)\frac{dT_{\text{PCM}}}{dt}=h_{\text{f}}A(T_{\text{f}}-T_{\text{PCM}}) \tag{3.2}$$

where:

- m is the PCM mass
- C_{base} is the baseline specific heat capacity of the PCM in solid or liquid phase, ignoring heat from phase transition;
- L_{s} is the latent heat of fusion;
- T_{m} is the melting temperature of the PCM;
- T_{PCM} is the PCM temperature;
- ΔT is the temperature interval where the phase change occurs;
- γ is the smoothing parameter that determines the sharpness of the transition;
- h_{f} is the convective heat transfer coefficient;
- A is the heat transfer surface area.

3.3.2 Energy balance on steam-side tubes

During the charging phase, saturated steam flows inside the dedicated tube bundle and undergoes condensation at nearly constant saturation temperature. Under these conditions, axial temperature gradients along the tube length are negligible, and steam-side thermal behavior can be modeled assuming a uniform condensation process [43].

The thermal power released by the condensing steam is therefore determined by the latent heat of vaporization and is expressed as:

$$\dot{Q}_{\text{steam}}=\dot{m}_{\text{steam}}h_{\text{f}} \tag{3.3}$$

where:

- $\dot{m}_{\text{steam}}$ is the steam mass flow rate;
- h_{f} is the latent heat of vaporization of the steam at the operating pressure.

This thermal power represents the maximum amount of energy that can be transferred from the steam to the PCM during the charging phase. The actual heat transfer to the PCM is governed by the temperature difference between the steam and the PCM and by the overall heat transfer characteristics of the exchanger.
Accordingly, the heat flux transferred to the PCM is coupled with the PCM energy balance through the convective heat transfer relation:

$$\dot{Q}_{\mathrm{steam}} = h_{\mathrm{f}} A (T_{steam} - T_{PCM}) \tag{3.4}$$

where h_f is the effective convective heat transfer coefficient and A is the heat exchange surface area.

3.3.3 Energy balance of water-side tubes

During the discharging phase, pressurized water flows inside the dedicated tubes and extracts thermal energy from the PCM. In this operating mode, the heat transfer fluid remains in the liquid phase, and the thermal interaction with the PCM is governed by sensible heat exchange.
The transient energy balance for the water flowing inside the tubes accounts for both the accumulation of thermal energy within the fluid control volume and the convective heat transport associated with the mass flow rate. The governing equation is expressed as [43]:

$$(mC_{\mathrm{p}})_f \frac{dT_{\mathrm{f}}}{dt} + \dot{m}_{\mathrm{f}} C_{p,f} (T_{f,out} - T_{f,inlet}) = h_{\mathrm{f}} A (T_{\mathrm{PCM}} - T_{\mathrm{f}}) \tag{3.5}$$

where:

- m is the mass of water contained in the tube bundle;
- $C_{\mathrm{p,f}}$ is the specific heat capacity of water;
- $\dot{m}_{\mathrm{f}}$ is the mass flow rate of circulating water;
- T_{f} is the average circulating water temperature, defined as:

$$T_{\mathbf{f}} = \frac{T_{f,out} + T_{\mathbf{f,inlet}}}{2}$$

- T_{PCM} is the PCM temperature;
- h_{f} is the effective convection heat transfer coefficient;
- A is the heat exchange surface area.

3.4 Heat transfer modeling

Heat transfer between the PCM and the heat transfer fluids is modeled through convective heat transfer coefficients derived from established empirical correlations. The selection of the correlations is based on the nature of the heat transfer process, the thermophysical properties of the fluids, and the operating flow regimes occurring during the charging and discharging phases.

During the charging phase, heat transfer is dominated by steam condensation inside the tube bundle, resulting in high heat transfer coefficients and nearly isothermal behavior on the steam side. Conversely, during the discharging phase, heat is transferred from the PCM to pressurized water flowing inside the tubes under single-phase forced convection conditions. These two operating modes require different modeling approaches and correlations in order to accurately represent the underlying heat transfer mechanisms.

3.4.1 Condensation of pure vapors on solid surfaces

During the charging phase, heat transfer from condensing steam to the tube wall is modeled assuming filmwise condensation of a pure vapor on horizontal tubes. Under these conditions, the classical Nusselt theory provides an analytical expression for the average convective heat transfer coefficient [44].

The convective heat transfer coefficient on the steam side is therefore evaluated as:

$$h_{\mathrm{f}} = 0.725 \left(\frac{k^3 \rho^2 g \Delta \hat{H}_{\mathrm{vap}}}{\mu D (T_{\mathrm{d}} - T_0)} \right)^{1/4} \tag{3.6}$$

where:

- k is the thermal conductivity of condensate;
- ρ is the density of the condensate;
- g is the gravitational acceleration;
- $\Delta \hat{H}_{vap}$ is the evaporation latent heat;
- μ is the dynamic viscosity of the condensate;
- D is the diameter of the steam tubes;
- T_d is the saturation temperature of steam;
- T_0 is the surface wall temperature.

3.4.2 Forced convection in tubes

During the discharging phase, thermal energy is transferred from the PCM to pressurized water flowing inside the tube bundle. In this operating mode, the heat transfer process is governed by single-phase forced convection under turbulent flow conditions.

The convective heat transfer coefficient on the water side is evaluated using the general relation [44]:

$$h_{\mathrm{f}} = \frac{Nu \cdot k}{D} \tag{3.7}$$

where:

- k is the thermal conductivity of water;
- D is the internal diameter of tubes;
- Nu is the Nusselt number estimated by the Gnielinski correlation [45, 44]:

$$Nu = \frac{\frac{f}{8}(Re - 1000)Pr}{1 + 12.7(\frac{f}{8})^{1/2}(Pr^{2/3} - 1)}$$

  valid for $0.5 \leq Pr \leq 2000$ and $3000 \leq Re \leq 5 \cdot 10^6$;
- f is the friction factor computed with:

$$f = (0.79 \cdot ln(Re) - 1.64)^{-2}\,. \tag{3.8}$$

3.5 Numerical implementation

The governing equations introduced in the previous sections are solved numerically using a transient time-marching approach implemented in MATLAB. The simulation time is discretized using a constant time step, selected to ensure numerical stability while providing sufficient temporal resolution to capture the evolution of the PCM temperature and the phase change process.

At each time step, the thermal state of the PCM is updated by solving the unsteady energy balance equation. Latent heat effects are incorporated through an effective heat capacity formulation, in which the apparent specific heat of the PCM is expressed as a continuous function of temperature. This approach enables a smooth representation of melting and solidification phenomena, avoids numerical discontinuities at the phase change temperature, and allows sensible and latent heat storage to be treated within a unified framework.

The charging and discharging phases are simulated separately, in accordance with the operational cycle defined for the reference case study. During the charging phase, the instantaneous thermal power transferred to the PCM is evaluated as the minimum between the maximum heat transfer capacity of the steam-side heat exchanger and the average thermal power required to store the target amount of energy within the available charging time. This formulation ensures that the recovered waste heat does not exceed the available thermal source and that the PCM temperature remains within the prescribed operating limits.

During the discharging phase, the thermal power extracted from the PCM is constrained by both the heat transfer capacity of the water-side heat exchanger and the imposed thermal demand. The water mass flow rate is dynamically adjusted to deliver the required thermal power while maintaining a fixed outlet temperature. The discharging process is automatically interrupted when the PCM temperature approaches the inlet water temperature, corresponding to a pinch condition that prevents further effective heat transfer.

Throughout the simulation, the cumulative thermal energy stored and released by the PCM is obtained by time integration of the instantaneous heat transfer rate. The numerical implementation allows tracking the temporal evolution of PCM temperature, liquid fraction, exchanged thermal power, and relevant performance indicators, providing a consistent basis for analyzing system behavior and supporting the subsequent design and sizing of the TES unit.

3.6 Heat exchanger design and system sizing

The thermal energy storage unit is designed as a shell-and-tube heat exchanger, a configuration widely adopted in latent thermal energy storage applications due to its robustness, modularity, and compatibility with different heat transfer fluids [29, 46].

The heat exchanger geometry is determined through a numerical sizing and optimization procedure embedded within the model. The objective of this procedure is to satisfy the thermal power requirements during both charging and discharging phases within the prescribed operating times, while minimizing the overall occupied volume of the storage system.

A discrete set of commercially available tube outer diameters and lengths is considered. For each candidate geometry, the minimum number of tubes required to meet the thermal duty is evaluated independently for the charging and discharging phases. During charging, the tube bundle is sized based on condensation heat transfer correlations for saturated steam, ensuring that the required heat transfer rate can be delivered under nominal operating conditions. During discharging, the tube bundle is sized using forced convection correlations for turbulent water flow.
Separate tube bundles are adopted for charging and discharging to allow independent optimization of the two operating modes, which are characterized by different temperature levels, heat transfer mechanisms, and hydraulic constraints [29, 46].

For each candidate geometry, the resulting heat transfer surface area, required number of tubes, and associated hydraulic conditions are evaluated. Only configurations satisfying all thermal and geometric constraints are retained. Among these feasible solutions, the configuration minimizing the total occupied volume of the TES unit is selected as the reference design and adopted for the subsequent transient simulations.

3.6.1 Evaluation of total occupied volume

In addition to thermal performance, the feasibility of integrating the TES system onboard cruise vessels is strongly influenced by geometric constraints and available installation space. For this reason, the total occupied volume of the PCM-based storage unit is explicitly evaluated and used as a key criterion in the design and optimization process.

In practical thermal energy storage applications, the gross system volume is significantly larger than the net volume of the storage material due to the presence of heat exchanger structures, containment shells, insulation layers, and auxiliary components. Neglecting these contributions may lead to an unrealistic assessment of system compactness and onboard feasibility [5, 15].

The total occupied volume is therefore computed by accounting for all elements contributing to the physical footprint of the TES unit, as described in the following.

3.6.1.1 PCM net volume

The net volume occupied by the phase change material is calculated from its mass and density as:

$$V_{PCM} = \frac{m_{PCM}}{\rho_{PCM}} \tag{3.9}$$

This volume represents the active thermal storage material only and does not include any structural or auxiliary components.

3.6.1.2 Tube bundles volume

The volume displaced by the tube bundles embedded within the PCM is estimated assuming cylindrical tubes with outer diameter D and length L:

$$V_{tubes} = N \cdot L \cdot \frac{\pi D^2}{4} \tag{3.10}$$

where N is the total number of tubes. When separate tube bundles are adopted for charging and discharging, the total number of tubes is given by $N = N_{ch} + N_{dis}$.

3.6.1.3 Internal shell volume

To ensure sufficient space for both the PCM and the tube bundles, a maximum PCM filling fraction Φ_{PCM} is imposed. This parameter represents the fraction of the internal shell volume effectively occupied by the PCM, while the remaining volume is reserved for tubes, manifolds, and internal voids. Typical values reported in the literature range between 0.6 and 0.7 [16, 46]. The required internal shell volume is therefore computed as:

$$V_{shell} = \frac{V_{PCM} + V_{tubes}}{\Phi_{PCM}} \tag{3.11}$$

3.6.1.4 Total occupied volume including insulation

Assuming a cylindrical shell of length L, the internal shell radius is derived from the shell volume. The total occupied volume of the TES unit, including a uniform insulation layer of thickness δ_{ins}, is expressed as:

$$V_{tot} = \pi \cdot L \cdot (R_{shell} + \delta_{ins})^2 \tag{3.12}$$

This formulation provides a conservative estimate of the space required for the TES unit, accounting for thermal insulation requirements and installation tolerances [15, 21].

Additional geometric feasibility constraints are imposed within the numerical model to ensure realistic configurations. These include limits on maximum fluid velocity in tubes, validity ranges of the heat transfer correlations, and consistency between the available non-PCM volume and the required tube bundle volume. Only configurations satisfying all thermal and geometric constraints are retained during the optimizations procedure.

The contribution of each volume component and the resulting total occupied volume are analyzed and discussed in **Chapter 4** for different operating scenarios, providing a quantitative basis for evaluating the onboard integration potential of the proposed TES system.

3.7 Performance indicators

The performance of the PCM-based TES system is evaluated using a set of dimensionless performance indicators. These indicators are employed to quantify the dynamic response of the TES unit during charging and discharging phases and to enable a consistent comparison between different operating scenarios. The selected metrics describe both the energetic state of the storage system and the effectiveness of heat transfer between the PCM and the heat transfer fluids.

3.7.1 State of Charge

The State of Charge (SoC) represents the fraction of thermal energy stored in the PCM at a given time during the charging process, relative to the maximum theoretical energy storage capacity of the system. It provides a normalized measure of the charging progress, varying from 0, corresponding to a fully discharged state, to 1, corresponding to a fully charged state.

The state of charge is defined as [43]:

$$SoC = \frac{\int_0^t \dot{Q}(t)dt}{E_{\text{stored}}} \tag{3.13}$$

where:

- $\dot{Q}(t)$ is the thermal power absorbed by the PCM during charging;

- E_{stored} is the maximum thermal energy that can be stored in the system.

3.7.2 State of Discharge

The State of Discharge (SoD) quantifies the fraction of stored thermal energy that has been released by the PCM during the discharging phase. Similarly to the SoC, it is a dimensionless quantity ranging from 0, corresponding to the fully charged state, to 1,corresponding to the fully discharged state.

The state of discharge is defined as [43]:

$$SoD = \frac{\int_0^t \dot{Q}(t)dt}{E_{\text{stored}}} \tag{3.14}$$

where:

- $\dot{Q}(t)$ is the thermal power released by the PCM and transferred to the heat transfer fluid;

- E_{stored} is the maximum energy initially stored in the system.

The SoD provides a direct measure of the discharge progression and allows identifying the point at which the TES unit is no longer able to deliver useful thermal energy.

3.7.3 Effectiveness

The effectiveness describes the efficiency of heat transfer between the PCM and the heat transfer fluids during operation. It expresses the ratio between the actual thermal power exchanged and the maximum theoretical thermal power that could be transferred under ideal conditions, assuming an infinte heat transfer area.

The effectiveness is defined as [43]:

$$\eta = \frac{\dot{Q}}{\dot{Q}_{max}} = \frac{T_{f,inlet} - T_{f,outlet}}{T_{f,inlet} - T_{PCM,initial}} \tag{3.15}$$

where:

- $\dot{Q}$ is the actual heat transfer rate;
- $\dot{Q}_{max}$ is the maximum achievable heat transfer rate;
- $T_{f,inlet}$ and $T_{f,outlet}$ are the inlet and outlet temperatures of the heat transfer fluid;
- $T_{PCM,initial}$ is the initial temperature of the PCM.

This indicator provides insight into the thermal performance of the heat exchanger and allows assessing how effectively the available temperature difference is exploited during the charging and discharging processes.

Chapter 4

Results

This chapter presents and discusses the quantitative results obtained from the application of the methodology described in **Chapter 2**. The analysis combines steady-state energy balances and transient numerical simulations of the PCM-based thermal energy storage system integrated within the cruise ship waste heat recovery framework.

The results are structured in progressive steps. First, the seasonal steam balance and the corresponding thermal energy balance are presented, highlighting the mismatch between waste heat availability and onboard thermal demand under different operating conditions. These results provide the basis for defining the storage sizing requirements. Subsequently, the PCM mass and volume required for each operational scenario are discussed, followed by an analysis of the enthalpy distribution during charging and discharging processes. Particular attention is given to the relative contributions of sensible and latent heat and to the dynamic thermal response of the storage system.

Transient simulation over extended operating periods are then presented to evaluate the stability, repeatability, and robustness of the TES system under realistic navigation and port cycles. The evolution of the PCM temperature, state of charge, and heat exchanger performance is analyzed in detail in order to assess the operational feasibility of the proposed integration.

Finally, a comparative assessment between the PCM-based TES and a conventional sensible water storage solution is performed in terms of required mass, storage volume, and indicative material cost. This comparison provides a system-level perspective on the advantages and limitations of latent heat storage for cruise ship applications, taking into account the volumetric and integration constraints typical of marine environments.

4.1 Steam balance results

The first step in the results analysis concerns the quantitative evaluation of the seasonal steam balance derived from the methodology described in **Chapter 2**. The objective of this assessment is to quantify the mismatch between steam generation from exhaust gas boilers and onboard thermal demand under representative summer and winter operating conditions.

The calculated steam demand, the average steam dumping during navigation, and the auxiliary steam top-up required during port stays are summarized in **Table 4.1**.

Table 4.1: *Seasonal variation in steam consumption and generation balance*

	Steam demand (kW)	**Steam dumping at sea (kW)**	**Steam top-up at berth (kW)**
Summer	550	650	150
Winter	850	350	450

Under summer operating conditions, the onboard thermal demand remains moderate, while navigation periods are sufficiently long and characterized by multi-engine operation. As a result, the thermal power recovered by the EGBs significantly exceeds the instantaneous steam demand during navigation, leading to substantial steam dumping. This excess thermal power represents the primary source of recoverable energy available for charging the TES system.

In contrast, winter operation is characterized by a markedly higher thermal demand, mainly driven by increased space heating and hot water requirements. At the same time, navigation periods are shorter and port stays are longer, reducing the cumulative availability of waste heat. Consequently, the amount of steam dumped during navigation decreases significantly, while the required auxiliary steam top-up during port stays increases.

These results clearly highlight the structural mismatch between heat availability and demand that motivates the integration of thermal energy storage. While summer conditions offer a favorable environment for charging the TES system due to abundant excess heat, winter scenarios represent more challenging operating conditions, in which the storage unit must operate under tighter energy constraints. This seasonal contrast provides the basis for the subsequent thermal energy and storage sizing analyses.

4.2 Thermal energy results

Building upon the seasonal steam balance, the corresponding thermal energy balance is evaluated by integrating the recovered and required thermal powers over the representative sailing and port durations for each operational scenario. This step allows the transition from an instantaneous power-based analysis to a cumulative energy-based assessment, which is directly relevant for storage sizing.

The recoverable thermal energy during navigation, $E_{\text{recoverable}}$, and the thermal energy required during port stays, E_{demand}, are summarized in **Table 4.2** for both cruise durations and seasonal conditions.

Table 4.2: *Thermal energy balance*

	Long cruise (15 days)		**Short cruise (8 days)**	
	$E_{recoverable}\,(MJ)$	$E_{demand}\,(MJ)$	$E_{recoverable}\,(MJ)$	$E_{demand}\,(MJ)$
Summer	46 800	6480	25 200	19 440
Winter	25 740	10 800	13 860	32 400

Under summer conditions, the recoverable thermal energy during navigation exceeds the thermal energy required during port stays for both cruise durations. This indicates that, from a purely energetic standpoint, the available waste heat is sufficient to fully cover port-side thermal demand through storage, provided that adequate storage capacity and heat exchange performance are ensured.

Winter operation presents a more constrained energy balance. For long cruise, the recoverable energy remains higher than the port-side demand, although the margin is significantly reduced compared to summer conditions. In the case of short winter cruises, however, the recoverable energy during navigation becomes lower than the energy required during port stays. This implies that, even under ideal storage conditions, the TES system cannot be fully charged to cover the entire port-side demand, and auxiliary boiler support remains necessary.

These results underline the importance of defining the usable storage energy as the minimum between recoverable and required energy, as introduced in the sizing methodology. They also demonstrate that storage feasibility is strongly scenario-dependent: while summer scenarios are characterized by energy surplus, winter short cruises represent limiting conditions that constrain achievable storage performance.
Overall, the thermal energy balance confirms that significant quantities of recoverable heat are available across most operational scenarios, thereby justifying the subsequent sizing of the PCM-based storage system and the analysis of its dynamic behavior.

4.3 PCM mass and volume results

Based on the usable thermal energy defined for each operational scenario, the required mass and volume of the selected PCM (*A95*) are determined according to the sizing formulation introduced in **Chapter 2**. The resulting storage requirements are summarized in **Table 4.3**.

Table 4.3: *A95 mass and volume*

	Long cruise (15 days)		**Short cruise (8 days)**	
	Mass (kg)	Volume (m^3)	Mass (kg)	Volume (m^3)
Summer	11 868	13	19 780	22
Winter	35 604	40	25 385	28

The results clearly reflect the strong dependence of storage sizing conditions and cruise duration. For long cruises, winter operation requires approximately three times the PCM mass compared to summer conditions, due to the combined effect of increased thermal demand and reduced energy surplus during navigation. The corresponding storage volume increases proportionally, reaching values that represent a significant integration challenge in the shipboard environment.

In summer conditions, the required PCM mass remains comparatively moderate, as the high recoverable energy during navigation allows the TES system to be fully charged while port-side demand remains limited. Under these conditions, the storage system can be dimensioned primarily based on port demand, without being constrained by insufficient charging energy.

The short cruise scenarios exhibit a different behavior. In the summer case, the required PCM mass is higher than in the long summer cruise despite similar daily operating patterns. This effect is associated with the shorter overall cruise duration, which limits the cumulative charging period and reduces the margin between recoverable and required energy.
The short winter scenario represents the most restrictive operating condition. As previously discussed in the energy balance analysis, the recoverable energy during navigation is lower than the port-side demand. Consequently, the storage system is sized based on the maximum recoverable energy rather than on the full port-side demand. This modeling choice avoids unrealistic oversizing of the TES unit and reflects practical operational constraints, ackowledging that auxiliary boiler support remains necessary under these conditions.

From an integration perspective, the obtained volume range between 13 and 40 m^3 provides a first indication of the feasibility of PCM-based storage onboard medium-sized cruise vessels. While the higher-end values associated with winter operation may impose layout constraints, the results demonstrate that latent heat storage enables a relatively compact solution compared to conventional sensible heat storage, as discussed in the following section.

4.4 Enthalpy distribution analysis

In order to further characterized the thermodynamic behavior of the PCM-based storage system, the distribution of sensible and latent heat contributions during charging and discharging is evaluated for the considered operational scenarios. This analysis provides insight into the relative importance of phase change phenomena in the overall storage process and clarifies the energetic mechanisms underlying the sizing results presented in the previous section.

The enthalpy contributions during the charging phase are reported in **Table 4.4**, while the corresponding energy release during discharging is summarized in **Table 4.5**.

Table 4.4: *Enthalpy storage during charging phase*

	Long cruise (15 days)		**Short cruise (8 days)**	
	Summer	*Winter*	*Summer*	*Winter*
Sensible heat (solid phase) [MJ]	1697	5091	2829	3630
Latent heat (phase change) [MJ]	3086	9257	5143	6600
Sensible heat (liquid phase) [MJ]	1697	5091	2829	3630
Total stored enthalpy [MJ]	6480	19 440	10 800	13 860

Table 4.5: *Enthalpy releasing during discharging phase*

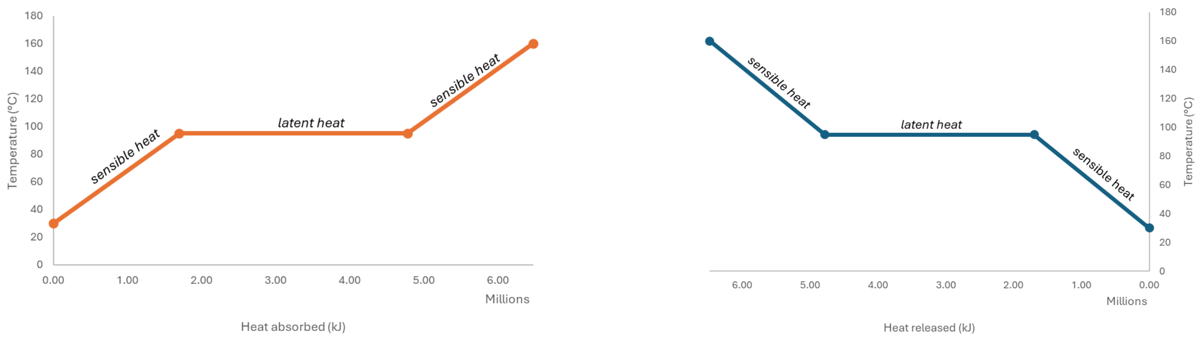
	Long cruise (15 days)		**Short cruise (8 days)**	
	Summer	*Winter*	*Summer*	*Winter*
Sensible cool (liquid phase) [MJ]	1697	5091	2829	3630
Latent cool (phase change) [MJ]	3086	9257	5143	6600
Sensible cool (solid phase) [MJ]	1697	5091	2829	3630
Total stored enthalpy [MJ]	6480	19 440	10 800	13 860

Across all operational scenarios, the latent heat contribution represents the dominant fraction of the total stored energy. In the long summer cruise, for instance, the latent term accounts for approximately half of the total stored enthalpy, while the remaining portion is symmetrically distributed between sensible heating of the solid and liquid phases. A similar proportional distribution is observed in the winter and short cruise scenarios, with absolute values scaling according to the total required storage energy.

This behavior confirms that the phase change process constitutes the core energy storage mechanism, while sensible heat contributions provide additional flexibility by extending the effective operating temperature range. Although sensible terms are not negligible, the high latent heat of the selected PCM enables substantial energy storage at nearly constant temperature, which is particularly advantageous for integrations with steam-based heat sources.

The reversible nature of the charging and discharging processes is illustrated in **Figures 4.1a and 4.1b**, which depict the enthalpy evolution for the long-cruise summer scenario. The characteristic three-stage behavior is clearly identifiable: an initial linear increase corresponding to sensible heating of the solid phase, a quasi-isothermal plateau during phase change, and a final linear increase associated with sensible heating of the liquid phase. During discharging, the enthalpy curve follows the reverse trajectory, indicating consistent thermodynamic reversibility under the assumed operating conditions.

Comparable trends are observed across all seasonal and duration scenarios considered in this study. The proportional scaling of sensible and latent contributions with total stored energy indicates that the thermodynamic behavior of the PCM remains consistent under varying boundary conditions. This repeatability supports the robustness of the storage concept and provides a thermodynamic foundation for the transient performance analysis presented in the following section.



(a) Charging phase *(b) Discharging phase*

Figure 4.1: *Summer long cruise scenario: enthalpy evolution during charging and discharging phases*

4.5 Summer cruise scenario

The summer cruise scenario is analyzed in detail as the reference operating condition for evaluating the transient performance of the PCM-based thermal energy storage system. As shown in the seasonal energy balance, summer operation is characterized by extended navigation periods and significant recoverable waste heat, making it a favorable condition for TES charging.

The operating parameters adopted for the long summer cruise are summarized in **Table 4.6**.

Table 4.6: *Summer cruise scenario operating conditions*

Cruise duration	15 days
Charging time	20 h
Discharging time	12 h
Target thermal power	150 kW
Target stored/released energy	6480 MJ

4.5.1 Optimized heat exchanger configuration

Based on the numerical model described in **Chapter 3**, the geometry of the shell-and-tube heat exchanger is optimized by minimizing the total occupied volume while satisfying the required thermal duties during both charging and discharging phases.

The optimized configuration is reported in **Table 4.7** . The selected solution consists of a single shell equipped with two independent tube bundles, dedicated respectively to charging and discharging. A tube outer diameter of 9.525 mm and a tube length of 1.83 m are adopted, resulting in a total of 16 tubes distributed between the two operating modes.

Table 4.7: *Optimized heat exchanger geometry and thermal-hydraulic parameters (summer scenario)*

Geometrical parameter		*Thermal-hydraulic parameters (water side)*		*Heat transfer coefficients*		*Mass flow rates*	
Tube outer diameter	9.525 mm	Water velocity	2.92 m/s	$h_{f,steam}$	10 278.3 $W/(m^2K)$	Steam mass flow rate	0.044 kg/s
Tube length	1.83 m	Reynolds number	54 430	$h_{f,water}$	17 465.7 $W/(m^2K)$	Water mass flow rate	1.025 kg/s
Number of tubes (charging)	11	Prandlt number	3.14				
Number of tubes (discharging)	5	Nusselt number	248.3				
Total number of tubes	16	Darcy friction factor	0.0206				

The obtained configuration ensures turbulent flow conditions on the water side, acceptable Reynolds number, and controlled friction losses, while maintaining sufficient overall heat transfer coefficients to meet the target thermal power.

4.5.2 Transient thermal behavior of the PCM

The temporal evolution of PCM temperature and liquid fraction during charging and discharging is shown in **Figure 4.2**.

During navigation, the PCM temperature increases progressively from the initial condition. A quasi-isothermal plateau is observed within the melting temperature range, corresponding to latent heat absorption and progressive increase in liquid fraction. After complete melting, further sensible heating of the liquid phase occurs.

During port stays, the temperature profile follows the reverse trend. The liquid fraction decreases steadily during the phase change interval, confirming sustained latent heat release. The symmetric evolution of melting and solidification demonstrates consistent thermodynamic behavior under cyclic operation.

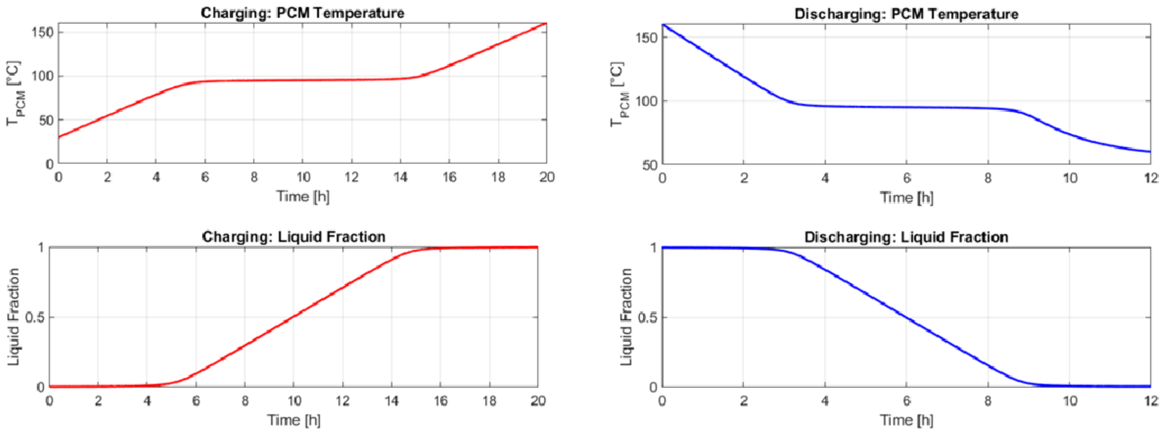


Figure 4.2: PCM temperature and liquid fraction during charging and discharging (summer scenario)

4.5.3 Effective heat capacity representation

In order to ensure numerical stability and accurately capture latent heat effects within the transient simulations, the PCM behavior is implemented through an effective heat capacity formulation. This approach distributes the latent heat over a finite temperature interval around the melting point, allowing a continuous representation of phase change phenomena.

The resulting effective heat capacity profile as a function of temperature is shown in **Figure 4.3**. A pronounced peak is observed within the phase change temperature range, reflecting the significant latent heat absorbed and released over a narrow thermal interval. Outside this region, the effective heat capacity approaches the sensible heat capacity values of the solid and liquid phases.

This representation enables a smooth numerical treatment of melting and solidification without introducing discontinuities in the governing equations, while preserving the correct energetic contribution of the latent heat term. The effective heat capacity curve confirms the dominant role of phase change in the storage process and supports the stability of the transient simulations.

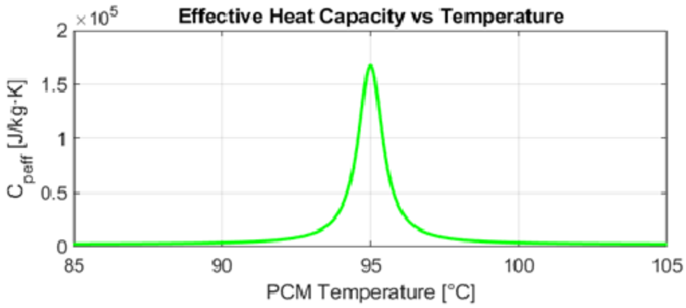


Figure 4.3: *Effective heat capacity as a function of PCM temperature*

4.5.4 Energy charging and discharging performance

The cumulative energy stored during charging and released during discharging is presented in **Figure 4.4** and summarized in **Table 4.8**.

During navigation, the stored energy increases approximately linearly, reflecting the nearly constant thermal power recovered from the exhaust gas boilers.
During discharging, the released energy follows a smooth decreasing trend, indicating stable heat delivery to the onboard network.

A difference between stored and released energy is observed and quantified as thermal losses. These losses originate from heat exchanger inefficiencies, finite temperature gradients within the PCM domain, and system-level heat dissipation accounted for the numerical model. Despite these losses, the overall storage efficiency remains high under summer operating conditions.

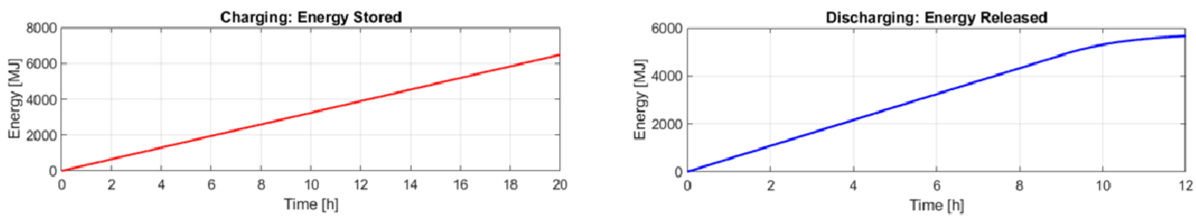


Figure 4.4: *Energy stored during charging and energy released during discharging (summer scenario)*

Table 4.8: *TES energy balance during summer cruise scenario*

Energy stored (MJ)	6480
Energy released (MJ)	5670
Energy losses (MJ)	810

4.5.5 Discharging control and performance indicators

The water mass flow rate and corresponding delivered thermal power during discharging are shown in **Figure 4.5**.For most of the discharge phase, the system maintains the target thermal power through approximately constant water mass flow.
As the PCM approaches complete solidification, the available latent heat decreases, resulting in a gradual reduction in both mass flow rate and delivered thermal power. This behavior highlights the intrinsic coupling between TES state of charge and achievable thermal output.

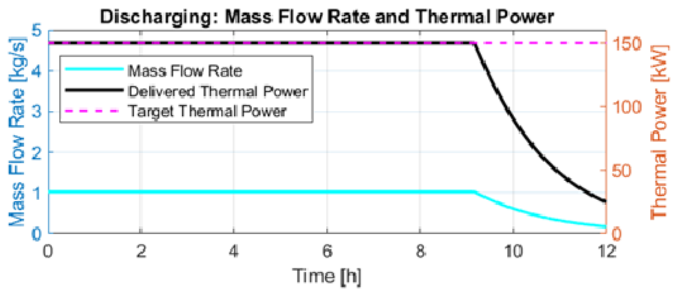


Figure 4.5: *Water mass flow rate and delivered thermal power during discharging (summer scenario)*

Performance indicators including State of Charge (SoC), State of Discharge (SoD), and heat exchanger effectiveness are reported in **Figure 4.6**.
The SoC increases steadily during charging and reaches full capacity at the end of the navigation, while the SoD exhibits a corresponding evolution during discharging.
The effectiveness remains stable during the phase change interval and varies mainly during sensible heat transfer regimes.

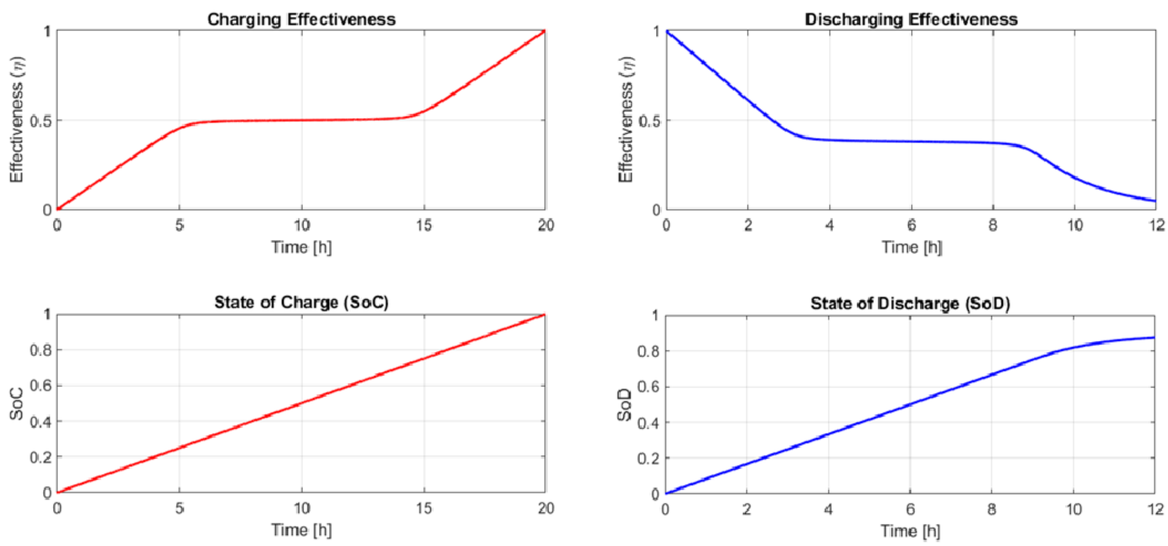


Figure 4.6: *Performance indicators (summer scenario)*

4.5.6 Volumetric implications

The volumetric breakdown of the TES system for the summer cruise scenario is reported in **Table 4.9**. The net PCM volume required to store the target thermal energy is approximately $13\,m^3$. When accounting for the heat exchanger shell, embedded tube bundles, and insulation, the total occupied volume reaches approximately $22.5\,m^3$.

This result demonstrates that structural and auxiliary components significantly contribute to the overall footprint of the storage unit. The obtained volume range provides a realistic estimate of onboard integration feasibility and serves as a reference for the comparison with the winter scenario and with conventional sensible heat storage.

Table 4.9: *TES volume breakdown during summer cruise scenario*

Net PCM volume	$13\,m^3$
Tube bundle volume	$0.002\,m^3$
Heat exchanger shell volume	$20\,m^3$
Insulation thickness	$0.10\,m$
Total occupied volume	$22.5\,m^3$

4.6 Winter cruise scenario

The winter cruise scenario represents the most demanding operating condition for the PCM-based thermal energy storage system. Compared to the summer case, it is characterized by significantly higher thermal demand during both navigation and port stays, leading to increased charging and discharging thermal powers and to a substantially larger amount of energy to be stored and released.

This scenario therefore constitutes a critical benchmark for assessing the robustness of the TES design under high-load conditions, where both thermal performance and volumetric constraints become more pronounced.
The main operating parameters defining the winter cruise scenario are summarized in **Table 4.10**.

Table 4.10: *Winter cruise scenario operating conditions*

Cruise duration	15 days
Charging time	20 h
Discharging time	12 h
Target thermal power	450 kW
Target stored/released energy	19 440 MJ

4.6.1 Optimized heat exchanger configuration

Following the same optimization procedure adopted for the summer scenario, the geometry of the shell-and-tube heat exchanger is re-optimized to satisfy the increased thermal duties of the winter cruise scenario while minimizing the total occupied volume. The optimized configuration is reported in **Table 4.11**. The tube outer diameter and length remain unchanged with respect to the summer case, while the number of tubes increases significantly in order to accommodate the higher charging and discharging thermal powers. In particular, both charging and discharging tube bundles are expanded to provide the additional heat transfer surface required under winter conditions.

Table 4.11: *Optimized heat exchanger geometry and thermal-hydraulic parameters (winter scenario)*

Geometrical parameter		*Thermal-hydraulic parameters (water side)*		*Heat transfer coefficients*		*Mass flow rates*	
Tube outer diameter	9.525 mm	Water velocity	2.92 m/s	$h_{f,steam}$	$10\,278.3\,W/(m^2K)$	Steam mass flow rate	0.133 kg/s
Tube length	1.83 m	Reynolds number	54 430	$h_{f,water}$	$17\,465.7\,W/(m^2K)$	Water mass flow rate	3.076 kg/s
Number of tubes (charging)	32	Prandlt number	3.14				
Number of tubes (discharging)	15	Nusselt number	248.3				
Total number of tubes	47	Darcy friction factor	0.0206				

Despite the increase in heat transfer area and mass flow rates, the thermal-hydraulic conditions on the water side remain within the turbulent flow regime. Reynolds and Nusselt numbers remain consistent with those obtained in the summer scenario, confirming that the system continue to operate within the validity range of the adopted heat transfer correlations and without approaching critical flow conditions.

4.6.2 Transient thermal behavior of the PCM

The thermal response of the PCM during charging and discharging under winter operating conditions is shown in **Figure 4.7**, which reports the temporal evolution of PCM temperature and liquid fraction.

During the charging phase, the PCM temperature increases sensibly until reaching the phase change temperature range, where a pronounced temperature plateau is observed. As in the summer scenario, this plateau corresponds to the latent heat storage and is associated with a progressive increase in the liquid fraction. Due to the higher charging power and larger target energy, the PCM undergoes a complete phase transition followed by additional sensible heating in the liquid phase.
During discharging, a symmetric behavior is observed. The PCM temperature remains approximately constant over a large fraction of the discharge period while the liquid fraction decreases, indicating that a substantial share of the thermal demand is met through latent heat release. This confirms the central role of latent heat storage also under more demanding winter conditions.

The extended duration of the phase change plateau reflects the larger enthalpy variation associated with the increased storage requirement, while the overall temperature evolution preserves the same thermodynamic structure observed in the summer case.

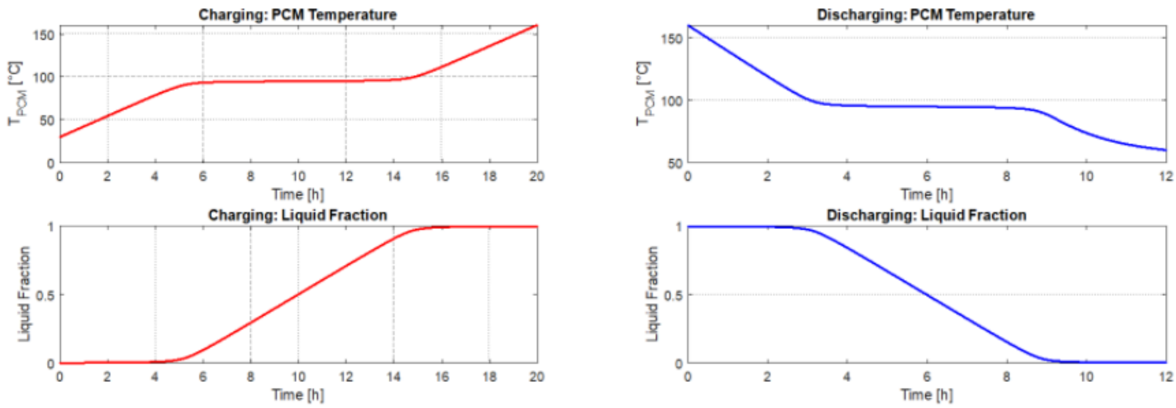


Figure 4.7: PCM temperature and liquid fraction during charging and discharging (winter scenario)

4.6.3 Effective heat capacity representation

As discussed for the summer scenario, the effective heat capacity formulation provides a smooth and numerically stable representation of the phase change process. Since the intrinsic thermophysical properties of the PCM are independent of the operating scenario, the effective heat capacity profile remains unchanged under winter conditions.

The higher thermal loads primarily affect the duration and extent of the phase transition, rather than the shape of the heat capacity curve. This confirms that the material properties govern the phase change behavior, while the operating conditions determine the dynamic evolution of the storage process.

4.6.4 Energy charging and discharging performance

The cumulative thermal energy stored during charging and released during discharging is shown in **Figure** . Compared to the summer scenario, the higher charging power results in a steeper increase of stored energy, leading to a significantly larger total amount of energy accumulated within the TES.

During the discharging phase, the stored energy is progressively released to meet the higher winter thermal demand. The smooth and continuous evolution of both stored and released energy indicates stable numerical convergence and physically consistent system behavior, even under elevated thermal loads.

The larger discrepancy between stored and released energy, compared to the summer scenario, reflects the increased impact of thermal losses as system size and operating temperature gradients grow.

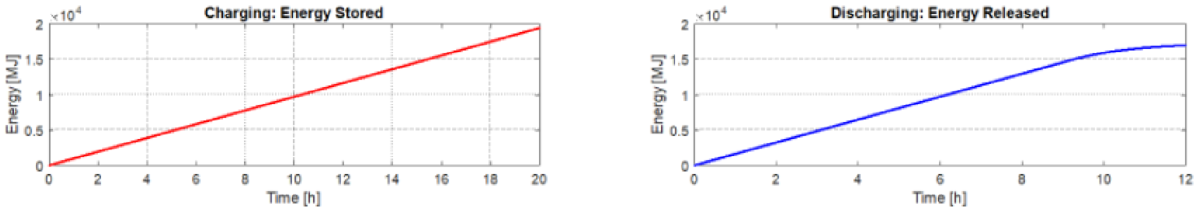


Figure 4.8: *Energy stored during charging and released during discharging (winter scenario)*

Table 4.12: *TES energy balance during winter cruise scenario*

Energy stored (MJ)	19 440
Energy released (MJ)	17 010
Energy losses (MJ)	2430

4.6.5 Discharging control and performance indicators

The evolution of water mass flow rate and delivered thermal power during the discharging phase is shown in **Figure 4.9**. For most of the discharge period, the system is able to deliver the target thermal power by maintaining an approximately constant mass flow rate.
As the PCM approaches the end of the phase change process, the reduction in available latent heat leads to a decrease in both mass flow rate and delivered thermal power. Under winter conditions, this limitations becomes more relevant due to the higher required power, emphasizing the importance of accurate state-of-charge management and control strategies in high-demand operating regimes.

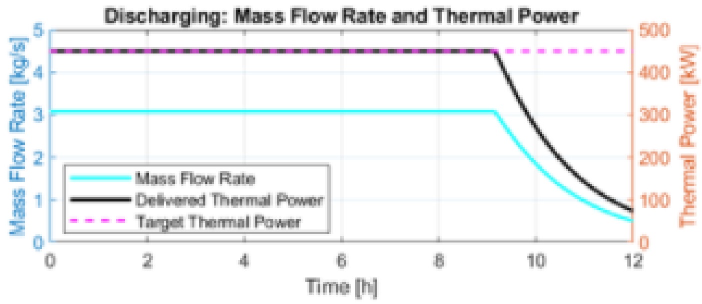


Figure 4.9: Mass flow rate and delivered thermal power during discharging (winter scenario)

Key performance indicators, including charging and discharging effectiveness, State of Charge (SoC), and State of Discharge (SoD), are reported in **Figure 4.10**. Both SoC and SoD exhibit smooth and monotonic trends, confirming stable and repeatable operation of the TES system throughout the winter operating cycle.

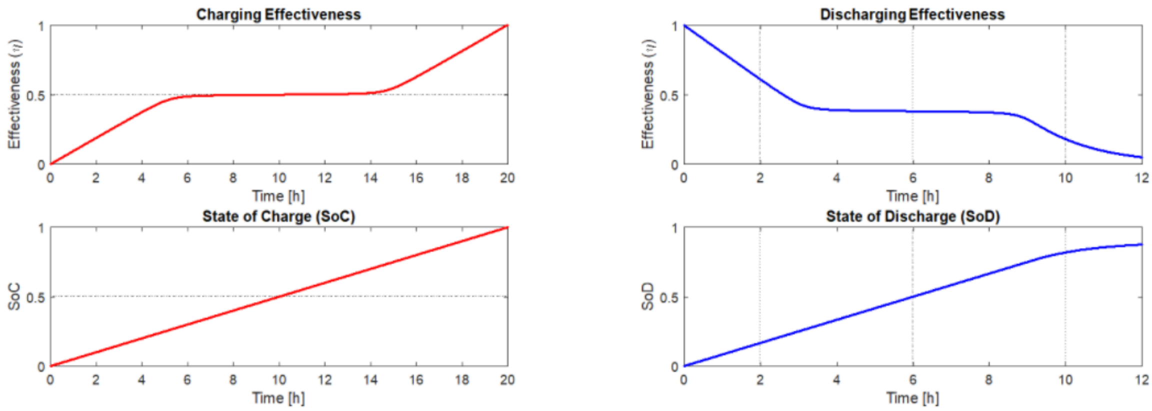


Figure 4.10: Performance indicators (winter scenario)

4.6.6 Volumetric implications

The volumetric breakdown of the TES system for the winter cruise scenario is reported in **Table 4.13**. The results highlight the strong impact of winter operating conditions on storage size and confirm that volumetric considerations become increasingly critical for shipboard integration as thermal demand increases.

The significant increase in required PCM volume and total occupied volume highlights the strong dependence of storage feasibility on seasonal operating conditions. Under winter demand levels, volumetric integration constraints become a primary design driver, potentially limiting the practical applicability of large-scale PCM storage without dedicated machinery space allocation.

This result reinforces the importance of considering both thermodynamic performance and spatial integration simultaneously when evaluating the suitability of PCM-based TES systems for cruise ship applications.

Table 4.13: *TES volume breakdown during winter cruise scenario*

Net PCM volume	$40\,m^3$
Tube bundle volume	$0.006\,m^3$
Heat exchanger shell volume	$61\,m^3$
Insulation thickness	$0.10\,m$
Total occupied volume	$65\,m^3$

4.7 Long-term performance simulations

In addition to the single-cycle analyses presented for the summer and winter cruise scenarios, long-term simulations are performed to evaluate the durability and performance stability of the PCM-based thermal energy storage system under extended operation. The primary objective of this analysis is to quantify the impact of repeated charge-discharge cycles and material aging on the thermal response and energy delivery capability of the system over its expected service life.

The simulations are conducted over a 25-year operating period, assuming 15 charge–discharge cycles per year, representative of typical cruise ship operational patterns. This corresponds to several hundred consecutive thermal cycles, enabling the investigation of cumulative performance variations and progressive degradation effects over time.

To account for long-term aging phenomena of the phase change material, two degradation mechanisms are explicitly introduced into the numerical model:

- a *0.5%* decrease in latent heat per cycle, representing the gradual reduction in energy storage capacity associated with repeated phase transitions;
- a *0.01 °C* shift in the melting temperature per cycle, accounting for possible long-term changes in the PCM phase change characteristics due to material aging.

These degradation parameters are applied progressively throughout the simulated lifetime, allowing the quantification of accumulated performance losses and the evaluation of how PCM aging influences thermal efficiency, controllability, and energy delivery capability over time.

Long-term performance is assessed by comparing two representative operating horizons, namely *Year 1* and *Year 25*, for both summer and winter cruise scenarios. The analysis focuses on the evolution of PCM temperature, liquid fraction, effective heat capacity, stored and released energy, and key performance indicators. This comparative approach provides insight into the long-term robustness and operational margin of the proposed TES configuration when subjected to prolonged cyclic operation.

4.7.1 Summer cruise scenario

4.7.1.1 Thermal behavior of the PCM under aging effects

Figure 4.11 compares the evolution of PCM temperature and liquid fraction during charging and discharging for the summer cruise scenario in *Year 1* and *Year 25*. The inclusion of aging mechanisms leads to observable, yet limited, modifications in the thermal response over long-term operation.

During the charging phase, the PCM temperature profile in *Year 25* shows a slight shift of the phase change plateau toward higher temperatures compared to *Year 1*, consistently with the cumulative increase in melting temperature imposed in the model. In parallel, the evolution of the liquid fraction is marginally altered, reflecting the gradual reduction in latent heat availability caused by aging effects.
Despite these changes, the PCM undergoes a complete phase change transition within the available charging time in both reference years. Under summer operating conditions, the adopted degradation mechanisms therefore do not prevent full exploitation of the latent storage potential throughout the system lifetime.

During the discharging phase, a similar behavior is observed. The temperature plateau remains clearly identifiable in *Year 25*, although it is slightly shifted and reduced in duration. The liquid fraction decreases more rapidly toward the end of the discharge process, highlighting the reduced latent heat contribution after long-term operation.

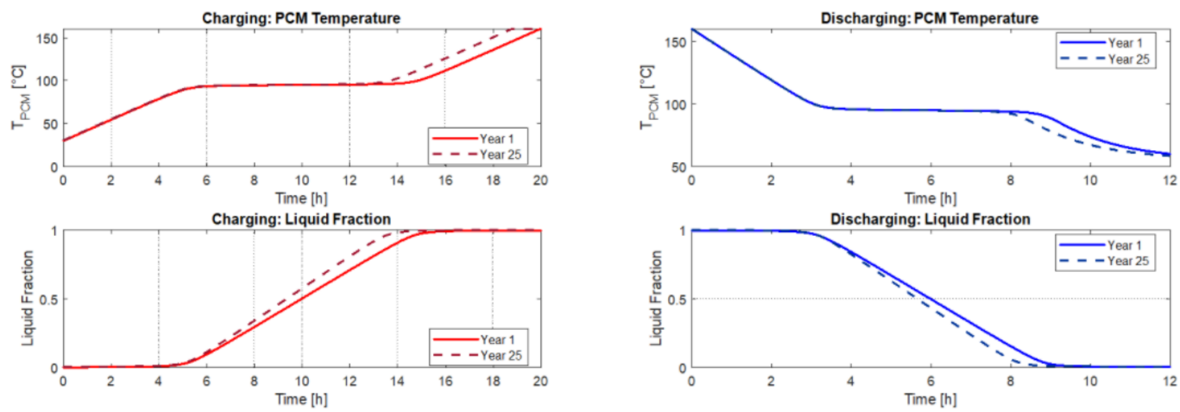


Figure 4.11: *PCM temperature and liquid fraction during charging and discharging (long-term performance of summer cruise scenario)*

4.7.1.2 Effective heat capacity evolution

Figure 4.12 shows the effective heat capacity of the PCM as a function of temperature for *Year 1* and *Year 25* under summer operating conditions. Compared to the initial condition, aging effects result in a moderate reduction of the peak magnitude and a slight displacement toward higher temperatures.

These variations are a direct consequence of the cumulative decrease in latent heat and the progressive shift of the phase change temperature introduced in the model. Nevertheless, the effective heat capacity curve retains a pronounced peak, confirming that latent heat storage remains the dominant mechanism even after prolonged operation. The preservation of the overall curve shape further indicates that the numerical formulation remains stable over long-term simulations and that aging effects do not introduce numerical artifacts or instabilities.

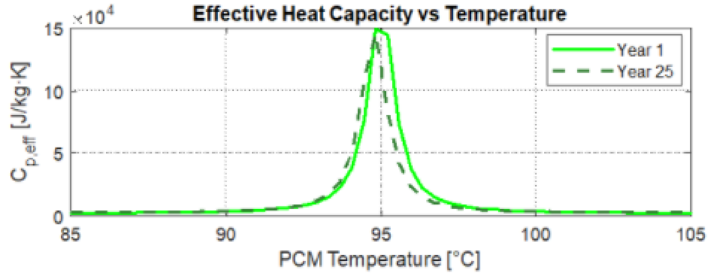


Figure 4.12: Effective heat capacity as a function of PCM temperature (long-term performance)

4.7.1.3 Energy storage and release over time

The cumulative thermal energy stored during charging and released during discharging for *Year 1* and *Year 25* is reported in **Figure 4.13**.

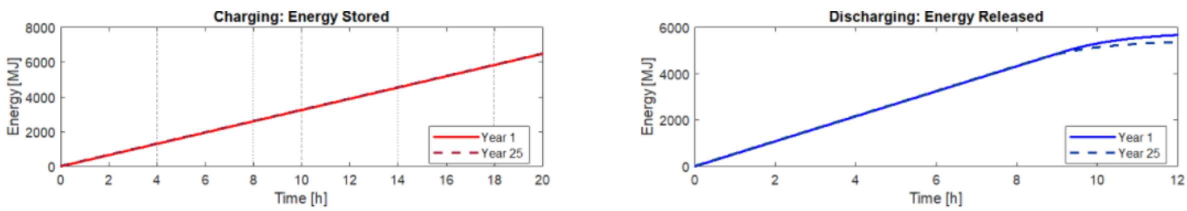


Figure 4.13: Energy stored during charging and released during discharging (long-term performance)

During charging, the total stored energy reaches the same target value in both reference years, as the storage process is constrained by the imposed thermal duty. However, the internal distribution between latent heat and sensible heat contributions progressively shifts due to aging effects, with a reduced latent heat share in *Year 25*.

During discharging, the reduction in available latent heat translates into a lower amount of energy effectively delivered, particularly toward the end of the discharge period. While the TES system continues to satisfy the thermal demand for most of the discharge duration, an energy deficit becomes more evident in the final stages, where sensible heat transfer dominates.

Overall, these results indicate that PCM aging primarily affects the recoverable energy and discharge robustness, while the qualitative structure of the charging and discharging processes remains unchanged.

Table 4.14 summarizes the corresponding energy balance for the two reference years.

Table 4.14: *TES energy balance during long-term performance of summer cruise scenario*

	Year 1	*Year 25*
Energy stored (MJ)	6480	6480
Energy released (MJ)	5670	5352
Energy losses (MJ)	810	1128

4.7.1.4 Discharging control and performance indicators

Figure 4.14 shows the evolution of the water mass flow rate and delivered thermal power during the discharging for *Year 1* and *Year 25*. In both cases, the target thermal power is delivered over a large fraction of the discharge period. However, in *Year 25*, the reduction in delivered thermal power occurs earlier than in *Year 1*.

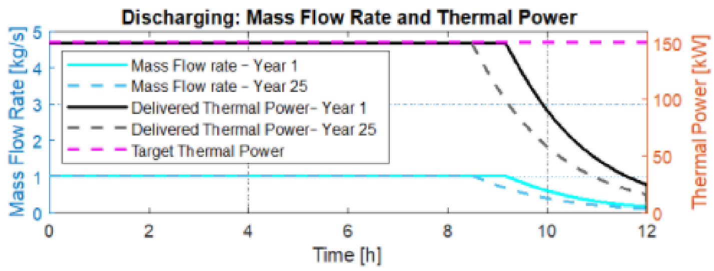


Figure 4.14: *Mass flow rate and delivered thermal power during discharging (long-term performance of summer cruise scenario)*

This behavior is a direct consequence of the reduced latent heat availability and the shifted phase change temperature, which limit the ability of the TES system to sustain the target power level toward the end of the discharge process. Although the mass flow rate based control strategy remains effective, the available operating margin is reduced after long-term aging.

The evolution of charging and discharging effectiveness, reported in (**Figure 4.15**), further confirms this trend. Effectiveness values remain comparable during the central portion of the cycle, while larger deviations appear near the end of the processes, where sensible heat transfer dominates.

The State of Charge (SoC) and State of Discharge (SoD) curves remain smooth and monotonic for both *Year 1* and *Year 25*, confirming stable system operation despite the presence of progressive material degradation.

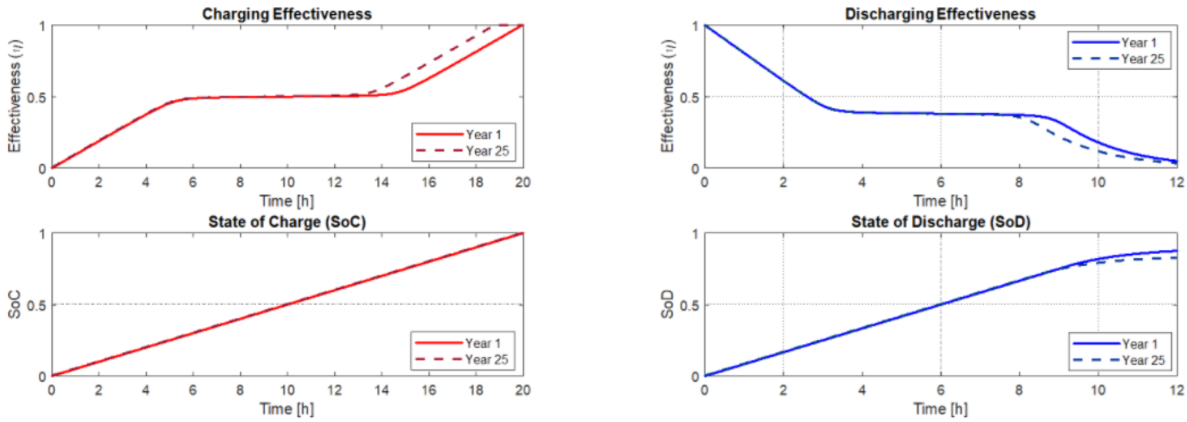


Figure 4.15: *Performance indicators (long-term performance of summer cruise scenario)*

4.7.2 Winter cruise scenario

4.7.2.1 Thermal behavior under aging conditions

Under winter operating conditions, the combined effect of higher thermal demand and PCM aging becomes more pronounced. **Figure 4.16** compares the evolution of PCM temperature and liquid fraction during charging and discharging for the winter cruise scenario in *Year 1* and *Year 25*.

During the charging phase, the PCM temperature exhibits an initial sensible heating stage followed by a well-defined phase change plateau in both reference years. In the aged condition (*Year 25*), however, the phase change interval is completed over a narrower temperature range and at an earlier time. This behavior reflects the combined effect of reduced latent heat capacity and the cumulative upward shift of the melting temperature introduced by aging.
The evolution of the liquid fraction confirms this trend. Although the PCM reaches a fully molten state in both *Year 1* and *Year 25*, the phase transition progresses more rapidly in the aged condition, indicating that a larger fraction of the charging process is governed by sensible heat storage rather than latent heat absorption.

During the discharging phase, the impact of aging becomes more evident. In *Year 25*, the PCM exits the phase change regime earlier, resulting in a faster decrease of the liquid fraction and a steeper temperature drop toward the end of the discharge period. Under winter operating conditions, characterized by higher discharge power requirements, this earlier transition shortens the effective latent heat delivery interval.

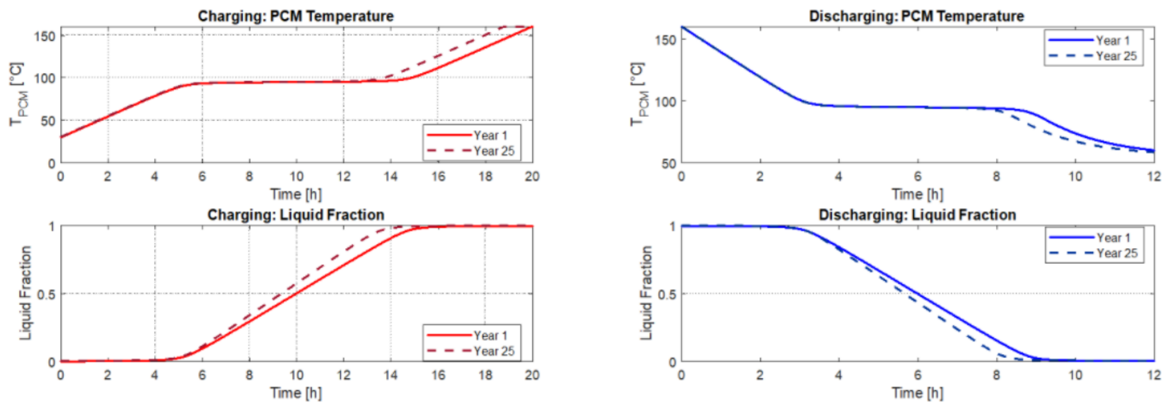


Figure 4.16: *PCM temperature and liquid fraction during charging and discharging (long-term performance of winter cruise scenario)*

4.7.2.2 Effective heat capacity evolution

As observed in the summer scenario, aging effects lead to a reduction in the peak magnitude of the effective heat capacity and a slight shift toward higher temperatures. These variations directly reflect the progressive decrease in latent heat and the cumulative shift of the melting temperature introduced in the degradation model.

Since the intrinsic thermophysical properties of the PCM govern the shape of the effective heat curve, the qualitative evolution remains consistent across operating scenarios.

However, under winter conditions, characterized by higher thermal demand, the shortening of the effective phase change interval has a more significant operational impact, reducing the margin available to sustain the target discharge power.

4.7.2.3 Energy storage and release over long-term operation

The cumulative thermal energy stored during charging and released during discharging for *Year 1* and *Year 25* is shown in **Figure 4.17**.

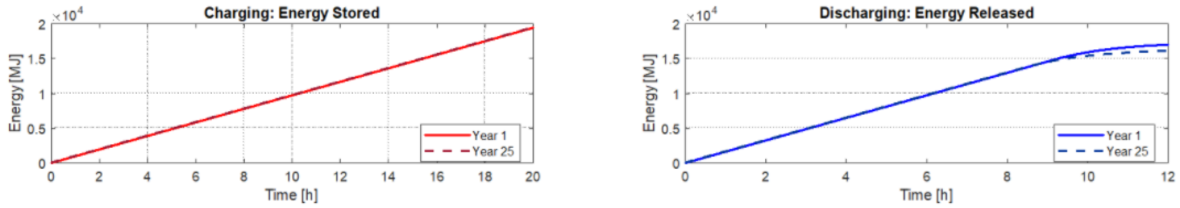


Figure 4.17: *Energy stored during charging and released during discharging (long-term performance of winter cruise scenario)*

During the charging phase, the total stored energy reaches the same target value in both reference years, as the charging process is constrained by the imposed thermal duty. However, the internal energy distribution progressively shifts toward a larger sensible contribution in *Year 25*, due to the reduction in latent heat capacity.

During discharging, the reduction in latent heat availability translates into a lower amount of energy effectively delivered, particularly toward the end of the discharge period. While the TES system continues to supply a significant portion of the required thermal energy, the deficit becomes more pronounced under winter conditions, where the reliance on latent heat storage is greater.

Overall, these results indicate that PCM aging primarily affects the quantitative energy delivery capability, while preserving the qualitative structure of the charge–discharge process.

Table 4.15 summarizes the corresponding energy balance for the two reference years.

Table 4.15: *TES energy balance during long-term performance of winter cruise scenario*

	Year 1	*Year 25*
Energy stored (MJ)	19 440	19 440
Energy released (MJ)	17 010	16 055
Energy losses (MJ)	2430	3385

4.7.2.4 Control implications and performance indicators

The evolution of water mass flow rate and delivered thermal power during discharging for *Year 1* and *Year 25* is shown in **Figure 4.18**. In both cases, the target thermal power is achieved over a substantial fraction of the discharge period through regulation of the heat transfer fluid mass flow rate. However, in the aged condition, the reduction in delivered thermal power occurs earlier compared to *Year 1*.

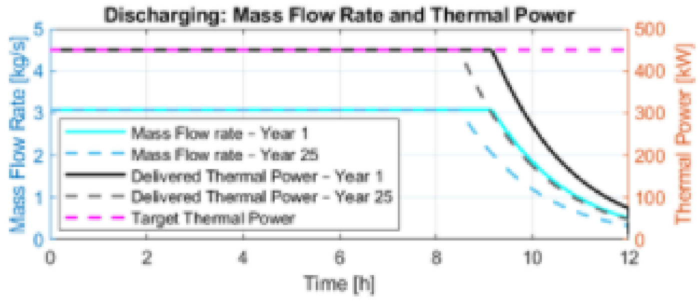


Figure 4.18: *Mass flow rate and delivered thermal power during discharging (long-term performance of winter cruise scenario)*

This behavior reflects the reduced latent heat availability and the shifted phase change temperature, which limit the ability of the TES system to sustain the target power level toward the end of the discharge process. As a result, the adopted control strategy remains effective but operates with a reduced safety margin under long-term aging, especially in high-demand winter conditions.

The evolution of charging and discharging effectiveness, together with the State of Charge (SoC) and Sate of Discharge (SoD), reported in (**Figure 4.19**, confirms stable and repeatable system operation over extended periods. While the SoC profiles remain nearly identical for *Year 1* and *Year 25*, small deviations in the SoD evolution appear toward the end of the discharge process, consistently with the observed reduction in latent heat contribution. These deviations indicate a progressive reduction in discharge robustness over time under elevated thermal loads.

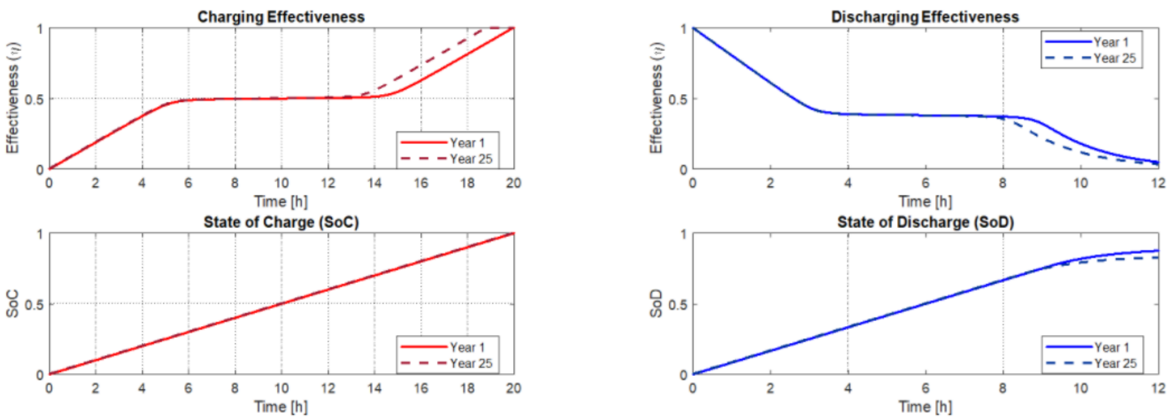


Figure 4.19: *Performance indicators (long-term performance of winter cruise scenario)*

4.8 Comparison between PCM-based and sensible water storage

The comparative assessment between PCM-based latent heat storage and conventional sensible heat storage using a pressurized water tank is performed under identical thermal requirements and operational conditions. The objective is to evaluate the practical implications of the two technologies in terms of integration feasibility, system compactness, and operational performance within cruise ship water heat recovery systems.

Both storage solutions are analyzed under the same operational scenarios, assuming equal thermal energy requirements during port stays. This consistent framework enables the intrinsic differences between sensible and latent storage technologies to be assessed independently of variations in energy demand or operating profile.

The comparison focuses on key parameters that are particularly relevant for shipboard integration. These metrics provide a concise and consistent basis for evaluating the trade-offs between conventional sensible storage and PCM-based storage in the specific context of cruise vessel energy management.

4.8.1 Overall system mass

The storage medium mass required to deliver the target thermal energy during port stays is summarized in **Table 4.16**. Across all operational scenarios, the sensible water tank requires approximately three to four times the storage mass of the PCM-based solution.

This difference is primarily attributable to the limited temperature variation available for sensible heat storage ($55 - 90\,^{\circ}\mathrm{C}$), which constrains the specific energy density of water. In contrast, the high latent heat of the selected PCM allows a substantially higher energy density per unit mass.

From a ship integration perspective, the reduction in storage mass contributes to improved weight distribution and reduced structural loading, particularly in machinery spaces where additional mass may impact vessel stability and structural reinformcement requirements.

Table 4.16: *Storage medium mass comparison between A95 PCM-based TES and sensible water tank*

	Long cruise (15 days)		**Short cruise (8 days)**	
	Summer	Winter	Summer	Winter
A95 PCM [kg]	11 868	35 604	19 780	25 385
Water tank [kg]	44 082	132 245	73 469	94 286

4.8.2 Required storage volume

Volumetric performance represents the most critical factor for onboard feasibility. The required storage volume for the PCM-based TES and the sensible water tank are compared in **Table 4.17**.

For all operational scenarios, the PCM-based system achieves a volume reduction between approximately 60% and 70%. This reduction becomes particularly significant under winter high-demand conditions, where the absolute storage requirements increase substantially.
While the sensible water tank would require very large dedicated volumes that may challenge practical installation within existing machinery spaces, the PCM-based configuration remains within a range that is more compatible with realistic onboard integration constraints.

These results confirm that latent heat storage provides a decisive advantage in applications where spatial constraints constitute the primary design limitation.

Table 4.17: *Storage volume comparison between A95 PCM-based TES and sensible water tank*

	Long cruise (15 days)		**Short cruise (8 days)**	
	Summer	Winter	Summer	Winter
A95 PCM [m^3]	13	40	22	28
Water tank [m^3]	46	137	76	98

4.8.3 Operational performance implications

Beyond geometric considerations, the two storage technologies differ fundamentally in their thermodynamic discharge behavior. Sensible storage delivers energy through continuous variation, whereas PCM-based storage provides quasi-isothermal heat release during the phase change interval.

For steam-based waste heat recovery systems, this quasi-isothermal behavior represents a significant operational advantage. The extended temperature plateau observed in the PCM simulations enables more stable thermal power delivery during discharge, improving compatibility with the onboard thermal distribution network.
In contrast, a sensible water tank would experience a continuous temperature decrease during discharge, potentially requiring larger oversizing or more complex strategies to maintain the required outlet temperature.

4.8.4 Indicative material cost

From a purely material standpoint, sensible water storage benefits from the negligible cost of water. Conversely, PCM-based storage systems involve higher upfront material costs, estimated between 7 and 10 €/kg for the selected A95 PCM.

However, when system-level aspects are considered, including tank size, insulation, structural integration, and space allocation, the economic gap between the two solutions is partially mitigated by the substantially lower volumetric requirements of the PCM-based system.
A complete techno-economic assessment would require inclusion of lifecycle costs and fuel savings associated with reduced auxiliary boiler operation, which are beyond the scope of the present analysis.

4.9 Overall performance assessment

The results obtained for both seasonal conditions and long-term operation confirm the technical feasibility of the proposed PCM-based thermal energy storage system within a cruise ship waste heat recovery framework. The system demonstrates stable cyclic behavior, consistent thermodynamic reversibility, and acceptable robustness under progressive material degradation.

Seasonal analysis shows that winter conditions lead to a more intensive utilization of the storage capacity, while summer operation provides larger operating margins. Although long-term aging slightly reduces the available latent heat and discharge duration, the overall qualitative behavior of the system remains unchanged over the considered service life.

When compared with conventional sensible heat storage based on a pressurized water tank, the PCM-based solution exhibits a decisive advantage in terms of volumetric efficiency and overall storage mass. Despite the higher material cost, the substantially reduced storage volume and quasi-isothermal discharge behavior significantly improve onboard integration feasibility.

Overall, the analysis indicates that PCM-based latent heat storage represents a more suitable solution than sensible water storage for cruise ship waste heat recovery applications, particularly where space constraints and temperature stability are critical design drivers.

Conclusions

This thesis investigated the integration of a phase change material based thermal energy storage system within the waste heat recovery strategy of cruise vessels, with the aim of mitigating the temporal mismatch between heat availability during navigation and thermal demand during port stays. A lumped-parameter numerical model was developed in MATLAB to simulate the charging and discharging dynamics of a shell-and-tube TES configuration employing the commercial organic PCM A95.

The model supported the heat exchanger sizing procedure, reproduced the main storage mechanisms, and enabled a quantitative assessment of system performance through dedicated indicators.The results demonstrate that the proposed PCM-based TES unit is capable of storing and releasing substantial amounts of thermal energy while maintaining realistic operating temperature levels compatible with onboard hot water and steam services. Under moderate thermal demand conditions, the storage target is reached during both charging and discharging, and a large fraction of the stored energy is effectively recovered. The residual energy is mainly associated with the final cooling stage, when the PCM temperature approaches the water inlet temperature and the thermal driving force becomes insufficient to sustain the required heat transfer rate.

Under higher thermal demand conditions, the TES system achieves a greater absolute energy release and a more intensive utilization of the storage capacity, while maintaining a comparable recovery ratio. However, increased discharge rates accelerate the reduction of the thermal driving temperature difference, leading to a larger fraction of residual sensible heat at the end of the discharge period. The seasonal comparison therefore indicates that winter operating conditions result in a more extensive exploitation of the storage capacity, whereas summer conditions are characterized by lower overall utilization due to reduced demand.

A long-term assessment over a 25-year operating horizon was also performed by introducing progressive degradation mechanisms affecting PCM properties. The simulations reveal a gradual reduction in discharge performance due to the cumulative decrease in latent heat capacity and the shift in melting temperature, while the charging phase remains comparatively less sensitive to aging. Even under conservative degradation assumptions, the TES system preserves a significant portion of its functionality over the considered service life, although a reduced operational margin is observed during the final stages of discharge period in aged conditions.

From an application standpoint, the study confirms that PCM-based TES can represent an effective complement to shipboard WHRS, enhancing recovered heat utilization and reducing reliance on auxiliary oil-fired boilers during port stays. This integration has the potential to contribute to lower fuel consumption and associated emissions, supporting ongoing decarbonization efforts in the maritime sector.

At the same time, several limitations must be acknowledged. The lumped-capacitance formulation neglects spatial temperature gradients within the PCM and heat transfer fluids, and the imposed boundary conditions do not capture real fluctuations in steam production and onboard thermal demand. Moreover, the adopted degradation model remains simplified compared to the nonlinear and cycle-dependent aging behavior observed in practice. Practical challenges such as the intrinsically low thermal conductivity of many PCMs, reliable encapsulation, and long-term material stability remain critical aspects for large-scale deployment.

Future work should therefore focus on:

- multidimensional modeling approaches capable of capturing non-uniform melting and solidification phenomena;
- enhanced heat transfer design solutions, including finned geometries, conductive additives, or hybrid sensible-latent configurations;
- experimental validation campaigns to calibrate degradation behavior and confirm long-term reliability under realistic marine operating conditions.

Addressing these aspects would strengthen the engineering maturity of PCM-TES systems and support their adoption as enabling technologies for next-generation marine energy systems.

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