

Evaluation of TEMS Designs in Yachts

Development of a Method to Assess the Effectiveness of
Onboard Thermal Management Solutions

Master Thesis Report

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Evaluation of TEMS Designs in Yachts

Development of a Method to Assess the Effectiveness of Onboard Thermal Management Solutions

By

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Feadship

This thesis (MT.25/26.028.M) is classified as confidential in accordance with the general conditions for projects performed by the TU Delft.

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Preface

I would like to take this opportunity to look back on the path I have followed during these years, and more broadly throughout my life, and to thank the people who have played an important role along the way. During my studies, I have built both my personal and technical background, which now forms a solid basis for the next stage of my life. This path has involved many choices, from choosing a technical education to deciding to live abroad. It has been challenging, but also enriching, and I can now fully appreciate what it has given me.

I would like to express my sincere gratitude to De Voogt Naval Architects for giving me the opportunity to work on this research and to experience closely a sector that I have admired since I was a child. In particular, I would like to thank the entire R&D department and my daily supervisor, Berend van Veldhuizen, for his guidance throughout the project. His support was valuable not only from a technical point of view, but also on a personal level while working on my first large research project.

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*Emanuele Mongardi
Delft, May 2026*

Summary

The superyacht sector is under increasing pressure to reduce operational emissions and improve onboard energy efficiency. One relevant opportunity is the better use of thermal energy, since yachts require heating and cooling under varying operating conditions while propulsion and power-generation systems can provide recoverable waste heat. Evaluating the effectiveness of a Thermal Energy Management System (TEMS) during the design stage is therefore challenging, because both thermal demand and heat availability depend on operational profile, climate zone, occupancy level, and system configuration.

This thesis develops a method to evaluate yacht TEMS designs across multiple operational scenarios. The method combines Multi-Criteria Decision Analysis (MCDA), adapted Scenario-Based Reasoning (SBR), and analytical calculations. MCDA provides the overall comparison structure, SBR is used to evaluate performance-based Key Performance Indicators (KPIs) across representative scenarios, and analytical calculations are used for design-dependent KPIs. The selected KPIs are Load Coverage, Coverage Durability, Usage Ratio, Combined Heat, Power, and Cooling (CHPC) Efficiency, Volume Ratio, Mass Ratio, and Cost Ratio.

The method is applied to M/Y *Obsidian*, an 84.2 m Feadship yacht used as reference case. The scenario matrix combines seven climate zones, three operational profiles, three occupancy levels, and four representative weather-parameter cases, resulting in 252 evaluated scenarios. For each scenario, the weather conditions, thermal demand, useful heat and cooling generation, and performance-based KPIs are calculated. The design-dependent KPIs are then determined from the installed volume, mass, and estimated cost of the TEMS components.

Two configurations are evaluated. Design 1 represents the baseline TEMS, based on engine heat recovery, an electrically driven chiller-heat-pump branch, an electric heater, and thermal storage. Design 2 is introduced as a first improvement iteration, in which the electrically driven chiller is downsized and an absorption chiller is added to use engine high-temperature heat for cooling production during anchor and sailing conditions.

The results show that both designs cover the required thermal demand in all evaluated scenarios. In Design 1, the most critical cases occur in high-occupancy Mediterranean scenarios, where the recovery heat exchanger, electric heater, and heat tank become highly loaded. The analysis also shows that a large share of the available engine high-temperature heat remains unused, indicating that the main limitation is not the availability of recoverable heat, but the capacity and configuration of the recovery path.

Design 2 improves the use of recoverable engine heat in anchor and sailing conditions and leads to a small increase in CHPC Efficiency in warm representative scenarios. However, the improvement is profile-dependent and does not affect harbour operation, where no engine heat is assumed to be available. In addition, the absorption chiller increases the installed volume, mass, and cost of the system.

The final ranking combines CHPC Efficiency, Volume Ratio, Mass Ratio, and Cost Ratio using equal weighting factors and ratio-to-best normalization. Under these assumptions, Design 1 is ranked first in all weather-parameter cases. Design 2 therefore shows a technically relevant improvement, but the efficiency gain is not sufficient to compensate for its larger spatial, mass, and economic impact.

Keywords: Thermal Energy Management System; yacht design; multi-criteria decision analysis; scenario-based evaluation; key performance indicators; effectiveness.

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Nomenclature

Abbreviations

Abbreviation	Definition
AHU	Air-Handling Unit
AIS	Automatic Identification System
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BSFC	Brake-Specific Fuel Consumption
CFD	Computational Fluid Dynamics
CHPC	Combined Heat, Power, and Cooling
CII	Carbon Intensity Indicator
CO	Carbon Monoxide
CO ₂	Carbon Dioxide
COP	Coefficient of Performance
DCS	Data Collection System
DVNA	De Voogt Naval Architects
DW	Domestic Water
DWS	Domestic Water System
ECA	Emission Control Area
EEDI	Energy Efficiency Design Index
EEXI	Energy Efficiency Existing Ship Index
EPLA	Electric Power Load Analysis
FCU	Fan-Coil Unit
GHG	Greenhouse Gas
GT	Gross Tonnage
HT	High Temperature
HVAC	Heating, Ventilation, and Air Conditioning
HVO	Hydrotreated Vegetable Oil
ICE	Internal Combustion Engine
IMO	International Maritime Organization
KPI	Key Performance Indicator
LHV	Lower Heating Value
LOA	Length Overall
LT	Low Temperature
MCDA	Multi-Criteria Decision Analysis
NO _x	Nitrogen Oxides
ORC	Organic Rankine Cycle
PCM	Phase Change Material
PEMFC	Proton Exchange Membrane Fuel Cell
SBR	Scenario-Based Reasoning
SCR	Selective Catalytic Reduction
SOFC	Solid Oxide Fuel Cell
SO _x	Sulfur Oxides
TEFD	Thermal Energy Flow Diagram
TEMS	Thermal Energy Management System
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
WHR	Waste Heat Recovery
YETI	Yacht Environmental Transparency Index

Symbols

Symbol	Definition	Unit
<i>Latin symbols</i>		
A	Area	[m ²]
C	Load Coverage	[-]
CD	Coverage Durability	[-]
C_i	TOPSIS relative closeness coefficient for alternative i	[-]
C_{TEMS}	Total estimated cost of the TEMS	[EUR]
c_p	Specific heat capacity	[kJ/(kg K)]
D_i^+	Distance from the positive ideal solution in TOPSIS	[-]
D_i^-	Distance from the negative ideal solution in TOPSIS	[-]
E	Stored thermal energy	[MJ]
h	Moist-air enthalpy	[kJ/kg _{da}]
h_{in}	Indoor-air enthalpy	[kJ/kg _{da}]
h_{out}	Outdoor-air enthalpy	[kJ/kg _{da}]
h_{sup}	Supply-air enthalpy	[kJ/kg _{da}]
M_{TEMS}	Total installed mass of the TEMS	[kg]
p	Atmospheric pressure	[Pa]
p_w	Actual water-vapour pressure	[Pa]
p_{ws}	Saturation water-vapour pressure	[Pa]
P	Power	[kW]
P_{cons}	Electrical power consumed by the thermal-energy system	[kW]
$P_{\text{el,prod}}$	Electrical power produced on board	[kW]
$P_{\text{fuel,in}}$	Fuel-energy input rate	[kW]
Q	Thermal energy or heat quantity	[kJ]
$\dot{Q}$	Heat-transfer rate or thermal power	[kW]
$\dot{Q}_{\text{AHU}}$	Air-handling-unit thermal load	[kW]
$\dot{Q}_{\text{cool,prov}}$	Useful cooling delivered by the TEMS	[kW]
$\dot{Q}_{\text{cool,req}}$	Required cooling load	[kW]
$\dot{Q}_{\text{dem}}$	Total thermal demand of a scenario	[kW]
$\dot{Q}_{\text{DWS}}$	Domestic-water-system thermal demand	[kW]
$\dot{Q}_{\text{FCU}}$	Fan-coil-unit thermal load	[kW]
$\dot{Q}_{\text{gen}}$	Useful generated thermal service	[kW]
$\dot{Q}_{\text{heat,prov}}$	Useful heating delivered by the TEMS	[kW]
$\dot{Q}_{\text{heat,req}}$	Required heating load	[kW]
$\dot{Q}_{\text{HVAC}}$	HVAC thermal demand	[kW]
$\dot{Q}_j$	Useful output delivered by subsystem j	[kW]
$\dot{Q}_{j,\text{max}}$	Reference capacity of subsystem j	[kW]
$\dot{Q}_{\text{loss}}$	Heat loss or rejected heat	[kW]
$\dot{Q}_{\text{pool}}$	Swimming-pool thermal demand	[kW]
$\dot{Q}_{\text{prov}}$	Total useful thermal service provided by the TEMS	[kW]
$\dot{Q}_{\text{prov,no tank}}$	Useful thermal service provided without storage contribution	[kW]
$\dot{Q}_{\text{req}}$	Total required thermal service	[kW]
$\dot{Q}_{\text{tank}}$	Useful thermal contribution from storage	[kW]
$\dot{Q}_{\text{unmet}}$	Unmet thermal demand	[kW]
r_{ij}	Normalized value of criterion j for alternative i in TOPSIS	[-]
s_{ij}	Normalized score of alternative i for KPI j	[-]
S_i	Final weighted score of design alternative i	[-]
t	Time	[min]
t_{recharge}	Reference recharge time of the thermal storage system	[min]
t_{tank}	Storage-supported duration	[min]
T	Dry-bulb temperature	[°C]

Symbol	Definition	Unit
$T_{\text{air},10}$	Outdoor air temperature at 10 m height	[°C]
T_{sea}	Seawater temperature	[°C]
U_j	Usage Ratio of subsystem j	[-]
U_{tank}	Usage Ratio of the thermal storage branch	[-]
V	Volume	[m ³]
V_{TEMS}	Total installed TEMS volume	[m ³]
w_j	Weighting factor assigned to KPI j	[-]
x	Humidity ratio	[kg _{wv} /kg _{da}]
x_{ij}	Original value of KPI j for alternative i	[varies]
<i>Greek symbols</i>		
ΔT	Temperature difference	[K]
ϵ	Emissivity	[-]
η	Efficiency	[-]
η_{CHPC}	Combined Heat, Power, and Cooling efficiency	[-]
η_{cost}	Cost Ratio	[EUR/GT]
η_{mass}	Mass Ratio	[kg/GT]
η_{space}	Volume Ratio	[m ³ /GT]
ρ	Density	[kg/m ³]
ρ_{air}	Air density	[kg/m ³]
σ	Stefan–Boltzmann constant	[W/(m ² K ⁴)]
ϕ	Relative humidity expressed as a fraction	[-]
ω_a	Ambient-air humidity ratio	[kg _{wv} /kg _{da}]
$\omega_{\text{sat},w}$	Humidity ratio of saturated air at pool-water temperature	[kg _{wv} /kg _{da}]

Disclosure

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN WRITING

During the preparation of this work the author used OpenAI in order to improve the readability of the paper. After using this tool/service, the author reviewed and edited the content as needed and takes full responsibility for the content of the publication.

1. Introduction

The global maritime industry is undergoing a transformative shift in response to mounting environmental pressures. As part of this transition, growing attention is being directed toward the sustainability performance of specialized segments, including the superyacht sector. While traditionally associated with luxury and innovation, this niche market now faces the urgent challenge of aligning with international climate goals. This chapter introduces the environmental context surrounding emissions in the yachting industry, outlines the role of leading shipbuilders such as Feadship in advancing sustainability, and explores the current and potential solutions to mitigate environmental impact—particularly those aimed at reducing waste heat and improving onboard energy efficiency.

1.1. Background

Maritime Emission Categories and Global Contribution

The two principal categories of emissions targeted by maritime environmental policies are greenhouse gases (GHGs) and air pollutants. GHGs—such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O)—contribute to global warming and are mainly linked to the energy efficiency of the vessel and the carbon intensity of its fuel. In contrast, air pollutants—including nitrogen oxides (NO_x), sulfur oxides (SO_x), carbon monoxide (CO), and particulate matter (soot)—originate from combustion processes. Here, NO_x forms at high temperatures, SO_x from the oxidation of sulfur in the fuel, and CO and soot from incomplete combustion. These emissions affect local air quality and human health, prompting stringent international regulations [1].

This distinction is relevant both for design and regulatory compliance. For instance, NO_x emissions from diesel generators are regulated under IMO Tier III requirements [2], while CO_2 emissions are increasingly subject to monitoring and reporting obligations through frameworks like the IMO Data Collection System (DCS) and the EU MRV Regulation [3]. Accordingly, effective emission reduction strategies must address both fuel conversion efficiency (to reduce GHGs) and combustion cleanliness (to reduce pollutants), often requiring different technological solutions.

The growing global concern over greenhouse gas emissions has intensified pressure on the maritime sector, which is responsible for approximately 3% of global CO_2 emissions [4]. In addition to carbon dioxide, shipping significantly contributes to atmospheric pollution through the release of sulfur oxides (SO_x) and nitrogen oxides (NO_x), accounting for around 9% and 18% of global totals, respectively [5]. In response, international regulatory bodies such as the International Maritime Organization (IMO) have implemented increasingly stringent environmental standards, including targets to reduce carbon intensity by 40% by 2030 and 70% by 2050, relative to 2008 levels [6]. Achieving these goals requires a transition toward cleaner technologies, alternative fuels, and more energy-efficient operational practices across the shipping industry.

Yachting Emissions and Regulations

Although the superyacht sector accounts for only 0.4% of global maritime emissions [7], its environmental impact remains disproportionate due to high energy consumption and continued reliance on fossil fuels. As a result, maritime sustainability regulations are increasingly relevant to the sector. Major frameworks such as the Energy Efficiency Design Index (EEDI), Energy Efficiency Existing Ship Index (EEXI), and Carbon Intensity Indicator (CII) primarily target large commercial vessels and do not typically apply to superyachts, which often fall below the gross tonnage thresholds (400 GT for EEDI/EEXI and 5,000 GT for CII) or lie outside the scope of these regulations [8]. By contrast, Tier III NO_x standards do apply to new superyachts over 24 meters built after 2021 when operating in Emission Control Areas (ECAs), unless exempted due to low propulsion power or classification as recreational vessels [2].

Since ECAs encompass major cruising regions such as the Mediterranean, Caribbean, and North American coasts (see Figure 1.1) non-compliance can lead to restricted access, increased operational costs, and reduced charter and resale value. In addition, sulfur regulations apply universally, mandating the use of marine fuels with a maximum sulfur content of 0.5% globally and 0.1% within ECAs [9].



Figure 1.1: Current ECAs around the world. It should be noted that the Mediterranean ECA came into effect as per 2025. Others are not yet official [10].

De Voogt Naval Architects & Feadship

De Voogt Naval Architects (DVNA), founded in 1913 by Henri de Voogt, is the design and engineering office of Feadship. Through its long-standing collaboration with the De Vries and Van Lent shipyards, DVNA has become responsible for the naval architecture and technical development of Feadship yachts [11].

Sustainability has become an important part of Feadship's innovation strategy. This is reflected in initiatives such as the Yacht Environmental Transparency Index (YETI), a data-driven framework developed with industry stakeholders to assess the environmental performance of yachts over their lifecycle [12]. In parallel, Feadship has focused on reducing operational emissions through more efficient hull forms, alternative-fuel-ready propulsion systems, electric drives, energy storage, and waste-heat recovery [13, 14].

The 84.2 m Feadship *Obsidian* illustrates this direction and is therefore relevant to the context of this thesis. The yacht combines an optimized hull and propulsion arrangement with contra-rotating thrusters, a 4.5 MWh battery bank, HVO operation, and waste-heat recovery from chillers and generators [15, 16]. According to Feadship's YETI assessment, *Obsidian* achieves a 27% lower environmental impact than comparable yachts, increasing to 60% when operating on HVO [17].

Current Emission Reduction Solutions

Several complementary strategies are currently used to reduce operational emissions in the yachting industry. These include improving hydrodynamic efficiency, reducing emissions from propulsion and power-generation systems, adopting alternative fuels and advanced power architectures, and increasing the efficiency of onboard energy systems.

Hydrodynamic optimization reduces the propulsion power required to operate the vessel. Recent developments in early-stage resistance prediction, including data-driven extensions of the Delft Systematic Yacht Hull Series and hybrid modelling approaches, have improved the accuracy of hull-performance assessment during design [18, 19]. In parallel, multi-objective hull-form optimization has shown potential for reducing resistance in large yachts [20]. These methods contribute to lower fuel consumption by reducing the energy demand associated with propulsion.

Emission reduction in propulsion and power-generation systems involves both pollutant control and the transition toward lower-carbon energy carriers. Air pollutants such as NO_x , SO_x , CO, and partic-

ulate matter are mainly linked to combustion conditions, while greenhouse gas emissions depend on fuel composition and conversion efficiency [21, 22]. Selective Catalytic Reduction (SCR) systems are therefore commonly applied to reduce NO_x emissions, with reductions of up to 95% reported in marine applications [23, 24]. These systems represent an established solution for pollutant control, although they do not remove the need to reduce lifecycle greenhouse gas emissions.

For this reason, increasing attention is being given to alternative fuels and advanced power systems. Hydrogen, ammonia, methanol, and advanced biofuels can reduce lifecycle emissions, although their actual benefit depends on the production pathway, onboard storage requirements, and system integration [25]. Among these options, methanol is particularly relevant for superyachts because it is liquid at ambient conditions, can use existing fuel-handling infrastructure more easily than cryogenic or compressed fuels, and produces lower SO_x and particulate emissions than marine diesel [26, 27]. Fuel cells also offer potential for low-emission operation. Proton Exchange Membrane Fuel Cells are suitable for auxiliary or hybrid applications because of their fast response, while Solid Oxide Fuel Cells can reach high electrical efficiencies and operate with several fuels through reforming [28, 29].

A further reduction route is the improvement of onboard energy efficiency. Large yachts have significant thermal and electrical loads, with HVAC often representing a major share of total energy demand [30]. At the same time, engines and fuel cells reject considerable amounts of heat that can be recovered and reused. Thermal energy recovery systems, such as absorption chillers and thermal storage, can therefore improve overall system efficiency by converting waste heat into useful heating or cooling services [31]. This is also consistent with more flexible design approaches that aim to keep yachts compatible with future low- and zero-emission technologies [32]. Within this broader context, this thesis focuses on the evaluation of Thermal Energy Management System (TEMS) designs as one contribution to reducing operational energy use and emissions.

1.2. Research Gap

Current approaches to TEMS design and evaluation highlight a research gap: the absence of a unified method capable of assessing the performance of a yacht's Thermal Energy Management System (TEMS) across diverse operational profiles. Most existing methods rely on generalized energy balances or manufacturer-reported data, which, while useful for estimating potential fuel savings, fail to capture the complexity of system behavior under varying propulsion configurations and onboard energy demands [33]. This limitation becomes especially relevant for hybrid or multi-fuel propulsion systems, where the quantity and quality of recoverable waste heat fluctuate with power source type, load factor, and mode of operation [34]. Consequently, current methods do not enable a reliable comparison of alternative system configurations, accurate estimation of long-term efficiency gains, or justification of capital investments.

1.3. Research Objective

This research aims to address this gap by developing a method to evaluate the effectiveness of Thermal Energy Management System (TEMS) designs, capable of providing both heating and cooling to yachts across multiple operational profiles. The proposed method integrates thermal demand mapping, heat source variability, and system adaptability to enable a robust assessment of TEMS performance tailored to the unique requirements of the yachting industry. These operational profiles account for varying thermal demands arising from user needs, different climate zones, and the availability of heat sources influenced by propulsion configurations and onboard systems.

1.4. Research Question

To achieve this objective, the following research question is proposed:

“How can the effectiveness of a Thermal Energy Management System (TEMS) design be evaluated across multiple operational scenarios in order to support design improvement?”

The main research question is answered through a series of targeted sub-questions, each aimed at exploring essential aspects of the topic.

1. How do the DVNA design process and the configuration of yacht TEMS shape the requirements for a methodology to evaluate TEMS effectiveness?
(Chapter 2)
2. Which KPIs and associated evaluation methods are most appropriate for assessing yacht TEMS effectiveness across multiple operational scenarios?
(Chapter 3)
3. How can the selected KPI framework and evaluation methods be translated into an operational model for TEMS effectiveness evaluation, and what input data, scenario definitions, and assumptions are required for its implementation?
(Chapter 4)
4. What results are obtained when the proposed evaluation method is applied to the selected yacht, and how do the baseline and improved TEMS designs compare?
(Chapter 5)
5. How can the accuracy of the proposed evaluation method be validated?
(Chapter 6)

2. Problem Analysis

This chapter addresses the first research sub-question: *“How do the DVNA design process and the configuration of yacht TEMS shape the requirements for a methodology to evaluate TEMS effectiveness?”*. As indicated by the question, the aim is to clarify the challenges associated with the design of Thermal Energy Management Systems (TEMS) in yachts. It begins with an analysis of the design method currently employed by DVNA (Section 2.1), with particular focus on how this approach may influence overall system performance. The discussion then shifts to the subsystems typically integrated within TEMS and explores additional components or configurations that could enhance energy efficiency (Section 2.2). Finally, based on the identified limitations, a set of requirements is established to guide the development of a new method capable of accurately evaluating the effectiveness of TEMS in yachts (Section 2.3).

2.1. DVNA Design method

2.1.1. DVNA Design & Engineering Process

The design method adopted by De Voogt Naval Architects (DVNA) is organized into five sequential phases: Concept Design, Contract Design, Development Design, Definitive Design, and Concurrent Design. This phased approach, as described by Odendaal [35], provides a structured framework in which engineering work progresses from broad conceptual sketches to detailed technical packages that support procurement, construction, and final delivery. The overall design approach followed by Feadship is illustrated in Figure 2.1, highlighting the phases where DVNA plays a central role.

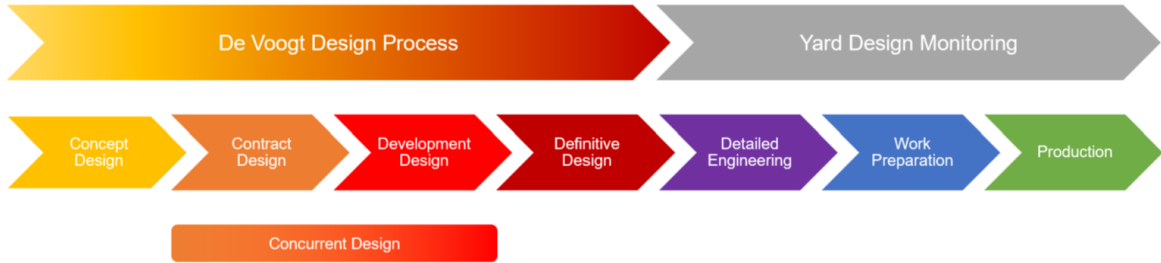


Figure 2.1: De Voogt Naval Architects (DVNA) design & engineering process [35]

This method follows the logic of the design spiral, originally described by Evans [36] and shown in Figure 2.2. The main characteristic of this approach is that the design is developed iteratively. After each cycle, earlier design choices can be reviewed and adjusted as more information becomes available, gradually improving the level of detail and accuracy of the design.

The process begins with a “blank sheet” approach in the Concept Design phase, where fundamental vessel parameters such as weight, stability, powering, and layout are estimated using empirical and comparative methods. At this stage, propulsion and auxiliary load predictions are acknowledged to be low in accuracy, serving merely as baselines for further refinement.

Once a client expresses interest, the project transitions into the Contract Design phase, during which DVNA supports the sales team by producing renderings and preliminary engineering drawings. Computational Fluid Dynamics (CFD) is introduced to estimate hull resistance, though results remain preliminary due to uncertainties in hull geometry. Auxiliary loads are approximated based on industry experience, but there is little transparency in the assumptions or methods used.

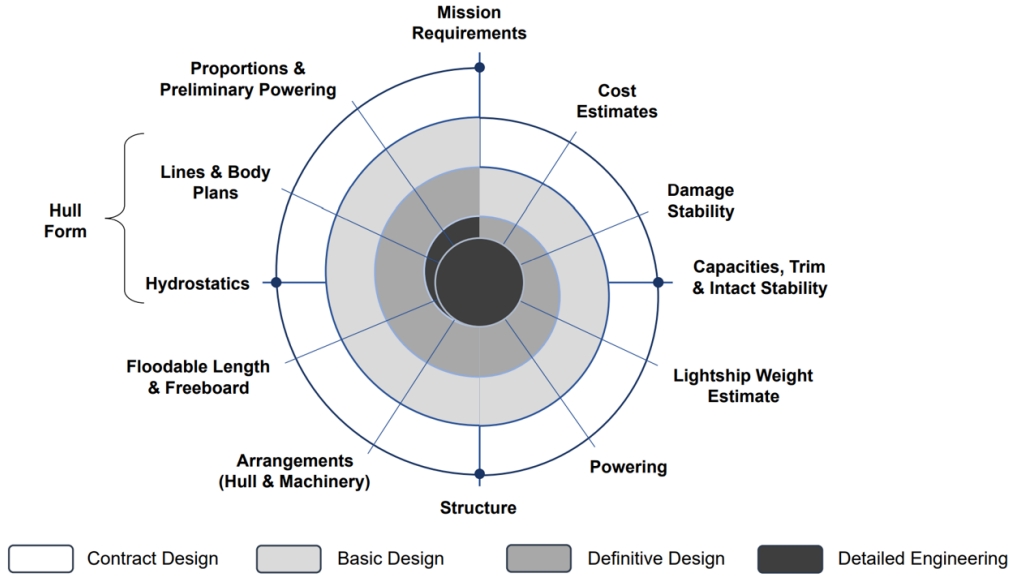


Figure 2.2: Traditional design spiral approach used by DVNA [36]

The Development Design phase, initiated post-contract signing, involves a multidisciplinary team from both DVNA and the selected yard. The primary goal here is risk identification and early design validation to avoid costly changes later. Further CFD iterations refine the hull design, appendages, and shaft-line layout, while wakefield interaction is assessed to support propulsion design. At this stage, HVAC loads are estimated using first-principles heat balance calculations, but the rest of the auxiliary load balance remains the responsibility of the yard or contractors.

In the Definitive Design phase, all systems, arrangements, and interior layouts are finalized to meet classification and regulatory requirements. Detailed CFD simulations are used to derive final speed–power curves, and auxiliary load balances are now defined with high fidelity. These include all major and minor components across multiple operational scenarios.

Lastly, while a Concurrent Design stage exists to improve communication and decision-making across disciplines, it does not contribute significantly to the technical evaluation of energy systems and is therefore not considered central to this study.

2.1.2. DVNA Design Method for TEMS

Currently, thermal systems on superyachts are usually designed separately from one another and follow standard rules or supplier recommendations, rather than being part of a coordinated, customized plan for the whole yacht. Naval architects and shipyard engineers typically determine the required capacity of each subsystem based on the worst-case environmental conditions and the highest yacht energy demand, relative to its operational profiles.

A common industry practice is to compile an Electric Power Load Analysis (EPLA) spreadsheet, together with a Heat Load Analysis spreadsheet, listing every significant consumer (e.g., HVAC chillers, pumps, galley appliances, lighting) with assigned load factors for various operational modes including cruising, anchoring, and port stays [37]. Figure 2.3 shows an example of an Energy Load Balance Spreadsheet, which can be used to predict both electrical and heat loads.

This spreadsheet-based approach typically informs the sizing of generator sets and thermal equipment. However, the simultaneous operation of multiple systems is not well evaluated or validated, often resulting in oversizing. To ensure passenger comfort under all conditions, HVAC systems are therefore intentionally designed to accommodate peak loads—particularly during periods of high or very low ambient temperature and full guest occupancy.

consumername	number installed	power at full load	installed power E-motor	absorbed electric power	in port				at sea	
		[kW]	[kW]	[kW]	number in service	load factor	sim. factor	average absorbed power	number in operation	etc.
Propulsion system										
-										
-										
Auxiliary systems										
-										
- etc.										
115 V, 60Hz, 1phase										
24V, DC										
Total										

Figure 2.3: Example of an Energy Load Balance spreadsheet [37]

While this strategy offers operational robustness, it frequently results in reduced efficiency during partial load conditions, which represent the majority of real-world operation. As previously noted, thermal energy demand on a yacht varies significantly depending on several dynamic factors, most notably the vessel's operational profile and the environmental conditions in which it operates. These contributions are further examined in the following paragraphs.

Operational Profiles

Operational profiles are a key determinant of thermal energy demand on superyachts, directly influencing the heat generation sources and heat consumption sinks within its TEMS. Figure 2.4 presents the results of an AIS-based analysis conducted on 133 active Feadship yachts. The data indicate that, on average, these vessels spend approximately 51% of their time in port, 32% at anchor, and just 8% underway. The remaining 9% corresponds to service uptime. Notably, the study also found that guest occupancy is frequently well below full capacity, with average figures ranging from 3% to 20% depending on the operational mode [37].

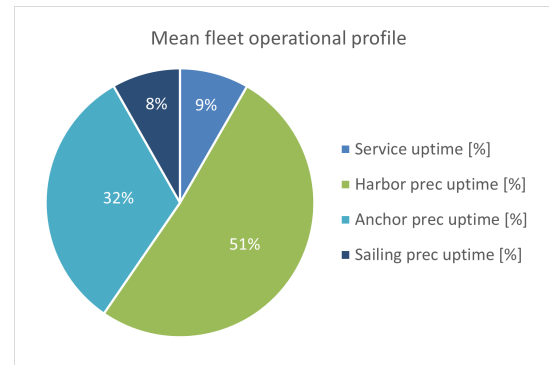


Figure 2.4: Feadship fleet Mean operational profile

Each operational mode presents different heat generation sources and sinks, as well as distinct thermal load characteristics:

- **Sailing:** While underway, the active propulsion system generates substantial waste heat, which can be recovered for heating or domestic hot water. Most interior spaces are closed and cooled, leading to high cooling demand. Wind-driven convection slightly reduces external thermal loads. Although this mode sees limited annual use, it influences installed HVAC capacity.
- **At Anchor:** Typically accounting for over one-third of operational time, this mode relies on generators or batteries, with propulsion systems inactive. Solar gains dominate external loads, particularly in tropical climates. Air conditioning must manage internal gains from guests, lighting, and cooking, making this the most demanding steady-state condition for thermal design.
- **In Harbor:** While docked—often more than half of the annual profile—shore power may be available, but HVAC systems remain active to preserve interior conditions. Guest presence is minimal, and energy use is concentrated in crew and technical areas. Without proper zoning or control, systems may operate inefficiently at baseline settings.
- **Service Time:** During crew-only periods or between charters, internal gains are low. However, oversized systems running at partial load can lead to short cycling and energy waste if not properly managed.

Table 2.1 summarizes the principal sources of heat generation and the corresponding consumption sinks.

Table 2.1: Main Heat Generation Sources and Consumption Sinks Across Superyacht Operational Modes

Operational Mode	Heat Generation Sources	Heat Consumption Sinks
Sailing	• Machinery spaces • Generators (for hotel load) • Solar Radiation • Occupancy (crew/guests)	• HVAC/Heating for guests and crew • Domestic hot water (via WHR) • Galley and laundry systems • Pools & SPA facilities
At Anchor	• Generators (for hotel load) • Solar radiation • Occupancy (crew/guests)	• HVAC/Heating for guests and crew • Domestic hot water • Galley and laundry systems • Pools & SPA facilities
In Harbor	• Generators (if no shore power)) • Solar Radiation • Occupancy (crew)	• HVAC (moderate base load) • Hot Water (washing purposes) • Galley and laundry systems
Service Time	• Minimal internal gains • Background equipment loads	• Maintenance cooling/heating and dehumidification

Environmental Conditions

Together with the multiple operational profiles, the environmental conditions the yacht is sailing in affects its thermal energy demand. Climate zones, as defined by classification systems like ASHRAE and Köppen, categorize global regions based on long-term patterns of temperature, humidity, and solar radiation. Figure 2.5 shows the world climate zones based ASHRAE Standard 169-2013 [38]. Each climate zone presents unique environmental challenges that directly impact thermal loads and system performance. For instance, tropical zones are characterized by high temperatures and humidity levels, necessitating robust cooling and dehumidification systems. On the contrary, temperate and polar zones may require systems capable of efficient heating and insulation.

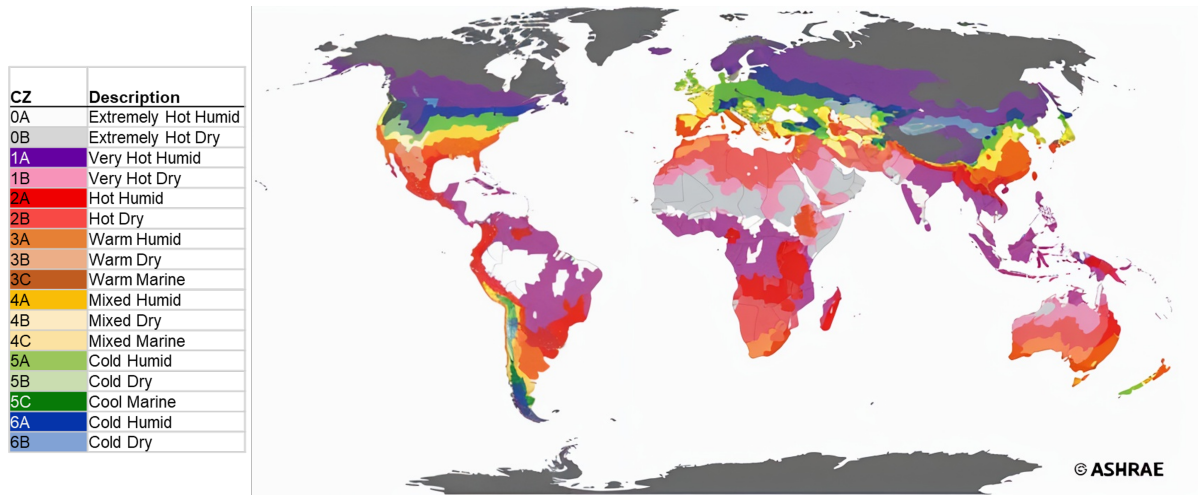


Figure 2.5: World climate zones map based on ASHRAE Standard 169-2013 [38]

The design and optimization of TEMS on yachts are significantly influenced by key environmental parameters: air temperature, seawater temperature, relative humidity, and solar radiation. Air temperature affects the thermal gradient between the yacht's interior and exterior, influencing heating and cooling requirements. Seawater temperature is critical for systems utilizing seawater for heat exchange; variations can impact the efficiency of heat rejection or absorption processes. Relative humidity levels dictate the need for dehumidification to maintain indoor air quality and prevent condensation-related issues. Solar radiation contributes to heat gain through the yacht's envelope, affecting cooling loads.

Accurate assessment and integration of these parameters into TEMS design ensure systems are appropriately sized and capable of maintaining thermal comfort across varying environmental conditions. Table 2.2 reports the main parameters for each Climate Zone.

Table 2.2: Environmental Parameters by Climate Zone Relevant to Yacht Operations [38]

Climate Zone	Air Temp. Range (°C)	Seawater Temp. Range (°C)	Rel. Humidity Range (%)	Solar Radiation (kWh/m ² /day)
Zone 1A (Very Hot – Humid)	24–38	27–32	70–90	5.5–6.5
Zone 2A (Hot – Humid)	22–35	25–30	60–85	5.0–6.0
Zone 3C (Warm – Marine)	10–30	12–22	60–80	4.5–5.5
Zone 4A (Mixed – Humid)	5–28	10–20	50–70	3.5–4.5
Zone 5A (Cool – Humid)	–5–20	5–15	40–60	2.5–3.5

Climate zones and parameter ranges adapted from ASHRAE (2013).

2.1.3. Influence of the Design Method on TEMS Performance

In the early design stages, the required thermal loads are estimated by identifying the most extreme environmental scenarios in which the yacht is expected to operate. These estimates are progressively refined using a design spiral approach, with the aim of achieving accurate and realistic heat demand calculations. Once these preliminary design parameters are established, the development of the TEMS is typically outsourced to specialized suppliers such as Heinen & Hopman [39], who are responsible for designing, manufacturing, and delivering the system to Feadship.

This method presents two key limitations. First, designing the system based on extreme boundary conditions, rather than on the yacht’s typical operational profile, often results in over-dimensioned systems that operate inefficiently under normal conditions. Second, by delegating the final design and performance optimization to an external supplier—without an internal evaluation tool or benchmark—Feadship lacks the means to verify whether the delivered system represents the most effective solution. These issues highlight the need for a more structured and integrated design method, along with a clear framework to evaluate system performance internally.

2.2. TEMS Configuration and Sub-systems

The design of a Thermal Energy Management System (TEMS) is tailored to the specific characteristics of each vessel. It depends on factors such as the yacht’s size, its heating and cooling demands, and the performance requirements defined by both De Voogt Naval Architects and the client. As a result, every yacht is equipped with a bespoke TEMS, which may differ significantly in terms of system configuration, component selection, and the number of integrated sub-systems.

2.2.1. Current TEMS Configuration

Although each TEMS is developed on a project-specific basis, recent designs increasingly converge toward a simplified and consistent configuration, regardless of yacht type. While the type and number of subsystems may vary, a general arrangement—illustrated in Figure 2.6—is commonly observed across

multiple vessels.

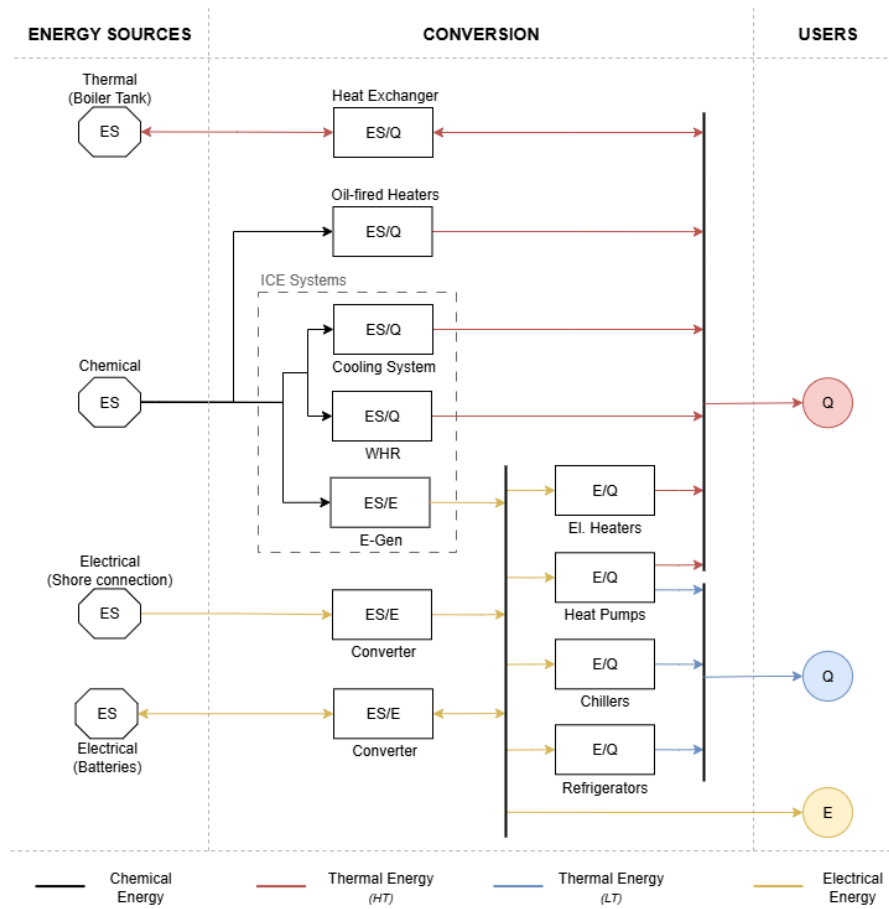


Figure 2.6: Basic thermal energy flow diagram illustrating energy sources and conversion systems.

The Thermal Energy Flow Diagram presented in Figure 2.6 illustrates how thermal energy is generated, converted, and distributed to meet user demands. Thermal energy in a yacht can be produced primarily through three pathways: (1) direct combustion using oil-fired heaters; (2) recovery of waste heat from internal combustion engines or fuel cell systems; and (3) conversion of electrical energy, either generated onboard or sourced from shore power during harbor operations.

In the first case, heat is generated directly through the combustion of fuel. In the second, thermal energy—available at either low or high temperature—is recovered as a byproduct of propulsion or power generation systems. This energy can be used immediately to serve onboard heating demands or stored in boiler tanks for later use. In the third case, electrical energy is converted into thermal energy through systems designed for either heating or cooling, depending on the operational requirements. Any excess heat generated in this process can also be stored in dedicated boilers.

The following paragraph provides a brief overview of the key systems integrated into current TEMS configuration:

- **Cooling Systems:** They regulate the operating temperature of power generators—such as ICE and Fuel Cells—and manage the resulting thermal energy. Based on generator type, they are typically divided into low-temperature (LT) and high-temperature (HT) circuits. These systems either dissipate heat or recover it for secondary uses as part of a waste heat recovery (WHR) strategy. Cooling is required when generators are active, making these systems relevant primarily during sailing or at-anchor operations with generator support.
- **Waste Heat Recovery Systems:** These systems recover heat produced as a byproduct of power generation. In internal combustion engines, heat is extracted via the cooling circuits, high-

temperature (HT) combustion air, and exhaust gases. Similarly, in fuel cells, low-temperature heat is recovered through cooling systems, while high-temperature heat is captured using economizer-like devices. WHRs are closely connected with the operation of the generators, making them a valid heat source during sailing, or at anchor.

- **Heaters:** Heaters can be classified as either electric or oil-/gas-fired. Electric heaters use resistive elements to heat air or water, while oil-fired heaters achieve this by burning fuel in a combustion chamber. Both types can operate across all yacht operational profiles. However, electric heaters are typically preferred when shore power is available, whereas oil-fired units may be favored at anchor due to higher onboard electrical loads.
- **Chillers & Refrigerators:** Chillers and refrigerators operate using a vapor-compression cycle, relying on electricity to transfer heat from a lower to a higher temperature. While the working principle is the same, they serve different purposes within the yacht. These systems are used across all operational profiles; however, they require a continuous energy source to function.
- **Heat Storage:** Heated water is stored in insulated thermal tanks, which retain high temperatures over extended periods. This stored heat is typically used when neither the main engines nor heaters are operating, such as during anchoring.

2.2.2. Additional Sub-systems

The overall system arrangement could be further optimized by integrating additional subsystems, depending on the yacht's type and operational profile. A more complete thermal energy flow diagram is presented in Figure 2.7, illustrating potential components that could enhance or replace elements within the existing configuration. Systems already discussed are shown in grey, while new, optional subsystems are highlighted.

The following paragraph provides a brief overview of the optional systems that could be integrated into current TEMS configuration:

- **Solar Thermal Collectors:** These devices absorb solar radiation and convert it into thermal energy, typically used to heat water or air. They can contribute directly to the heat production of the yacht and they can be used in every operational profile, as they rely solely on solar radiation.
- **Chillers:** High-temperature heat can be converted into low-temperature cooling using absorption or adsorption chillers. Absorption systems use heat to separate and evaporate a refrigerant, while adsorption systems rely on solid materials (e.g., silica gel or zeolite) to alternately capture and release refrigerant in thermal cycles. These chillers can operate in any profile with a heat source and are particularly suitable at anchor due to their low electrical demand.
- **Heat Storage:** Thermal energy can also be stored using Phase Change Materials (PCMs), which absorb and release heat by transitioning between solid and liquid phases at defined temperatures. Unlike boilers, PCMs are suitable for storing low-temperature heat, helping to reduce HVAC cycling. They operate passively and are especially advantageous at anchor, as they require no additional energy input.
- **Organic Rankine Cycle (ORC):** This system enables the conversion of thermal energy into electrical energy. When high-temperature heat—such as that from exhaust gases—is available in excess, it can be harnessed to generate electricity, which may then be used to power onboard systems or be stored in batteries.

2.2.3. Conclusion

Modern yachts are typically equipped with hybrid propulsion systems, in which internal combustion engines and/or fuel cells generate onboard electricity. This electricity powers propulsion motors, auxiliary systems, and batteries. As a result, the majority of thermal energy is produced through electrical conversion for both heating and cooling. Waste heat from engines or fuel cells is then recovered and reused for heating purposes, increasing the overall system efficiency.

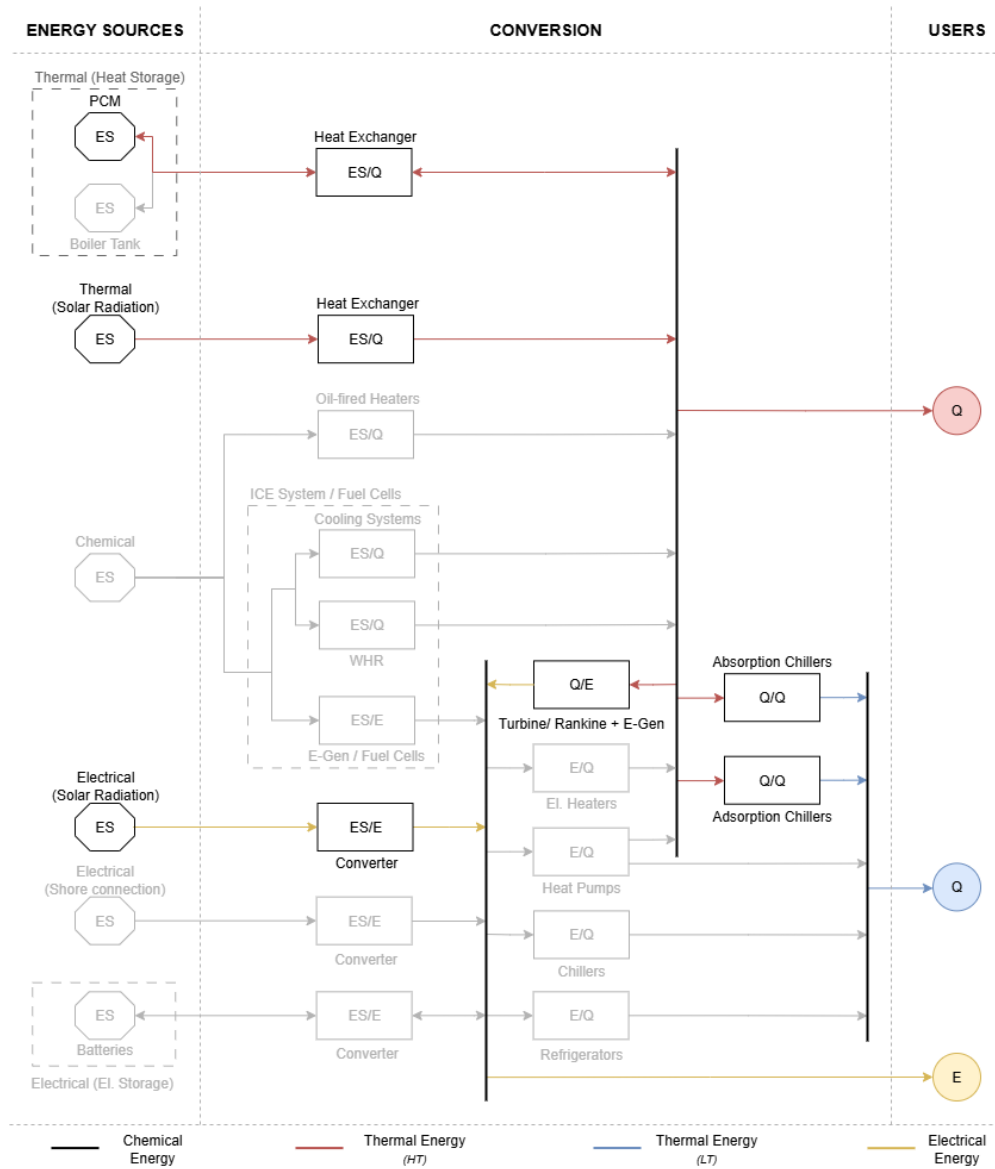


Figure 2.7: Thermal flow diagram illustrating additional sources and conversion systems.

However, the heat recovered by the waste heat recovery system can also be repurposed for other applications, such as cooling or electricity generation, further enhancing the effectiveness of a yacht's TEMS. For example, integrating absorption and adsorption chillers—capable of converting high-temperature heat into low-temperature cooling with minimal electrical input—would extend the utility of waste heat. Additionally, excess high-temperature thermal energy could be converted into electricity through an Organic Rankine Cycle. Heat storage performance may also be improved by incorporating Phase Change Materials (PCMs), which help reduce HVAC cycling. Collectively, these additions would enable more effective utilization of waste heat, thereby improving the overall energy efficiency of the vessel.

Each yacht is a custom project with specific design requirements. A model capable of accounting for these variations—while evaluating the performance of different TEMS configurations and subsystems—could support more efficient system designs, ultimately contributing to reduced emissions.

2.3. Method Requirements

Sections 2.1 and 2.2 analyzed current design practices and configurations of yacht-based Thermal Energy Management Systems (TEMS), revealing key limitations and highlighting the need for a structured method to evaluate system effectiveness during the design phase. To support the development of such a method, it is necessary to establish two core elements: (1) a set of methodological requirements that define the boundary conditions and essential capabilities the method must fulfill, and (2) a set of evaluation criteria—expressed as Key Performance Indicators (KPIs)—that determine how effectiveness is measured. The methodological requirements are introduced and summarized in Table 2.3, while the KPIs are further explored in Chapter 3.

Table 2.3: Breakdown of the Method Requirements

No.	Requirement	Description
1	Multi-KPI effectiveness evaluation	It must evaluate effectiveness through multiple KPIs to capture all key performance aspects.
2	Flexible KPI determination method	It must allow different calculation methods for each KPI, depending on data and design stage.
3	Multi-output decision support	It must provide a set of KPI results rather than a single score, supporting customized decisions.
4	Comparative and traceable framework	It must ensure transparent and repeatable evaluation for consistent comparison between alternatives.
5	Data-driven and feasible within Feadship/DVNA	It must rely on available data and integrate into current design work-flows.
6	Steady-State Basis of Evaluation	It must integrate KPI results based on steady-state design conditions, without time-dependent simulations.
7	Multi-scenario evaluation capability	It must assess TEMS performance under different operational and environmental scenarios.
8	Scenario- or Design-Dependent Evaluation Output	It must provide scenario-specific and aggregated results for performance-based KPIs, or a single representative value for design-dependent KPIs.

3. Solution Approach

This chapter addresses the second sub-research question: “Which KPIs and associated evaluation methods are most appropriate for assessing yacht TEMS effectiveness across multiple operational scenarios?” Section 3.1 identifies the Key Performance Indicators (KPIs) that define effectiveness in this context and introduces their governing equations. Section 3.2 then identifies the methodological framework used to evaluate those KPIs. Finally, Section 3.3 summarizes the complete evaluation model and clarifies how the selected KPIs and methods are combined.

3.1. Exploration of the Key Performance Indicators

The objective of this thesis is to evaluate the effectiveness of a yacht’s Thermal Energy Management System (TEMS) design. Effectiveness is defined as the degree to which a system achieves its intended purpose [40]. For a TEMS, this means providing the required thermal services under the relevant operating conditions while remaining feasible from a design and integration perspective. Since this objective involves technical, spatial, and economic aspects, the evaluation must rely on multiple criteria expressed as Key Performance Indicators (KPIs).

According to their role in the evaluation framework, the KPIs are divided into two groups:

- **Performance-based KPIs:** These indicators describe how the TEMS performs under different operating conditions. Their evaluation requires a scenario-based, steady-state approach in which each scenario is defined by a combination of operational profile, climate zone, occupancy level, and representative weather-parameter case.
- **Design-dependent KPIs:** These indicators describe the physical and economic implications of the system configuration itself. Their evaluation is based on static design data and does not depend on scenario-by-scenario operating variations.

3.1.1. Performance-based KPIs

Load Coverage

The first performance-based KPI evaluates whether the TEMS can cover the total thermal demand of a given scenario. This indicator, referred to as *Load Coverage* (C), is defined as the ratio between the useful thermal service provided by the system and the corresponding scenario demand:

$$C = \frac{\dot{Q}_{\text{prov}}}{\dot{Q}_{\text{dem}}} \quad (3.1)$$

where $\dot{Q}_{\text{dem}}$ is the total thermal demand of the scenario and $\dot{Q}_{\text{prov}}$ is the total useful thermal service delivered by the TEMS.

The useful thermal service generated directly by the active TEMS subsystems is defined as:

$$\dot{Q}_{\text{gen}} = \dot{Q}_{\text{heat,prov}} + \left| \dot{Q}_{\text{cool,prov}} \right| \quad (3.2)$$

where $\dot{Q}_{\text{heat,prov}}$ is the useful heating delivered by the system and $\left| \dot{Q}_{\text{cool,prov}} \right|$ is the useful cooling expressed as a positive magnitude. Thermal storage is not included in $\dot{Q}_{\text{gen}}$, since it does not represent newly generated thermal service but only the temporary release of previously stored energy.

The total useful thermal service available to cover the demand is then obtained by adding the useful contribution from thermal storage:

$$\dot{Q}_{\text{prov}} = \dot{Q}_{\text{gen}} + \dot{Q}_{\text{tank}} \quad (3.3)$$

where $\dot{Q}_{\text{tank}}$ is the useful thermal contribution from storage.

The interpretation of this KPI is straightforward:

- $C \geq 1$: the total demand is covered,
- $C < 1$: the total demand is not fully covered.

Load Coverage therefore provides the primary scenario-level indicator of whether the system is thermally feasible under the considered conditions. It should be interpreted as a minimum feasibility threshold rather than only as a comparative performance measure. A value of $C \geq 1$ is required for the TEMS to satisfy the thermal demand of the scenario, whereas $C < 1$ indicates that the design is not capable of fully covering the required thermal service under those conditions.

Coverage Durability

Meeting the demand in a scenario is not sufficient on its own. It is also necessary to distinguish whether this can be achieved continuously or only for a limited time through storage support. For this reason, the second performance-based KPI is defined as *Coverage Durability*.

Using the generated thermal service defined in Equation 3.2, Coverage Durability is expressed through the following classification:

$$CD = \begin{cases} \text{Unlimited,} & \dot{Q}_{\text{gen}} \geq \dot{Q}_{\text{dem}} \\ t_{\text{tank}}, & \dot{Q}_{\text{gen}} < \dot{Q}_{\text{dem}} \text{ and } \dot{Q}_{\text{gen}} + \dot{Q}_{\text{tank}} \geq \dot{Q}_{\text{dem}} \\ \text{Unable,} & \dot{Q}_{\text{gen}} + \dot{Q}_{\text{tank}} < \dot{Q}_{\text{dem}} \end{cases} \quad (3.4)$$

This KPI therefore distinguishes between three cases: scenarios in which the demand is met without storage, scenarios in which storage can bridge the remaining gap for a limited duration, and scenarios in which the demand cannot be met even with storage support. It complements Load Coverage by adding a temporal interpretation to the demand-coverage assessment.

Usage Ratio

The third performance-based KPI evaluates how intensively the available thermal subsystems are used relative to their reference capacity. This indicator, referred to as the *Usage Ratio* (U_j), is defined for a generic subsystem j as:

$$U_j = \frac{\dot{Q}_j}{\dot{Q}_{j,\text{max}}} \quad (3.5)$$

where $\dot{Q}_j$ is the useful output delivered by subsystem j in the considered scenario and $\dot{Q}_{j,\text{max}}$ is the corresponding reference capacity.

For the thermal-storage branch, the usage ratio is instead based on the ratio between the storage-supported duration and the reference recharge time:

$$U_{\text{tank}} = \frac{t_{\text{tank}}}{t_{\text{recharge}}} \quad (3.6)$$

The Usage Ratio therefore provides a subsystem-level measure of how strongly the available thermal-service pathways are utilized in each scenario. This is useful for identifying heavily loaded subsystems and for understanding which parts of the TEMS are most critical under different operating conditions.

Combined Heat, Power, and Cooling (CHPC) Efficiency

The fourth performance-based KPI evaluates the overall energetic effectiveness of the TEMS by considering the combined production of useful heating, useful cooling, and electrical power. For this reason, the indicator is referred to as the *Combined Heat, Power, and Cooling (CHPC) Efficiency*.

The useful generated thermal service, $\dot{Q}_{\text{gen}}$, is taken from Equation 3.2. Thermal storage is excluded from this KPI, since it does not represent newly generated energy but only the temporary release of previously stored thermal energy.

For operational profiles in which the onboard fuel input and electrical power production are represented explicitly, the CHPC efficiency is defined as:

$$\eta_{\text{CHPC}} = \frac{\dot{Q}_{\text{gen}} + P_{\text{el,prod}} - P_{\text{cons}}}{P_{\text{fuel,in}}} \quad (3.7)$$

where $P_{\text{el,prod}}$ is the electrical power produced on board, P_{cons} is the electrical power consumed by the thermal-energy system, and $P_{\text{fuel,in}}$ is the corresponding fuel-energy input.

For operational profiles in which the fuel-based machinery input is not represented in the same way, the CHPC efficiency is reduced to:

$$\eta_{\text{CHPC}} = \frac{\dot{Q}_{\text{gen}}}{P_{\text{cons}}} \quad (3.8)$$

This KPI therefore expresses how effectively the available energy input is converted into useful thermal service, while also accounting for the interaction between thermal production and electrical power. It is not intended to represent the efficiency of a single component, but rather the combined scenario-level efficiency of the integrated thermal-energy system.

3.1.2. Design-Dependent KPIs

Volume Ratio

The first design-dependent KPI is the *Volume Ratio* (η_{space}). In yacht design, technical systems must be integrated while limiting the space they occupy, since machinery volume directly affects the space available for other functions on board. This KPI is therefore defined as the ratio between the total TEMS volume and the yacht's Gross Tonnage (GT):

$$\eta_{\text{space}} = \frac{V_{\text{TEMS}}}{GT} \quad (3.9)$$

where V_{TEMS} is the total installed volume of the Thermal Energy Management System and GT is the yacht's Gross Tonnage. Lower values of η_{space} indicate a more spatially efficient solution.

Mass Ratio

The second design-dependent KPI is the *Mass Ratio* (η_{mass}). Since the installed mass of the thermal-energy system affects vessel integration and may influence other naval-architectural considerations, it is useful to compare alternative designs through a normalized mass indicator:

$$\eta_{\text{mass}} = \frac{M_{\text{TEMS}}}{GT} \quad (3.10)$$

where M_{TEMS} is the total installed mass of the TEMS. Lower values of η_{mass} indicate a less mass-intensive solution relative to vessel size.

Cost Ratio

The final design-dependent KPI is the *Cost Ratio* (η_{cost}). Although superyacht projects are not driven by cost alone, comparing the installed cost of alternative TEMS configurations still provides useful design insight. In the present thesis, the comparison is based on a normalized cost indicator rather than on the absolute capital cost alone:

$$\eta_{\text{cost}} = \frac{C_{\text{TEMS}}}{GT} \quad (3.11)$$

where C_{TEMS} is the total estimated installed cost of the TEMS. Lower values of η_{cost} indicate a less cost-intensive solution relative to vessel size. This KPI is intended as a concept-stage comparison indicator and does not represent the full life-cycle cost of the system.

It is important to distinguish between the scaling included in the KPI formulation and the normalization used later for the final MCDA ranking. The design-dependent KPIs are expressed relative to the yacht's Gross Tonnage in order to make volume, mass, and cost comparable with respect to vessel size. This scaling is part of the KPI definition itself, because it gives the indicator a direct engineering interpretation, such as cubic metres per GT, kilograms per GT, or euros per GT.

The normalization used in the final design comparison has a different purpose. It does not define the KPI, but converts selected KPI values into dimensionless preference scores so that indicators with different units, magnitudes, and directions of preference can be combined in one ranking procedure. The raw KPI values are therefore retained for interpretation, while the normalized scores are used only in the final aggregation step.

3.1.3. Conclusion

The KPI set defined in this section captures both the operational effectiveness and the design implications of a yacht TEMS. The four performance-based KPIs evaluate whether the system can meet the thermal demand of the considered scenarios, for how long this can be sustained, how intensively the subsystems are used, and how effectively the system converts the available energy into useful combined heat, power, and cooling output. The three design-dependent KPIs complement this assessment by quantifying the spatial, mass, and cost implications of the selected configuration. Together, these indicators define what must be evaluated by the methodological framework developed in the next section.

An overview of the selected KPIs is provided in Table 3.1.

Table 3.1: Key Performance Indicators (KPIs)

No.	KPI	Description
Performance-based KPIs:		
1	Load Coverage	Degree to which the TEMS covers the total thermal demand of a scenario.
2	Coverage Durability	Classification of whether the demand is met continuously, only for a limited time through storage support, or not at all.
3	Usage Ratio	Degree to which each thermal subsystem is utilized relative to its reference capacity.
4	CHPC Efficiency	Combined heat, power, and cooling efficiency of the integrated TEMS under scenario-specific conditions.
Design-dependent KPIs:		
5	Volume Ratio	Ratio between the total TEMS volume and the yacht's Gross Tonnage (GT).
6	Mass Ratio	Ratio between the total TEMS mass and the yacht's Gross Tonnage (GT).
7	Cost Ratio	Ratio between the total TEMS cost and the yacht's Gross Tonnage (GT).

3.2. Method Identification

This section identifies the methodological framework used to evaluate the effectiveness of yacht Thermal Energy Management Systems (TEMS). Since the KPIs defined in Section 3.1 differ in nature, no single evaluation approach is sufficient on its own. The method must support both scenario-based performance assessment and direct design-based comparison, while remaining consistent with the methodology requirements defined in Section 2.3.

The final solution approach therefore combines *Multi-Criteria Decision Analysis* (MCDA) as the main evaluation framework with an adapted *Scenario-Based Reasoning* (SBR) approach for the performance-based KPIs. The design-dependent KPIs are evaluated through direct analytical calculations. Section 3.2.1 reviews these approaches, Section 3.2.2 assesses their compliance with the methodological requirements, and Section 3.2.3 explains how they are integrated into the final TEMS evaluation framework.

3.2.1. Review of Applicable Methodologies

Multi-Criteria Decision Analysis (MCDA)

Multi-Criteria Decision Analysis (MCDA) is a structured decision-making approach used to evaluate and compare alternatives based on multiple, often conflicting criteria. As described by Lin and Ren [41], MCDA provides a systematic framework for organizing data, assigning relative importance to criteria, and translating multiple criterion values into a transparent comparison between alternatives. This makes it suitable for engineering design problems in which technical, spatial, and economic considerations must be assessed together.

In its general form, MCDA consists of six main steps. First, the problem and the alternatives are defined. Second, the evaluation criteria are selected. Third, the criteria are weighted according to their relative importance. Fourth, the criteria values are determined. Fifth, the results are arranged into a decision matrix. Finally, the alternatives are compared through a scoring, ranking, or aggregation procedure.

For the present thesis, MCDA is well suited to act as the main evaluation framework because it can combine multiple KPIs into a consistent and traceable design comparison. However, by itself, MCDA remains essentially static. It does not natively describe how a system should be evaluated under multiple operating conditions, and it therefore requires a complementary approach for the performance-based KPIs.

Scenario-Based Reasoning (SBR)

Scenario-Based Reasoning (SBR) is used when system performance depends strongly on changing external conditions and cannot be represented adequately by a single reference case. As discussed by Comes et al. [42], scenario-based approaches support decision-making under uncertainty by evaluating alternatives across a set of plausible situations rather than under one assumed condition.

In its broadest form, SBR may involve qualitative storylines, causal links, and robustness analysis across alternative futures. In the present thesis, however, SBR is used in a more focused engineering sense. Its role is to structure the evaluation of the performance-based KPIs across a discrete set of representative operating scenarios defined by the main sources of variation affecting yacht TEMS behaviour. These sources of variation are operational profile, climate zone, occupancy level, and representative weather-parameter case.

Within this adapted use of SBR, each scenario defines one combination of those operating conditions. The TEMS is then evaluated under each scenario in steady-state form, and the resulting KPI values are aggregated using predefined weighting factors where appropriate. In this way, SBR adds the multi-scenario capability that a classical MCDA framework does not provide on its own.

Analytical Calculation

The design-dependent KPIs do not require scenario-based evaluation, because they depend on the physical and economic characteristics of the TEMS configuration itself rather than on operating conditions. For this reason, they are determined through direct analytical calculations based on component dimensions, installed mass, and estimated cost. Analytical calculations are therefore not a separate decision-making framework, but a supporting evaluation approach used within the broader MCDA structure.

Comparison between the Main Evaluation Approaches

Tables 3.2 and 3.3 compare the general steps of the classical MCDA framework with the adapted scenario-based extension used in this thesis for the performance-based KPIs.

Table 3.2: Classical MCDA Steps		Table 3.3: Adapted Scenario-Based Evaluation Steps	
Step	Description	Step	Description
1	Definition of the problem and alternatives.	1	Identification of scenario-defining variables.
2	Criteria (KPI) selection.	2	Assignment of scenario weighting factors.
3	Weight determination.	3	Construction of the scenario matrix.
4	Data evaluation and collection.	4	Scenario-specific KPI evaluation.
5	Matrix building.	5	Aggregation of scenario results.
6	Ranking or aggregation of alternatives.		

3.2.2. Assessment of Methodological Compliance

Table 3.4 assesses the capability of MCDA and the adapted SBR approach to satisfy the methodology requirements defined in Chapter 2. MCDA provides the overall multi-KPI comparison structure, while SBR provides the multi-scenario logic required for the performance-based KPIs. Used together, the two approaches satisfy the full set of requirements.

Table 3.4: Evaluation of MCDA and SBR Capabilities with Respect to the Defined Methodology Requirements

No.	Requirement	MCDA	SBR	Explanation
1	Multi-KPI effectiveness evaluation	✓	✗	MCDA structures the comparison of multiple KPIs within one framework. SBR does not aggregate multiple KPIs by itself.
2	Flexible KPI determination method	✓	✗	MCDA allows different KPI formulations and scales. SBR defines scenarios but does not determine KPI equations.
3	Multi-output decision support	~	✓	MCDA often leads to one final ranking, while SBR produces scenario-specific results before aggregation.
4	Comparative and traceable framework	✓	✓	MCDA provides transparent comparison rules, while the adapted SBR approach uses an explicit and repeatable scenario structure.
5	Data-driven and feasible within Feadship/DVNA	✓	~	MCDA works directly with available design data. The adapted SBR approach can also be supported by available operational and environmental data, although some scenario assumptions may still be required.
6	Steady-State Basis of Evaluation	✓	~	MCDA is compatible with steady-state design comparison. In this thesis, SBR is also applied through steady-state scenario evaluations, although this is imposed by the evaluation model rather than by SBR itself.
7	Multi-scenario evaluation capability	✗	✓	Classical MCDA does not natively define multi-scenario evaluation. SBR provides the required scenario-based structure.
8	Scenario- or Design-Dependent Evaluation Output	~	✓	MCDA supports final design-level comparison, while SBR naturally produces scenario-specific outputs that can be aggregated when needed.

MCDA: Multi-Criteria Decision Analysis; **SBR:** Scenario-Based Reasoning.

3.2.3. Adaptation to Yacht TEMS Evaluation

The final evaluation framework adopted in this thesis combines MCDA, adapted SBR, and analytical calculations into one coherent process. In its applied form, the method is structured as a four-step procedure tailored to yacht TEMS evaluation rather than as a direct sequence of generic MCDA steps. This applied structure is summarized in the next paragraphs and forms the basis of the case-study implementation presented in Chapter 4.

Step 1: Problem, objective, and KPIs definition

The first step defines the basis of the evaluation. It establishes the design problem, the objective of the assessment, and the KPI set through which TEMS effectiveness is evaluated. It also distinguishes between KPIs that act mainly as feasibility or diagnostic indicators and those retained for the final design comparison. In this way, the method separates the broad assessment of system behaviour from the reduced KPI set used for the final ranking.

Step 2: Scenarios definition for the performance KPIs

The performance-based KPIs require scenario-based evaluation because the thermal behaviour of the TEMS changes with the operating conditions. For this reason, the second step defines the scenario structure used in the assessment. This includes the identification of the scenario-defining variables, the assignment of scenario weighting factors, and the construction of the complete scenario matrix.

In the present thesis, the scenario-defining variables are the operational profile, climate zone, occupancy level, and representative weather-parameter case. Their combination provides the multi-scenario structure needed to evaluate whether the TEMS is thermally feasible, how long demand can be sustained, how strongly the subsystems are used, and how effective the integrated system is in terms of CHPC efficiency.

Step 3: Design selection and improvement loop

The third step represents the core iterative part of the method. Once a design has been selected, the input data required for its evaluation are collected. The performance-based KPIs are then evaluated through a scenario-based sequence in which the environmental conditions are first defined, the yacht thermal demand is estimated, the useful heat and cooling generation of the selected TEMS is calculated, and the KPI values are determined for each scenario. The resulting scenario-specific KPI values are then aggregated where required to obtain representative design-level results.

In parallel, the design-dependent KPIs are determined directly from static design data, namely the dimensions, installed mass, and estimated cost of the TEMS components. These values are then normalized by the yacht Gross Tonnage in order to produce comparable design indicators.

The outcome of this step can be used not only to assess the selected design, but also to identify possible improvements. The method therefore supports a structured design-improvement loop in which a revised TEMS configuration can be defined and evaluated again using the same procedure.

Step 4: Designs evaluation and ranking

The final comparison of the TEMS alternatives requires an additional normalization step, because the selected design-level KPIs are not directly comparable in their raw form. KPI IV is an efficiency-related performance indicator, while KPI V, KPI VI, and KPI VII are expressed as volume, mass, and cost ratios. These indicators also have different directions of preference: a higher CHPC Efficiency is favourable, whereas lower Volume Ratio, Mass Ratio, and Cost Ratio values are favourable. Without normalization, the final weighted score would be dominated by the numerical scale and unit of each KPI rather than by its relative design preference.

This normalization is deliberately applied at the end of the method, rather than being embedded in the KPI definitions. The reason is that the raw KPIs must remain physically interpretable. For example, the Volume Ratio should still indicate the installed TEMS volume per unit Gross Tonnage, and the Cost Ratio should still indicate the estimated system cost per unit Gross Tonnage. If the KPIs were normalized directly inside their formulation, they would become dependent on the set of alternatives being compared and would lose part of their diagnostic value. The method therefore first calculates the KPIs in their engineering form and only afterwards converts the selected design-level KPIs into dimensionless scores for the final MCDA ranking. A common approach in multi-criteria decision analysis is to normalize the selected KPIs and then combine them through a weighted additive model [43, 44].

Four candidate approaches were considered for this purpose: ratio-to-best normalization with weighted additive aggregation, min-max normalization with weighted additive aggregation, target-based normalization with weighted additive aggregation, and TOPSIS. Min-max normalization is simple and explicitly reflects the observed spread of the KPI values, but it can exaggerate small differences when only a very limited number of alternatives is available. By contrast, it becomes more informative when a larger number of alternatives is considered, since the observed range then better reflects the design space [45, 44]. Target-based normalization has a clear engineering interpretation, but it requires credible target and threshold values for each KPI [46, 47]. For this reason, the two preferred methods within the present framework are ratio-to-best and TOPSIS.

Ratio-to-best normalization with weighted additive aggregation normalizes each KPI relative to the best observed value among the available alternatives. For a benefit criterion, the normalized score is expressed as:

$$s_{ij} = \frac{x_{ij}}{\max(x_j)} \quad (3.12)$$

whereas for a cost criterion it becomes:

$$s_{ij} = \frac{\min(x_j)}{x_{ij}} \quad (3.13)$$

Once the KPI values have been normalized, the final score of design i is obtained through a weighted additive model:

$$S_i = \sum_{j=1}^m w_j s_{ij} \quad (3.14)$$

with

$$\sum_{j=1}^m w_j = 1 \quad (3.15)$$

where w_j is the weight assigned to KPI j . This aggregation produces one final score per design, and the alternatives are then ranked according to the value of S_i . The main advantages of this method are its simplicity, transparency, and ease of interpretation. It also preserves part of the magnitude of the observed differences between designs [46, 44]. Its main limitation is that it remains fully relative to the available design set and does not explicitly capture the full spread of each KPI.

TOPSIS (*Technique for Order Preference by Similarity to Ideal Solution*) ranks the alternatives according to their distance from an ideal best solution and an ideal worst solution [48, 49]. The method begins from a normalized decision matrix, which is then weighted according to the relative importance of each KPI. In simplified form, the weighted normalized score is written as

$$v_{ij} = w_j r_{ij} \quad (3.16)$$

where r_{ij} is the normalized value of criterion j for alternative i . The positive ideal solution is then formed from the best weighted criterion values, and the negative ideal solution from the worst ones. For each alternative, the distances to these two reference points are computed, and the relative closeness to the ideal solution is expressed as

$$C_i = \frac{D_i^-}{D_i^+ + D_i^-} \quad (3.17)$$

where D_i^+ is the distance from the positive ideal solution and D_i^- is the distance from the negative ideal solution. The preferred design is the one with the highest value of C_i , so this coefficient directly forms the basis of the final ranking. The strength of TOPSIS is that it simultaneously rewards closeness to the best attainable performance and remoteness from the worst. This makes it especially attractive when several alternatives are compared and the design space is sufficiently rich for the ideal and anti-ideal solutions to be informative. Its main limitation is that, like other relative methods, it remains sensitive to the composition of the available design set and to the normalization procedure adopted [44, 50].

Overall, both ratio-to-best and TOPSIS are suitable methods for the final design comparison, but they are better suited to different decision contexts. TOPSIS becomes more informative when a larger number of alternatives is available, because the ideal and anti-ideal solutions then represent a broader design space [48, 49]. By contrast, when only two designs are compared, ratio-to-best is generally more transparent and more robust, since it avoids constructing ideal reference points from an extremely limited option set. The framework therefore retains ratio-to-best as the preferred method for two-design comparisons and TOPSIS as the preferred method when a larger set of alternatives is available.

The overall evaluation process is illustrated in Figure 3.1. The diagram summarizes the applied four-step structure of the method and shows how the scenario-based evaluation of the performance KPIs is combined with the analytical evaluation of the design-dependent KPIs within the broader MCDA framework.

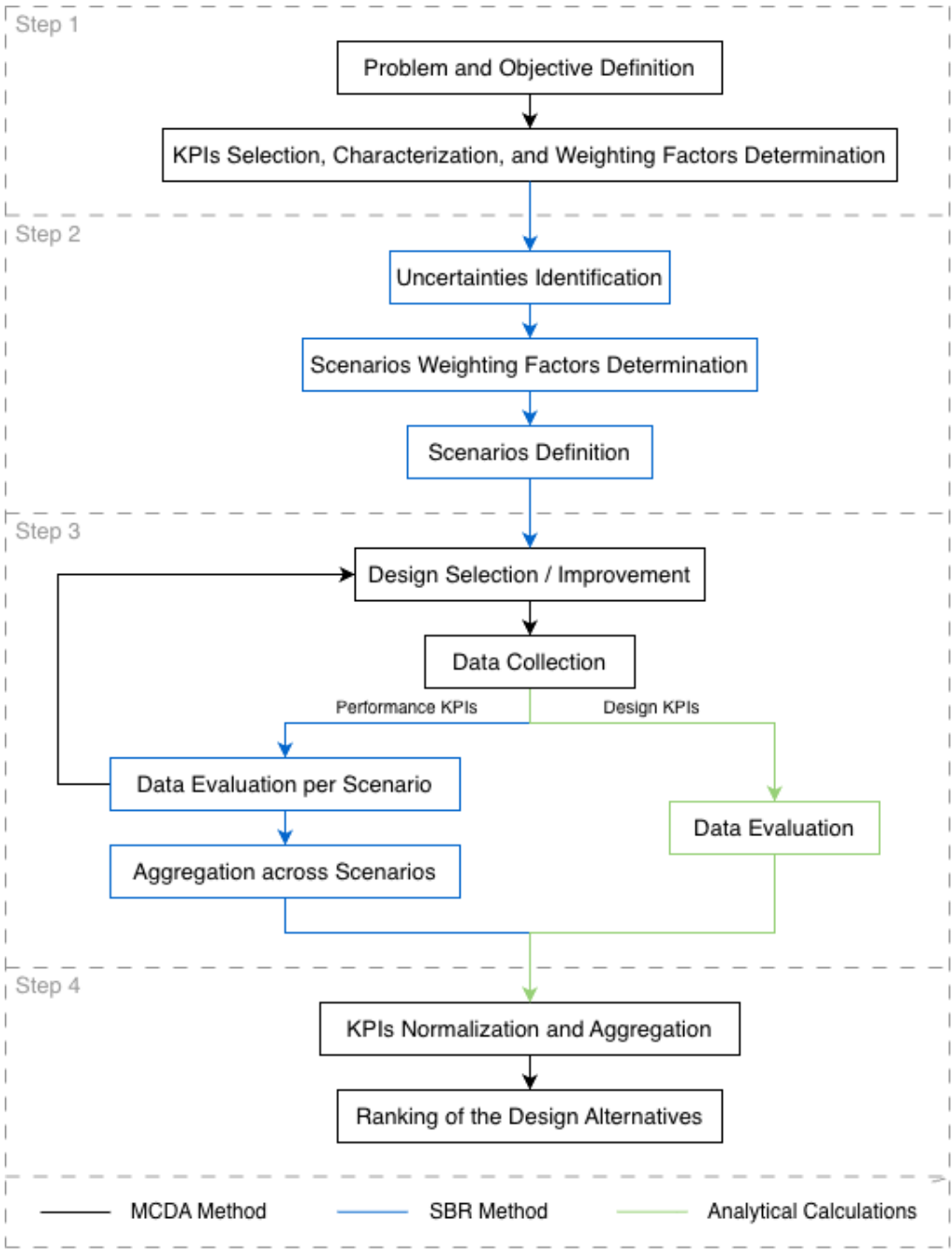


Figure 3.1: Overview of the applied four-step evaluation framework combining MCDA and SBR.

3.3. Overview of the Complete Evaluation Model

Sections 3.1 and 3.2 defined the KPIs and the methods used to evaluate them. This section brings these elements together by clarifying how the complete model should be interpreted. The aim is not only to obtain a final ranking, but also to generate intermediate results that explain why a TEMS design performs well or poorly under different operating conditions.

The complete model is structured as a multi-output evaluation framework. The first output level is the scenario-specific assessment of the performance-based KPIs. At this level, the TEMS is evaluated for each representative operating scenario in order to determine whether the required thermal demand is covered, whether storage support is needed, and which subsystems become highly loaded. These results are mainly used to assess feasibility, robustness, and system behaviour.

The second output level is the aggregated performance assessment. Since the scenario-specific results can be numerous, selected performance indicators are combined across scenarios using the scenario weighting factors. In this thesis, this aggregation is mainly relevant for CHPC Efficiency, which is retained as the representative performance KPI for the final comparison. Load Coverage, Coverage Durability, and Usage Ratio are still evaluated because they are necessary to interpret the design, but they are not used directly in the final ranking.

The third output level is the design-dependent assessment. This part of the model evaluates the spatial, mass-related, and economic implications of each TEMS configuration from static design data. These indicators do not vary between scenarios, but they are essential because a design with better thermal performance may also require more space, mass, or cost.

Finally, the selected design-level KPIs are normalized and combined through the chosen ranking method. This final step produces a concise comparison between alternative TEMS configurations. However, the final score should not be interpreted in isolation. It is a decision-support output that must be read together with the scenario-specific and diagnostic results, since these results reveal the causes of the final ranking and identify possible directions for design improvement.

The complete framework is illustrated in Figure 3.1. Table 3.5 summarizes the output structure of the model, while Table 3.6 clarifies the role of each KPI within the evaluation.

Table 3.5: Output structure of the complete evaluation model

Output level	Methodological basis	Main output	Role in the evaluation
Scenario-specific performance assessment	Adapted SBR and analytical thermal calculations	KPI values for each operating scenario	Tests feasibility, identifies critical scenarios, and explains subsystem behaviour.
Aggregated performance assessment	Scenario weighting and KPI aggregation	Representative design-level performance indicators	Condenses the scenario results into values that can support comparison between designs.
Design-dependent assessment	Analytical calculation from static design data	Volume Ratio, Mass Ratio, and Cost Ratio	Quantifies the spatial, mass-related, and economic impact of each TEMS configuration.
Final design comparison	MCDA normalization and aggregation / ranking	Final score or ranking coefficient per design	Compares the alternatives on a common basis while preserving the possibility to inspect the underlying KPI results.

Table 3.6: Allocation of KPIs within the complete evaluation model

No.	KPI	Category	Role in the framework
1	Load Coverage	Performance-based	Evaluates whether the TEMS covers the total thermal demand of each scenario. Used as a feasibility indicator.
2	Coverage Durability	Performance-based	Distinguishes whether the demand is met continuously, only for a limited time through storage support, or not at all. Used as a feasibility and robustness indicator.
3	Usage Ratio	Performance-based	Indicates how intensively the available thermal subsystems are used under each scenario. Used as a diagnostic indicator for identifying bottlenecks and improvement opportunities.
4	CHPC Efficiency	Performance-based	Evaluates the combined heat, power, and cooling performance of the integrated TEMS. Used as the representative performance KPI in the final design comparison.
5	Volume Ratio	Design-dependent	Quantifies the installed TEMS volume relative to vessel size. Included in the final design comparison as a spatial-impact indicator.
6	Mass Ratio	Design-dependent	Quantifies the installed TEMS mass relative to vessel size. Included in the final design comparison as a mass-impact indicator.
7	Cost Ratio	Design-dependent	Quantifies the estimated installed TEMS cost relative to vessel size. Included in the final design comparison as an economic-impact indicator.

This structure reflects the intended use of the evaluation model. The method first checks whether a design is technically feasible across the scenario set. It then identifies the scenarios and subsystems that limit performance. Finally, it combines the representative performance result with the design-dependent indicators in order to compare alternative TEMS configurations. In this way, the framework supports both design diagnosis and design ranking, rather than reducing the assessment to a single score without explanation.

On this basis, the next chapter explains how the proposed evaluation model is applied to the selected case study, including the definition of the scenarios, the collection of the required input data, and the implementation of the KPI calculations.

4. Method Application

This chapter addresses the third research sub-question: “*How can the selected KPI framework and evaluation methods be translated into an operational model for TEMS effectiveness evaluation, and what input data, scenario definitions, and assumptions are required for its implementation?*” It applies the evaluation framework developed in Chapter 3 to the selected yacht and shows how the proposed four-step procedure is implemented in practice. Whereas Chapter 3 defined the KPI structure, the scenario logic, and the overall ranking approach, this chapter translates them into an operational evaluation model by specifying the required inputs, assumptions, and calculation sequence. It begins by defining the problem, objective, and KPI set used for the application, then establishes the scenario structure adopted for the performance-based assessment. The chapter subsequently describes the design selection and improvement loop, including data collection and KPI evaluation, and finally presents the procedure used to combine the selected indicators into a final design ranking. The analyzed design alternatives and the corresponding results obtained from this application are presented in Chapter 5.

4.1. Step 1: Problem, Objective, and KPIs Definition

The first step establishes the case-study basis for the evaluation. This includes selecting the yacht used as reference case, defining the objective of the assessment, and specifying how the KPI framework from Chapter 3 is used in the present application.

4.1.1. Problem & Objective Definition

The yacht selected for the present case study is *Obsidian*, an 84.2 m custom motor yacht launched by Feadship in 2023, shown in Figure 4.1. Its main technical specifications are summarized in Table 4.1.



Figure 4.1: Picture of Feadship’s Obsidian Yachts (Hull 710), edited from [51].

The objective of the case study is to evaluate and improve the effectiveness of the yacht’s TEMS design. In particular, the method is applied to support the development of a design with improved thermal performance and CHPC efficiency, while ensuring that other relevant design aspects, such as cost, mass, and volume, remain feasible from an engineering perspective.

Table 4.1: Technical overview of M/Y *Obsidian* (Feadship)

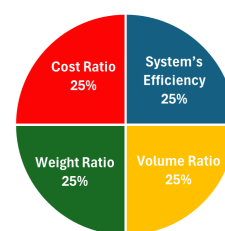
Parameter	Specification
Length overall (LOA)	84.2 m
Beam	13.65 m
Draft	3.75 m
Gross tonnage	2,554 GT
Guests	Up to 14 guests
Crew	27 crew
Propulsion concept	Diesel-electric hybrid / advanced electrical drive
Battery bank	4.5 MWh battery bank
Generators	2 × Caterpillar C32 ACERT DITTA-SCAC 873 kW at 2100 rpm, 2 × Caterpillar C32B 1461 kW at 2300 rpm
Propulsors / steering	Twin Veth contra-rotating thrusters (propulsion and steering)
Alternative fuel capability	HVO (Hydrotreated Vegetable Oil) biofuel
Cruising speed	12 kn
Top speed	17 kn
Range	5,500 nm at 12 kn

4.1.2. KPIs Selection, Characterization, and Weighting Factor Determination

For the present case study, the adopted KPI set is the one defined in Chapter 3. The performance-based KPIs are retained to assess whether the TEMS can meet the required thermal demand across the defined scenarios and to interpret how the system behaves under different operating conditions. The design-dependent KPIs are used to compare the physical and economic implications of the alternative TEMS configurations.

Not all KPIs, however, play the same role in the final comparison. Load Coverage, Coverage Durability, and Usage Ratio are evaluated for all scenarios because they provide essential information on feasibility, robustness, and subsystem utilisation. At the same time, their function in the present case study is mainly diagnostic. The final design-level comparison is instead based on CHPC efficiency together with the three design-dependent KPIs, namely Volume Ratio, Mass Ratio, and Cost Ratio.

The final aspect to be defined in this step is the relative importance assigned to the KPIs included in the final aggregation. In general, these weighting factors depend on project priorities and stakeholder preferences. In the present case study, however, equal weights are adopted in order to keep the comparison transparent and to avoid introducing an additional preference assumption at this stage. The weighting factors used in the final design comparison are shown in Figure 4.2.

**Figure 4.2:** KPI's Weighting Factors.

4.2. Step 2: Scenarios Definition for the Performance KPIs

The second step defines the scenarios used to evaluate the performance-based KPIs. Because these KPIs depend on operating and environmental conditions, the TEMS cannot be assessed through a single representative situation. Instead, its performance must be evaluated across a set of scenarios that captures the main sources of variation in yacht operation.

4.2.1. Uncertainties Identification

The first task in this step is to identify the uncertainties that define the operating scenarios. Four scenario-defining uncertainties are considered: operational profile, climate zone, occupancy level, and weather-parameter case.

The operational profile describes the yacht's mode of operation. It affects the environmental interaction conditions adopted in the model, the systems that are active on board, and therefore both the thermal demand and the heat or cooling generation potential of the TEMS. The climate zone defines the external operating environment and determines the weather conditions used in the evaluation, such as ambient air temperature and seawater temperature, which directly influence thermal loads and system performance. The occupancy level represents the internal load condition on board and affects the required heating and cooling demand, the target temperature requirements, and the operation of specific subsystems.

A fourth scenario-defining element is the weather-parameter case. For each climate-zone and operational-profile combination, four representative environmental cases are retained: *Min*, *Max*, *Mode 1*, and *Mode 2*. These correspond respectively to the lowest observed combination of air and seawater temperatures, the highest observed combination, the most frequent combination, and the second most frequent combination. In this way, the performance assessment includes both boundary conditions and the most representative recurring operating conditions. The corresponding relative humidity values are retained together with each temperature case and are used in the subsequent psychrometric calculations. Together, these four uncertainties define the main operating variations that must be captured in the performance assessment.

4.2.2. Scenarios Weighting Factors Determination

Once the scenario-defining uncertainties have been identified, weighting factors must be assigned to their respective levels. These weighting factors represent the fraction of time the yacht is expected to spend in each operational profile, climate zone, and occupancy level. In principle, such values may be derived from different sources, including literature, Automatic Identification System (AIS data) from a comparable yacht or fleet, operational statistics, or customer-specific assumptions. Within the scope of this thesis, the weighting factors are based on the most representative information available.

The weighting factors associated with the operational profiles were derived directly from the Feadship fleet-average AIS dataset used in this study. This dataset provides an estimate of the fraction of time spent in harbour, at anchor, and underway, and therefore offers a suitable basis for defining the operational-profile distribution. The service-time category identified in Chapter 2 is therefore not treated as a separate operational profile in the scenario definition, but is considered to be sufficiently represented within the low-activity harbour conditions.

In principle, the same AIS-based approach could also have been extended to derive weighting factors for climate-zone distribution and onboard occupancy level. However, this would have required additional processing and classification work beyond the intended scope of the thesis. For this reason, the weighting factors for climate zone and occupancy level were defined through project-specific assumptions informed by published evidence on superyacht operating patterns.

More specifically, the climate-zone distribution was based on sources indicating that the Mediterranean remains the dominant superyacht cruising region for most of the year, while the Caribbean acts as the main secondary winter basin and transatlantic passages occur primarily as seasonal repositioning legs [52, 53]. Similarly, the occupancy-level distribution was informed by evidence showing that superyachts carry crew year-round, whereas owners and guests are on board for a much smaller fraction of the year. This suggests that low-occupancy conditions are likely to dominate annual operation [54, 55].

The adopted weighting factors for climate zone and occupancy level should therefore be interpreted as engineering assumptions supported by available sector evidence, rather than as direct outputs of a dedicated AIS-based analysis.

4.2.3. Scenarios Definition

After defining the uncertainties and their associated weighting factors, the scenarios can be constructed. In the implemented method, each scenario is defined as one unique combination of operational profile, climate zone, occupancy level, and weather-parameter case. The complete scenario set is therefore obtained by combining all levels of these four scenario-defining elements. This leads to a total of $7 \times 3 \times 3 \times 4 = 252$ scenarios.

Each scenario is associated with an overall weighting factor, obtained by combining the weighting factors of its corresponding operational profile, climate zone, and occupancy level. The four weather-parameter cases – here named *Min*, *Max*, *Mode 1*, and *Mode 2* – are instead used to represent the environmental variability within each operating combination. In this way, the later aggregation of the performance-based KPIs reflects not only how the TEMS performs under each individual condition, but also how representative each condition is within the expected annual operation of the yacht.

The identified uncertainties, their discrete levels, and the corresponding weighting factors are summarized in Table 4.2.

Table 4.2: Scenario-defining uncertainties and associated weighting factors

Uncertainty	Level / Case	Weighting factor
Climate zone	Atlantic Crossing	6.00%
	Caribbean	18.00%
	West Mediterranean	40.00%
	West–East Mediterranean	3.00%
	East Mediterranean	20.00%
	Hong Kong	5.00%
	Middle East	8.00%
Operational profile	At anchor	35.00%
	Sailing	9.00%
	Harbour	56.00%
Occupancy level ^a	Low	61.00%
	Medium	10.00%
	High	29.00%

^a Low = crew only; Medium = crew plus half guests; High = full occupancy.

4.3. Step 3: Design Selection and Improvement Loop

Steps 1 and 2 define the problem, the evaluation objective, the KPIs, and the scenarios used for the performance assessment. Step 3 applies this framework to a specific TEMS design and forms the core iterative part of the method. In this step, a design is selected, the data required for its evaluation are collected, and the relevant KPIs are calculated. The outcome of this evaluation is then used to identify possible improvements and, if necessary, to define a revised design for a new iteration.

4.3.1. Design Selection / Improvement

The first task in this step is to select the initial TEMS design to be evaluated. This design may be derived from a similar reference yacht or developed specifically during the early design stage, as is commonly done within DVNA. Here, the starting point is a realistic TEMS configuration defined to represent as closely as possible the system installed on the selected yacht.

The selected baseline design is based on the main thermal pathways of the yacht's TEMS. In the underlying system architecture, these pathways are associated with the high-temperature (HT) side, where recoverable engine heat is available from the engines; the low-temperature (LT) side, where heat can be rejected to seawater; and the recovery side, where useful heat is transferred to onboard consumers. In this chapter, however, the design is introduced through a simplified Thermal Energy Flow Diagram (TEFD), shown in Figure 4.3. The figure should therefore be interpreted as a thermal energy-flow representation of the modelled sources, conversion units, and users, rather than as a detailed circuit or piping diagram.

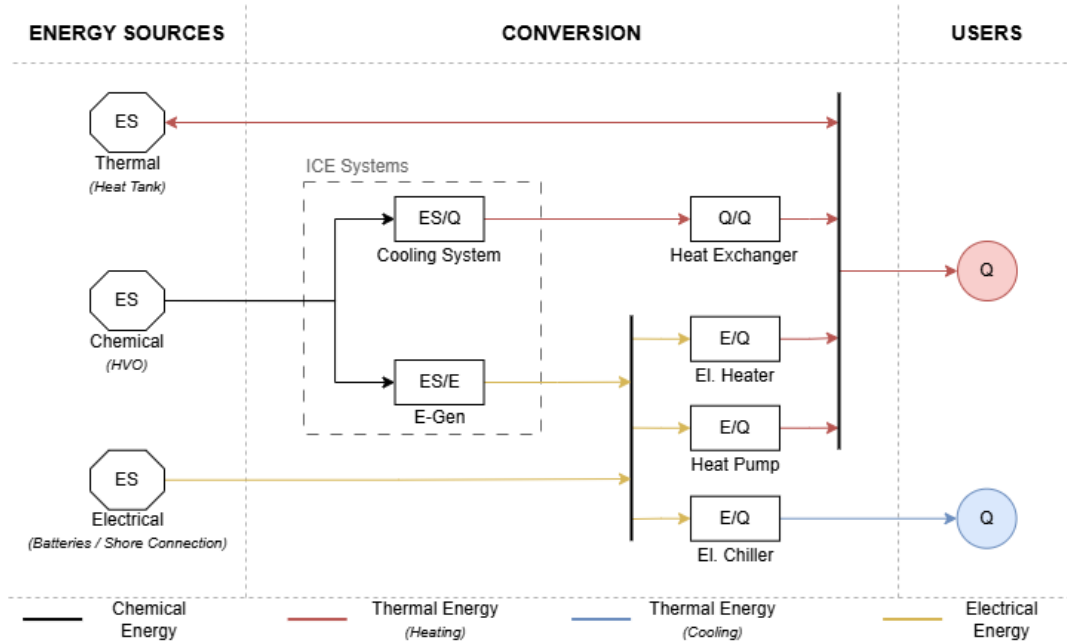


Figure 4.3: Thermal Energy Flow Diagram of Design 1

This initial energy-flow representation serves as the reference design for the first evaluation cycle. After its performance has been assessed, the same procedure can be repeated for an improved configuration. In this way, the method supports a structured design-improvement loop in which each new iteration is evaluated against the same problem definition, KPI structure, and scenario set.

4.3.2. Data Collection

Once a TEMS design has been selected, the input data required for its evaluation must be collected. These data provide the basis for the calculation of both the performance-based and the design-dependent KPIs. They include environmental data, design-specific technical data, and the weighting factors used to represent the expected operating distribution of the yacht.

Table 4.3 summarizes the main input data used in the application of the method, together with their source and an indicative assessment of their reliability. Environmental data such as air temperature, relative humidity, and seawater temperature are treated as high-reliability inputs because they are based on established datasets. In contrast, the scenario weighting factors and some design-specific technical parameters rely partly on engineering assumptions or manufacturer information, and therefore involve a greater degree of uncertainty.

Table 4.3: Overview of the collected input data

Data item	Source	Reliability
Air temperature and relative humidity at 10 m across multiple climate zones and operational profiles	Feadship fleet-average AIS dataset	High
Sea surface water temperature across multiple climate zones	Copernicus Climate Data Store (satellite-based observations)	High
TEMS technical specifications	Feadship, manufacturers	Moderate
Scenario weighting factors	Feadship fleet-average AIS dataset, [52, 53, 54, 55]	Moderate / Low

4.3.3. Performance KPIs: Data Evaluation and Aggregation

Once the required input data have been collected, the performance-based KPIs can be evaluated. As defined in Chapter 3, these KPIs are assessed through a scenario-based approach, since the thermal behaviour of the TEMS depends on the operating conditions represented by the scenario set introduced in Step 2.

The evaluation of the performance-based KPIs is carried out through four main stages. First, a weather-parameter matrix is constructed for all scenarios. Second, the total yacht heat demand is determined for each scenario. Third, the selected TEMS design is modelled in order to estimate the useful heat and cooling that can be generated under those same conditions. Finally, the resulting demand and generation outputs are combined to evaluate the performance KPIs on a scenario-by-scenario basis.

Once the KPIs have been determined for a given design, the scenario results are analysed to identify the conditions under which the system performs well or poorly. This provides the basis for design improvement. In the following iteration, the weather-parameter matrix and the heat-demand model remain unchanged, since they are linked to the problem definition and not to the design itself. What changes is the TEMS configuration used in the heat-generation model, together with the corresponding KPI calculations where needed. In this way, the same evaluation framework can be repeated for a revised design and used to support a structured improvement loop. Both the baseline design and the first improved design are analysed in Chapter 5.

After the performance KPIs have been calculated for all scenarios of a given design, the scenario-based results are aggregated using the weighting factors defined in Step 2. This leads to one representative result for each performance KPI and allows the overall thermal behaviour of the design to be compared in a structured and traceable way. The four stages of this evaluation process are described in the following subsections.

1. Weather Parameters Matrix

The first stage consists of constructing a weather-parameter matrix containing the environmental data required for each scenario. This matrix is used both to determine which systems are activated under the corresponding conditions and to derive additional thermodynamic properties, such as moist-air enthalpy.

More specifically, the air temperature and relative humidity at a height of 10 m are obtained from a fleet-average AIS-based dataset built from Feadship yachts equipped with the relevant sensors. The use of data at this height is consistent with the fact that yacht air inlets are typically located high in the superstructure. The seawater temperature is taken from the Copernicus Climate Data Store dataset *Global sea surface temperature derived from satellite observations* [56].

Moist-air enthalpy is calculated from dry-bulb temperature and relative humidity using standard psychrometric relations, expressed per unit mass of dry air [57, 58]. First, the saturation vapour pressure is estimated using the August–Roche–Magnus approximation:

$$p_{ws} = 610.94 \exp \left(\frac{17.625 T}{T + 243.04} \right) \quad (4.1)$$

The actual water-vapour pressure is then obtained as

$$p_w = \phi p_{ws} \quad (4.2)$$

from which the humidity ratio is determined:

$$x = \frac{0.621945 p_w}{p - p_w} \quad (4.3)$$

Finally, the moist-air enthalpy is computed as

$$h = 1.006 T + x (2501 + 1.86 T) \quad (4.4)$$

where h is the moist-air enthalpy in kJ kg^{-1} of dry air, T is the dry-bulb temperature in $^{\circ}\text{C}$, ϕ is the relative humidity expressed as a fraction, p_{ws} is the saturation vapour pressure in Pa, p_w is the partial pressure of water vapour in Pa, x is the humidity ratio in $\text{kg}_{\text{wv}}/\text{kg}_{\text{da}}$, and p is the atmospheric pressure in Pa. Equation 4.4 represents the sum of the sensible enthalpy of dry air and the latent and sensible enthalpy contributions of the water vapour. In the implemented script, p is assumed constant and equal to standard sea-level pressure, 101325 Pa. This formulation is suitable for standard engineering psychrometric calculations, while the Magnus approximation is generally considered valid over typical atmospheric temperature ranges [57, 58].

The resulting air and seawater data are then combined into a single scenario-based matrix that serves as input for the subsequent demand calculations. Table 4.3 summarizes the data sources used, while the complete weather-parameter matrix and the temperature profiles by climate zone and operational profile are reported in Appendix A and B, respectively.

2. Yacht's Heat Demand Estimation

Once the weather parameters have been defined for all scenario combinations and for the four representative weather-parameter cases, the yacht's thermal demand can be estimated. This is done by considering which heat-using systems are active under each operational profile and occupancy level, and by evaluating the corresponding heating or cooling requirements under the scenario-dependent environmental conditions.

For this purpose, three pre-existing workbooks are used. These are the same subsystem models that were originally employed to define the starting TEMS design. More specifically, one workbook is used for the domestic hot water system, one for the HVAC system, and one for the swimming-pool system. The Python routine does not perform the underlying physical calculations directly. Instead, it provides the scenario-dependent boundary conditions to the workbooks and retrieves the resulting thermal demand. In this way, the Excel models act as subsystem calculation modules, while the script acts as the scenario manager that links environmental conditions, operational profile, and occupancy level to the corresponding demand output.

For each scenario, the boundary conditions are taken from the weather-parameter matrix. Depending on the operational profile, the script extracts the outdoor air state at the relevant height, the corresponding moist-air enthalpy, and the seawater temperature. These quantities are then passed to the workbooks according to the role they play in each subsystem. The domestic hot water and swimming-pool models use the scenario water temperature as inlet or source temperature, whereas the HVAC model uses the outdoor air state together with a corresponding supply-air condition.

a. Domestic hot water workbook The domestic hot water workbook determines the thermal demand through a fixture-based representation of the yacht's potable-water system. Its logic is based on three main elements: the installed fixtures, their characteristic water flows, and a simultaneity correction used to represent realistic peak operation.

First, the workbook defines the sanitary fixtures present on board, such as showers, washbasins, sinks, dishwashers, toilets, and laundry equipment. For each fixture type, a delivery flow rate, a use temperature, and a duration of use are assigned. The total number of fixtures is then introduced through grouped accommodation and service-area layouts. In physical terms, the workbook starts from the basic heating relation

$$Q = mc_p \Delta T \quad (4.5)$$

applied to the water drawn by each fixture during a representative use event.

For fixture i , the corresponding thermal energy requirement is expressed as

$$Q_i = n_i \rho_i c_p \dot{V}_i \Delta T_i t_i \quad (4.6)$$

where n_i is the number of fixtures of that type, ρ_i is the water density at the delivery temperature, c_p is the specific heat capacity of water, $\dot{V}_i$ is the fixture flow rate, t_i is the duration of use, and

$$\Delta T_i = T_i - T_{\text{cold}} \quad (4.7)$$

In the workbook, the specific heat capacity of water is treated as $c_{p,w} = 4.18 \text{ kJ}/(\text{kg K})$, while the water density is taken from the workbook property data for the relevant water temperature. A key feature of the workbook is that the cold-water inlet temperature is not treated as constant. Instead, the scenario water temperature supplied by the Python routine is used as boundary condition. As a result, the domestic hot water demand varies with the scenario-dependent seawater temperature: colder inlet water leads to a higher required temperature lift and therefore to a higher heating demand. The hot water outlet, instead, is not scenario-dependent, but system-dependent.

To avoid the unrealistic assumption that all fixtures operate simultaneously at full flow, the workbook applies a Hunter-type simultaneity approach based on tap units. The total simultaneous demand flow is expressed as

$$\dot{V}_{\text{H,tot}} = \frac{300 \sqrt{\sum TU_i}}{3600} \quad (4.8)$$

where TU_i denotes the tap-unit contribution of fixture i , and the factor $300/3600 = 0.083 \text{ L/s}$ is the reference fixture flow used to convert fixture flows into tap units. This total simultaneous flow is then distributed over the individual fixtures proportionally to their characteristic flow rates, yielding a simultaneous design flow for each fixture category.

The corresponding domestic hot water power demand is obtained from

$$\dot{Q}_{\text{DW}} = \sum_i \rho_i c_p \dot{V}_{i,\text{H}} \Delta T_i \quad (4.9)$$

where $\dot{V}_{i,\text{H}}$ is the Hunter-based simultaneous flow assigned to fixture i . This is the output used in the overall demand model. Although the workbook also includes auxiliary calculations, such as total heating energy and boiler volume, the script extracts the simultaneous thermal power, since this is the relevant quantity for the scenario-based comparison.

b. HVAC workbook The HVAC workbook determines the thermal demand by combining an air-side psychrometric calculation with a room-level cooling-load aggregation for local fan-coil units. Its structure is therefore based on two complementary parts: the ventilation and air-handling requirement, and the internal room loads.

The first step is the determination of the air quantities. For each room or zone, the enclosed volume is calculated from

$$V_r = A_r H_r \quad (4.10)$$

where A_r is the floor area and H_r is the room height. A required air-change rate is then assigned according to room type, so that the supply airflow becomes

$$\dot{V}_{\text{sup},r} = N_r V_r \quad (4.11)$$

where N_r is the prescribed number of air changes per hour.

The workbook then separates the total supplied air into exhaust air, recirculated air, and fresh air. In simplified form, the recirculated fraction is taken as the part of the supply stream that remains after the exhaust requirement has been satisfied:

$$\dot{V}_{\text{rec},r} = \max(\dot{V}_{\text{sup},r} - \dot{V}_{\text{exh},r}, 0) \quad (4.12)$$

The fresh-air requirement is assigned through room-type rules and, for specific spaces such as the galley, through dedicated ventilation constraints.

Once the airflow distribution is known, the workbook evaluates the air-handling load from moist-air enthalpy differences rather than from dry-bulb temperature alone. This is an important methodological choice, because enthalpy captures both sensible and latent effects. The heating or cooling duty associated with the air-handling unit is calculated as

$$\dot{Q}_{\text{AHU}} = \rho_{\text{air}} \left(\frac{\dot{V}_{\text{rec}}}{3600} \right) (h_{\text{in}} - h_{\text{sup}}) + \rho_{\text{air}} \left(\frac{\dot{V}_{\text{fa}}}{3600} \right) (h_{\text{out}} - h_{\text{sup}}) \quad (4.13)$$

where $\dot{V}_{\text{rec}}$ and $\dot{V}_{\text{fa}}$ are the total recirculated and fresh-air flow rates in m^3/h , and h_{in} , h_{out} , and h_{sup} are the indoor, outdoor, and supply-air enthalpies. In the workbook, the air density is treated as a fixed value of $\rho_{\text{air}} = 1.2 \text{ kg}/\text{m}^3$.

In the implemented HVAC model, the heating or cooling demand is determined not only by the thermodynamic state of the air, but also by the required ventilation flow rates. The indoor design condition is prescribed in the workbook as the target comfort state, whereas the outdoor air state is scenario-dependent and imported from the weather data. In addition, the supply-air state is selected externally through a lookup routine and passed to the workbook. The resulting HVAC load is therefore governed by both the air-state differences and the occupancy- and operational-profile-specific ventilation configuration embedded in the workbook, which defines the required supply, exhaust, recirculation, and fresh-air flow rates for the conditioned spaces.

The second component of the HVAC demand is the local room load handled by fan-coil units. For each space, the workbook sums the internal equipment or room loads according to

$$\dot{Q}_{\text{FCU}} = \sum_r \dot{Q}_{\text{int},r} \quad (4.14)$$

The resulting load is then matched to an appropriate fan-coil size through embedded equipment tables.

The total HVAC thermal demand returned by the workbook is therefore

$$\dot{Q}_{\text{HVAC}} = \dot{Q}_{\text{AHU}} + \dot{Q}_{\text{FCU}} \quad (4.15)$$

Strictly speaking, the workbook is organised as a chiller-dimensioning tool, so the result is expressed as a required HVAC capacity. Nevertheless, because the air-side term is enthalpy-based, the formulation remains physically meaningful under both cooling-dominated and heating-dominated conditions.

c. Swimming-pool workbook The swimming-pool workbook estimates the heating demand required to bring the pool water from its initial condition to the target pool temperature. The workbook is not used as a detailed dynamic simulation of pool operation. Instead, it converts the pool-heating process into an equivalent thermal power demand, expressed in kW, which can be added to the domestic hot water and HVAC demands in the scenario-based heat-demand matrix.

The first step is the definition of the pool geometry. The workbook represents the pool through an equivalent rectangular geometry, from which the pool volume V_{pool} and the free-surface area A are obtained. These quantities are fixed for a given workbook. The target pool-water temperature, the pool heater capacity, the air velocity above the water surface, and the relative-humidity assumption are also treated as fixed workbook inputs. The scenario-dependent inputs supplied by the Python routine are the ambient air temperature used in the heat-loss calculation and the source-water temperature used as the initial water temperature. In the implementation, the ambient air temperature is rounded to the nearest design value used by the workbook lookup tables, while the source-water temperature is passed from the weather-parameter matrix.

The starting point of the calculation is the sensible energy required to heat the pool water. If the initial water temperature is T_{in} and the target pool-water temperature is T_{pool} , the required heating energy is

$$Q_{\text{req}} = \rho c_p V_{\text{pool}} (T_{\text{pool}} - T_{\text{in}}) \quad (4.16)$$

where ρ and c_p are the density and specific heat capacity of water, respectively. The same water-property convention introduced for the domestic-water workbook is used here. In this expression, V_{pool} and T_{pool} are fixed workbook inputs, while T_{in} changes with the scenario-dependent source-water temperature. Colder source water therefore increases the energy required to bring the pool to its target temperature.

During the heating process, the pool also loses heat to the environment. These losses reduce the net heating rate available to increase the pool-water temperature, and therefore affect the heating time. The total heat loss is calculated as the sum of evaporation, radiation, and convection or conduction:

$$\dot{Q}_{\text{loss}} = \dot{Q}_{\text{evap}} + \dot{Q}_{\text{rad}} + \dot{Q}_{\text{conv}} \quad (4.17)$$

The evaporative heat loss is based on the humidity-ratio difference between saturated air at the pool-water temperature and the ambient air:

$$\dot{Q}_{\text{evap}} = A (25 + 19v) (\omega_{\text{sat},w} - \omega_a) \frac{h_{fg} 1000}{3600} \quad (4.18)$$

where A is the pool surface area, v is the air velocity above the water surface, $\omega_{\text{sat},w}$ is the humidity ratio of saturated air at the pool-water temperature, ω_a is the humidity ratio of the ambient air, and h_{fg} is the latent heat of evaporation. In the workbook, A , v , T_{pool} , and the relative-humidity assumption are fixed, while ω_a changes with the scenario-dependent ambient air temperature.

The radiative heat loss is calculated using the Stefan–Boltzmann relation:

$$\dot{Q}_{\text{rad}} = \varepsilon \sigma A \left[(T_w + 273)^4 - (T_a + 273)^4 \right] \quad (4.19)$$

where ε is the emissivity, σ is the Stefan–Boltzmann constant, T_w is the pool-water temperature, and T_a is the ambient air temperature. Since the pool-water temperature is fixed at its target value, the scenario influence enters mainly through T_a .

The convective or conductive heat loss is represented through an overall heat-transfer coefficient:

$$\dot{Q}_{\text{conv}} = UA(T_w - T_a) \quad (4.20)$$

where U is the overall heat-transfer coefficient derived from the thermal resistances included in the worksheet. This simplified formulation accounts for the heat transfer through the pool boundary and insulation layers. As with the radiative term, the scenario effect enters through the ambient air temperature.

After the required heating energy and the heat losses have been determined, the workbook calculates the heating time. This time depends on the energy still to be supplied and on the net heating power available after pool heat losses have been deducted from the heater capacity:

$$t_{\text{heat}} = \max\left(\frac{Q_{\text{req}} - Q_{\text{boiler}}}{\dot{Q}_{\text{heater}} - \dot{Q}_{\text{loss}}}, 0\right) \quad (4.21)$$

where Q_{boiler} is the energy contribution that can be supplied by available boiler volume, $\dot{Q}_{\text{heater}}$ is the installed pool-heater capacity, and $\dot{Q}_{\text{loss}}$ is the continuous pool heat loss. In the workbook used for the present application, the available boiler contribution for pool heating is set to zero. The heating time is therefore governed mainly by the required pool-heating energy, the fixed heater capacity, and the scenario-dependent heat losses.

The workbook then reports the equivalent pool-heating power associated with this heating process. This conversion follows the same energy-rate relation used elsewhere in the model, so it is not introduced as an additional governing equation here. The resulting value is extracted by the Python routine as the swimming-pool thermal demand and added to the domestic hot water and HVAC demands. The workbook also contains supporting calculations, such as hot-water mixing and drain-time checks, but these are not used as separate outputs in the scenario-based heat-demand model.

Together, the domestic hot water, HVAC, and swimming-pool workbooks provide the scenario-based thermal demand used in the subsequent heat-generation and KPI calculations. The complete heat-demand results for all scenarios are reported in Appendix C, with the corresponding graphical representation provided in Appendix D.

3. Yacht's Heat Generated Calculation

Once the scenario-based thermal demand has been determined, the next stage is to estimate the useful heat and cooling that can be generated by the selected TEMS design under the same operating conditions. The heat-generation model is implemented as a scenario-based steady-state calculation routine. Its purpose is not to reproduce the detailed control sequence of the thermal-energy system, but to determine, for each scenario, how much of the onboard thermal demand can be covered by the available heat sources and conversion units, how much energy is lost during conversion, and how much residual heat must be rejected to the environment.

For each scenario, the model takes as input the previously calculated thermal demands of the domestic hot water system, the HVAC system, and the swimming pool, together with the relevant environmental boundary conditions and the operational profile. The primary scenario-dependent inputs can therefore be written as

$$T_{\text{air},10}, \quad T_{\text{sea}}, \quad \dot{Q}_{\text{DWS}}, \quad \dot{Q}_{\text{HVAC}}, \quad \dot{Q}_{\text{pool}} \quad (4.22)$$

supplemented by the operating mode associated with the scenario.

The method assumes that the recoverable thermal energy available on board is known for each operational profile. Rather than deriving this quantity from a detailed machinery model, the script uses predefined heat-source values that represent the thermal energy that can be recovered under the corresponding operating condition. The model is therefore based on the assumption that the thermal

source terms are available *a priori* and can be combined with the scenario-dependent demand data in a steady-state balance.

The first step in the calculation is the definition of the required thermal service. Depending on the environmental conditions, the total demand is separated into a heating requirement and, where applicable, a cooling requirement. In the present model, this distinction is made on the basis of the outdoor air temperature. When the ambient temperature exceeds a prescribed threshold, the HVAC demand is treated as a cooling load, whereas the domestic hot water and swimming-pool demands remain heating loads. Under lower outdoor temperatures, the HVAC demand is added to the heating side. In simplified form, the cooling requirement can therefore be written as

$$\dot{Q}_{\text{cool,req}} = \begin{cases} \dot{Q}_{\text{HVAC}}, & T_{\text{air},10} > 21^\circ\text{C} \\ 0, & T_{\text{air},10} \leq 21^\circ\text{C} \end{cases} \quad (4.23)$$

while the heating requirement becomes

$$\dot{Q}_{\text{heat,req}} = \begin{cases} \dot{Q}_{\text{DWS}} + \dot{Q}_{\text{pool}}, & T_{\text{air},10} > 21^\circ\text{C} \\ \dot{Q}_{\text{HVAC}} + \dot{Q}_{\text{DWS}} + \dot{Q}_{\text{pool}}, & T_{\text{air},10} \leq 21^\circ\text{C} \end{cases} \quad (4.24)$$

The total required thermal service is then defined as

$$\dot{Q}_{\text{req}} = \dot{Q}_{\text{heat,req}} + \dot{Q}_{\text{cool,req}} \quad (4.25)$$

The available thermal sources are then passed through a set of conversion stages. Each stage is represented in the model by a maximum capacity and, where relevant, by a fixed efficiency or coefficient of performance. In general form, the useful thermal output of a conversion step is written as

$$\dot{Q}_{\text{useful}} = \eta \dot{Q}_{\text{in}} \quad (4.26)$$

where η is the relevant efficiency and $\dot{Q}_{\text{in}}$ is the thermal or electrical input to the process. For electrically driven thermal production, the input-output relation is represented through

$$P = \frac{\dot{Q}}{COP} \quad (4.27)$$

where COP denotes the coefficient of performance.

A key feature of the method is that it explicitly distinguishes between available energy and useful delivered energy. Not all recoverable heat can be fully utilized, because the conversion stages are constrained by finite capacities and non-ideal efficiencies. The difference between the energy entering a conversion stage and the useful thermal output is treated as a loss term:

$$\dot{Q}_{\text{loss}} = \dot{Q}_{\text{in}} - \dot{Q}_{\text{useful}} \quad (4.28)$$

This formulation makes it possible to evaluate not only the useful heat and cooling supplied to the onboard consumers, but also the thermodynamic penalty associated with the conversion process.

After the available useful outputs have been determined, they are compared with the scenario demand. The resulting balance can be written in general form as

$$\dot{Q}_{\text{unmet}} = \max(\dot{Q}_{\text{req}} - \dot{Q}_{\text{prov}}, 0) \quad (4.29)$$

where $\dot{Q}_{\text{prov}}$ is the total useful thermal output provided by the onboard system. In this way, the model identifies whether the scenario demand can be fully covered or whether a remaining thermal deficit exists.

If a residual heating deficit remains, the method allows additional support from thermal storage. This storage is represented as an energy-limited backup source rather than as a dynamic storage model. Its contribution is therefore evaluated through

$$t = \frac{E}{P} \quad (4.30)$$

where E is the stored thermal energy and P is the thermal power required from storage. This means that storage is used only to assess whether, and for how long, a remaining heating gap can be supported under the scenario considered.

4. KPIs Evaluation

The final stage of the performance assessment consists of converting the outputs of the heat-demand and heat-generation models into KPI values for each scenario. The KPI definitions themselves were already established in Section 3.1. At this stage, those definitions are applied using the scenario results produced by the implemented calculation routine.

More specifically, the KPI evaluation uses as input the total scenario demand obtained from the demand model, together with the useful heating and cooling delivered by the TEMS, the possible contribution of thermal storage, the corresponding storage-supported duration, and the relevant auxiliary power terms obtained from the heat-generation model. The KPI routine therefore acts as a post-processing step: it does not introduce new thermal calculations, but translates the previously calculated scenario balances into performance indicators.

Only the first four KPIs are evaluated here, since these correspond to the performance-based indicators.

KPI I: Load Coverage KPI I is calculated by applying the Load Coverage definition introduced in Equation 3.1, using the total scenario demand from the heat-demand model and the total useful thermal service provided by the heat-generation model. The provided thermal service is assembled according to Equation 3.3, that is, by combining useful heating, useful cooling, and any useful contribution from thermal storage. In practice, this KPI indicates whether the thermal service delivered under a given scenario is sufficient to cover the required demand.

KPI II: Coverage Durability KPI II is determined by applying the classification logic already defined through Equations 3.2 and 3.4. The script first checks whether the demand can be covered without storage support. If this is not possible, it then checks whether the remaining gap can be bridged by the available thermal storage and, if so, for how long. The scenario output is therefore expressed either as *Unlimited*, as a storage-supported duration, or as *Unable*. This preserves the temporal meaning of the KPI while keeping it directly linked to the scenario results obtained from the heat-generation routine.

KPI III: Usage Ratio KPI III is evaluated by relating the useful output of each active subsystem to its corresponding reference capacity, following Equation 3.5. For the thermal-storage branch, the ratio is based on the storage-supported duration and the reference recharge time, as defined in Equation 3.6. In the implementation, this KPI is used to identify which thermal-service pathways are most heavily utilized under the different scenarios and to highlight subsystems that may become critical during operation.

KPI IV: CHPC Efficiency KPI IV is evaluated by applying the CHPC Efficiency formulation defined in Chapter 3. The useful generated thermal service is first identified according to Equation 3.2, which excludes the contribution of thermal storage. The KPI is then calculated using either Equation 3.7 or Equation 3.8, depending on the operational profile and on the way the corresponding energy inputs

are represented in the model. In this way, the efficiency metric remains consistent with the available energy-balance information for each scenario.

Once the scenario-level KPI values have been obtained, they are combined using the weighting factors defined in Step 2 in order to produce representative design-level outputs. For KPI I, KPI III, and KPI IV, this is done through weighted aggregation of the scenario results. KPI II is instead retained in a mixed categorical-duration form, so that the distinction between *Unlimited*, storage-supported, and *Unable* conditions is preserved. These aggregated results provide the basis for identifying design weaknesses, comparing design iterations, and supporting the improvement loop described in Step 3.

4.3.4. Design KPIs: Data Evaluation

Unlike the performance-based KPIs, which are evaluated separately for each operating scenario, the design-dependent KPIs are derived directly from the properties of the selected TEMS configuration. Their purpose is to quantify the spatial, mass-related, and economic implications of the system layout itself. They therefore do not depend on climate zone, occupancy level, weather-parameter case, or operational profile, but only on the characteristics of the installed equipment.

The design-dependent KPI model is implemented as a direct calculation based on a system matrix containing, for each component included in the TEMS configuration, its characteristic dimensions, mass, and cost. From these component-level data, the script determines the total installed volume, total installed mass, and total estimated cost of the system. These totals are then expressed per unit Gross Tonnage in order to obtain indicators that can be compared consistently across alternative designs of the same vessel scale.

Let the complete set of components in the TEMS design be denoted by $j = 1, 2, \dots, n$. For each component, the model defines a characteristic volume V_j , a mass m_j , and a cost C_j . The total design quantities are then obtained as

$$V_{\text{TEMS}} = \sum_{j=1}^n V_j \quad (4.31)$$

$$M_{\text{TEMS}} = \sum_{j=1}^n m_j \quad (4.32)$$

$$C_{\text{TEMS}} = \sum_{j=1}^n C_j \quad (4.33)$$

The component volume is estimated through simplified geometric representations. For components that can be approximated by a rectangular envelope, the volume is determined from

$$V_j = L_j W_j H_j \quad (4.34)$$

where L_j , W_j , and H_j are the characteristic length, width, and height of component j . For storage elements or other components represented as cylindrical bodies, the volume is instead approximated by

$$V_j = \pi \left(\frac{D_j}{2} \right)^2 H_j \quad (4.35)$$

where D_j is the characteristic diameter and H_j is the height. In this way, the equipment data are converted into a single estimate of the total installed TEMS volume.

The three design-dependent KPIs are then obtained by applying the definitions introduced in Chapter 3 to the totals calculated above.

KPI V: Volume Ratio KPI V is calculated by applying the Volume Ratio definition given in Equation 3.9. In practice, the total installed TEMS volume obtained from Equation 4.31 is normalized by the yacht gross tonnage. This KPI therefore expresses the volumetric footprint of the selected configuration relative to vessel size and provides a direct measure of how demanding the design is from an integration and arrangement perspective.

KPI VI: Mass Ratio KPI VI is calculated using the Mass Ratio definition given in Equation 3.10. The total installed mass obtained from Equation 4.32 is normalized by the yacht gross tonnage, resulting in one indicator of the mass burden associated with the selected TEMS configuration. This KPI is used to compare alternative layouts in terms of installed system mass relative to vessel scale.

KPI VII: Cost Ratio KPI VII is calculated using the Cost Ratio definition given in Equation 3.11. The total estimated installed cost obtained from Equation 4.33 is normalized by the yacht gross tonnage, providing a design-level economic indicator for the selected configuration. Within the scope of this thesis, this KPI is used as a comparative capital-cost measure rather than as a full life-cycle economic assessment.

Taken together, these three design-dependent KPIs provide a complementary perspective to the scenario-based performance assessment. While the first four KPIs describe how the system behaves under different operating conditions, KPI V to KPI VII describe how demanding the configuration is in terms of volume, mass, and cost. Because they are derived from static design data and expressed on the same vessel-size basis, they can be used directly in the final comparison between design alternatives.

4.4. Step 4: Designs Evaluation and Ranking

The final step combines the selected design-level KPIs into one overall score used to compare and rank the alternative TEMS designs. As defined in Step 1, the final comparison includes KPI IV, CHPC Efficiency, together with KPI V, Volume Ratio, KPI VI, Mass Ratio, and KPI VII, Cost Ratio.

These KPIs must first be converted to a common dimensionless preference scale. KPI IV is a benefit criterion, since higher CHPC Efficiency is favourable, whereas KPI V, KPI VI, and KPI VII are cost criteria, since lower volume, mass, and cost ratios are preferable. Without this normalization, the final score would depend on the numerical scale and unit of each KPI rather than on its relative design preference.

This final MCDA normalization is different from the Gross-Tonnage scaling used in the design-dependent KPIs. Expressing volume, mass, and cost per GT makes these indicators comparable with respect to vessel size, but it does not make them directly comparable with CHPC Efficiency or suitable for aggregation. The ratio-to-best normalization is therefore applied only at the final ranking stage, after the raw KPI values have been calculated and interpreted.

As explained in Chapter 3, ratio-to-best normalization with weighted additive aggregation is adopted because it is transparent, does not require predefined target values, and is suitable for a two-design comparison. More advanced methods, such as TOPSIS, remain relevant for future applications with a larger set of alternatives.

Once normalized, the KPI scores are combined through the weighted additive model defined in Equation 3.14, subject to the weighting condition in Equation 3.15. Since equal importance is assigned to the four selected KPIs, each receives a weighting factor of 0.25. The resulting score provides a concise ranking output, where a higher value indicates a more favourable balance between CHPC performance and design impact in terms of volume, mass, and cost. This ranking does not replace the individual KPI results, which remain necessary for interpretation.

Overall, this chapter has shown how the evaluation framework developed in Chapter 3 is implemented for the selected yacht. The problem definition, KPI structure, scenario set, data-processing steps, and final aggregation procedure have been specified so that alternative TEMS designs can be evaluated consistently. The next chapter presents the selected design alternatives and discusses the results obtained from applying the method.

5. Results Evaluation

This chapter addresses the fourth research sub-question: “*What results are obtained when the proposed evaluation method is applied to the selected yacht, and how do the baseline and improved TEMS designs compare?*” It presents the results obtained from the application of Step 3 and Step 4 of the method described in Chapter 4. As explained in Section 4.3.3, the performance-based KPI evaluation is carried out through four stages: construction of the weather-parameter matrix, estimation of the yacht’s heat demand, calculation of the yacht’s heat generated, and final KPI evaluation. The first two stages were described in Chapter 4, since they form part of the implementation of the method itself. This chapter therefore focuses on the results of the heat-generation model, the resulting KPI values, and the final comparison and ranking of the two designs.

For each design, the evaluation is carried out over the complete set of scenario-condition combinations considered in the application. These combinations are obtained by combining the selected operational profiles, climate zones, occupancy levels, and weather-parameter cases. The results are first analysed at design level and are then compared in order to assess the effectiveness of the alternative TEMS configurations. The chapter begins by stating the main assumptions adopted for the evaluation. It then presents Design 1 and its results, followed by Design 2 and its corresponding assessment. Finally, the two designs are compared on the basis of the selected KPIs in order to support their final ranking.

5.1. Assumptions

The results presented in this chapter are based on a number of assumptions related to the scope of the evaluation, the demand and heat-generation models, the design-based KPI calculations, and the final comparison of the alternatives. These assumptions do not invalidate the method, but they define the level of detail of the case study and therefore the way in which the results should be interpreted.

5.1.1. Scope and representativeness of the evaluation

The first assumption concerns the definition of the scenario space. The evaluation assumes that the selected operational profiles, climate zones, occupancy levels, and weather parameter cases are sufficient to capture the main variation relevant to TEMS performance. Other possible sources of variation are therefore not modelled explicitly and are treated as secondary within the present case study.

A second assumption concerns the aggregation of the scenario-based results. Since the performance KPIs are first evaluated for each case and then weighted and aggregated, it is assumed that the aggregated values provide a meaningful representation of the overall behaviour of each design across the expected operation of the yacht.

Finally, the method is intended as a tool for early-stage design support and comparative evaluation rather than as a high-fidelity prediction of detailed onboard operation. The results should therefore be interpreted primarily as a basis for structured comparison and design improvement.

5.1.2. Demand and heat-generation modelling assumptions

On the demand side, it is assumed that the domestic hot water, HVAC, and swimming-pool workbooks are sufficiently reliable for the present case study. These pre-existing Excel models are used as subsystem calculation modules, and are therefore assumed to be accurate, up to date, and suitable for the scenario-dependent demand estimation adopted in this thesis.

It is also assumed that the operational logic used to populate these workbooks is sufficiently represen-

tative. The selection of which heat-using systems are active under each case, and the corresponding assumptions on their duration of operation, are based on engineering judgement rather than on measured operational data.

For the heat-generation model, each case is represented through a steady-state thermal balance. Transient effects, detailed control actions, charging and discharging dynamics, and other time-dependent interactions are therefore not modelled explicitly.

A further assumption is that the recoverable onboard heat available in each operational profile is known *a priori*. Instead of deriving this quantity from a detailed machinery model, predefined heat-source values are used for the different operating modes.

Engine operation is also assumed to be fixed for each operational profile. In other words, the engine configuration is prescribed by the selected operating mode and is not adjusted dynamically as a function of the instantaneous thermal or electrical demand, the required engine rpm, or possible hybrid operating behaviour.

Where exact efficiencies or coefficients of performance are not available, realistic constant values are adopted. These values are assumed to be sufficiently representative for comparative evaluation, even though actual performance may vary with operating point and load.

Finally, the HVAC demand is classified as cooling when the outdoor air temperature exceeds 21 °C, and as heating otherwise. This provides a practical and transparent modelling rule, but it simplifies the actual control logic of the onboard HVAC system.

5.1.3. Design-based KPI simplifications

In the design-based assessment, the installed volume of the main system components is approximated using simple geometric shapes, such as rectangular or cylindrical envelopes. This simplification is considered acceptable because the purpose of these KPIs is to provide a concept-level estimate of spatial impact rather than a detailed integration study.

In addition, the design-based KPIs are derived from the selected system-component dataset adopted for each design. They should therefore be interpreted as comparative indicators of volume, weight, and cost, rather than as final detailed design values.

5.1.4. Comparison and ranking assumptions

In the final comparison, it is assumed that no reliable external target values are available for the selected KPIs. For this reason, the evaluation is based on relative comparison between the available design alternatives rather than on comparison against predefined engineering targets or threshold values.

It is also assumed that the KPI framework can support both diagnosis and decision-making. In practice, the performance-based KPIs are used to analyse the behaviour and weaknesses of each design, whereas the reduced KPI set selected in Chapter 4 is used for the final aggregated comparison and ranking.

Taken together, these assumptions reflect the intended role of the method as a structured and comparative design-support tool. The results presented in the following sections should therefore be interpreted as a consistent basis for evaluating and improving alternative TEMS configurations, rather than as a high-fidelity prediction of detailed onboard operation.

5.2. Design 1

Design 1 is the baseline configuration used as the starting point for the application of the method. In line with the approach introduced in Chapter 4, it is intended to represent the TEMS installed on *M/Y Obsidian* as realistically as possible while remaining suitable for scenario-based modelling. It is therefore not a one-to-one reproduction of the real yacht. Some interactions between subsystems, as well

as part of the technical specifications required by the model, were not fully available and were therefore approximated on the basis of the available design information, manufacturer data, and engineering estimates.

For the purpose of the present thesis, two levels of description must be distinguished. The first is the overall TEMS architecture of the yacht. The second is the smaller subset of equipment that is explicitly evaluated in the heat-generation model and that therefore drives the performance-based results. This distinction is important because the full TEMS includes all systems connected to the onboard heating and cooling loops, whereas the present thesis refers as TEMS the smaller subset of equipment responsible for recovering, converting, storing, and delivering useful thermal energy.

5.2.1. TEMS Configuration

A schematic representation of the baseline configuration adopted for Design 1 is given in Figure 4.3. The figure distinguishes between energy sources, conversion units, and users. On the left-hand side, three main energy sources are identified. The first is thermal energy stored in the heat tanks. The second is chemical energy, represented by the HVO fuel consumed by the internal-combustion engines. The third is electrical energy, which may originate from the batteries, the shore connection, or onboard electricity generation. On the right-hand side, the thermal users are represented. In the present model, these users are not described individually, but through their thermal demand, separated into heating and cooling duty.

The centre of the diagram shows the subsystem that is explicitly evaluated in the heat-generation model. This subsystem consists of the units that convert the available chemical, electrical, and stored thermal energy into useful onboard heating or cooling. In Design 1, the main heating source during sailing and anchoring is the recoverable heat from the engines. This heat is transferred from the HT side to the recovery circuit through a dedicated heat exchanger. In the implemented model, the engine operating configuration is fixed by operational profile: during sailing all four engines are assumed to be active, whereas at anchor only the two smaller middle engines are considered to operate. In harbour, no recoverable engine heat is assumed to be available.

When cooling is required, the main electrically driven conversion unit is the electrical chiller / heat-pump branch. This unit provides the cooling required by the HVAC demand and, at the same time, allows part of the extracted heat to be recovered and reused on the heating side. In addition, the model includes an auxiliary heat-pump cooling branch that can contribute to the cooling demand under specific environmental conditions. If the recovered engine heat and the electrically driven heat recovery are not sufficient to satisfy the total heating demand, an electric heater is used as auxiliary heating source. Finally, if a remaining heating deficit still exists, the thermal storage system is used as backup for a limited duration.

From the modelling point of view, Design 1 can therefore be interpreted as a recovery-oriented baseline configuration. Its logic is to prioritize the direct use of available engine waste heat, supplement the cooling demand through electrically driven equipment, recover part of that cooling-side heat for heating purposes, and rely on electric heating and thermal storage only when the previous sources are insufficient. Heat that cannot be used within the recovery path is ultimately rejected through the LT side to seawater.

Tables 5.2 and 5.1 summarize the main assumed engine operating configurations and the principal equipment characteristics used for the explicit performance modelling of Design 1.

Table 5.1: Main heat-generation equipment represented explicitly in the Design 1 performance model

System	Length (m)	Width (m)	Height (m)	Mass (kg)	Cost (€)	Maximum Heat Capacity
Heat Tank 1	0.9900	0.9900	2.1350	175.0	700.0	227.6 MJ
Heat Tank 2	0.9900	0.9900	2.1350	175.0	700.0	227.6 MJ
Heat Exchanger	0.3897	0.6300	1.7300	905.0	9000.0	580.0 kW
Electric Heater	1.1660	0.9000	1.3300	310.0	15000.0	350.0 kW
Electrical Chiller / Heat Pump	3.2000	2.0500	2.0650	7200.0	400000.0	750 kW (cooling) 350 kW (heating)

Table 5.2: Engine specifications and operating configurations for the sailing and anchor operational profiles

Engine Type	Load (-)	BSFC (-)	LHV Energy (kW)	Power (bkW)	HT Heat Recovered (kW)
Sailing					
Caterpillar C32B	78%	41%	2825.0	1144.0	819.0
Caterpillar C32 ACERT DITTA-SCAC	89%	40%	1964.0	781.0	478.0
Anchor					
Caterpillar C32B	—	—	—	—	—
Caterpillar C32 ACERT DITTA-SCAC	100%	39%	2224.0	873.0	541.0

5.2.2. Heat-Generation Results

The heat-generation results for Design 1 are presented in Figures 5.1 and 5.2. The discussion focuses primarily on the most frequent temperature conditions, since these represent the most typical operating case within the scenario set. The second most frequent temperature conditions are then used as a short comparison in order to verify whether the same trends remain valid under a slightly different, but still representative, thermal regime.

Figure 5.1 shows the heat supplied by the different subsystems under the most frequent temperature conditions. The first clear trend is the effect of occupancy level, which can be observed directly by comparing the three subplots. Moving from low occupancy to medium and high occupancy leads to a strong increase in total supplied heat in all climate zones and operational profiles. This increase is especially pronounced in the anchor cases. Under low occupancy, the total supplied heat generally remains below about 320 kW, whereas under high occupancy the anchor cases in the Mediterranean climate zones exceed about 1000 kW. The composition of the bars also changes with occupancy. At low occupancy, the system remains largely recovery-driven, whereas at medium and high occupancy the electric heater becomes much more relevant and, in the most demanding cases, the heat tank also starts to contribute. This shows that the increase in onboard demand affects not only the magnitude of the supplied heat, but also the extent to which the design must rely on auxiliary support.

A second pattern concerns the differences between climate zones. Under the most frequent temperature conditions, the Mediterranean cases generally require the highest supplied heat, especially the East Mediterranean, West-East Mediterranean, and West Mediterranean. By contrast, the Caribbean, Hong Kong, and particularly the Middle East tend to show lower total values. This distinction is already visible at low occupancy, but it becomes much more pronounced at medium and high occupancy, where the Mediterranean cases clearly stand out as the most demanding. The climatic influence is therefore

significant, although it remains secondary to the effect of occupancy level, which is the main driver of the increase in supplied heat.

The third main trend concerns the operational profiles. Across most climate zones, sailing provides the highest total supplied heat at low occupancy, while anchor becomes the dominant profile at medium and high occupancy. This shift reflects the different balance between available recoverable heat and total thermal demand. In the lower-demand cases, the recoverable heat available during sailing is generally sufficient to keep the system largely recovery-driven. As demand increases, however, the anchor cases show a stronger reliance on the electric heater and, in the most demanding scenarios, on the heat tank. Harbour remains systematically the lowest profile. This is consistent with the adopted modelling logic, since no recoverable engine heat is assumed to be available in harbour and the demand must therefore be covered mainly through the electrically driven branches.

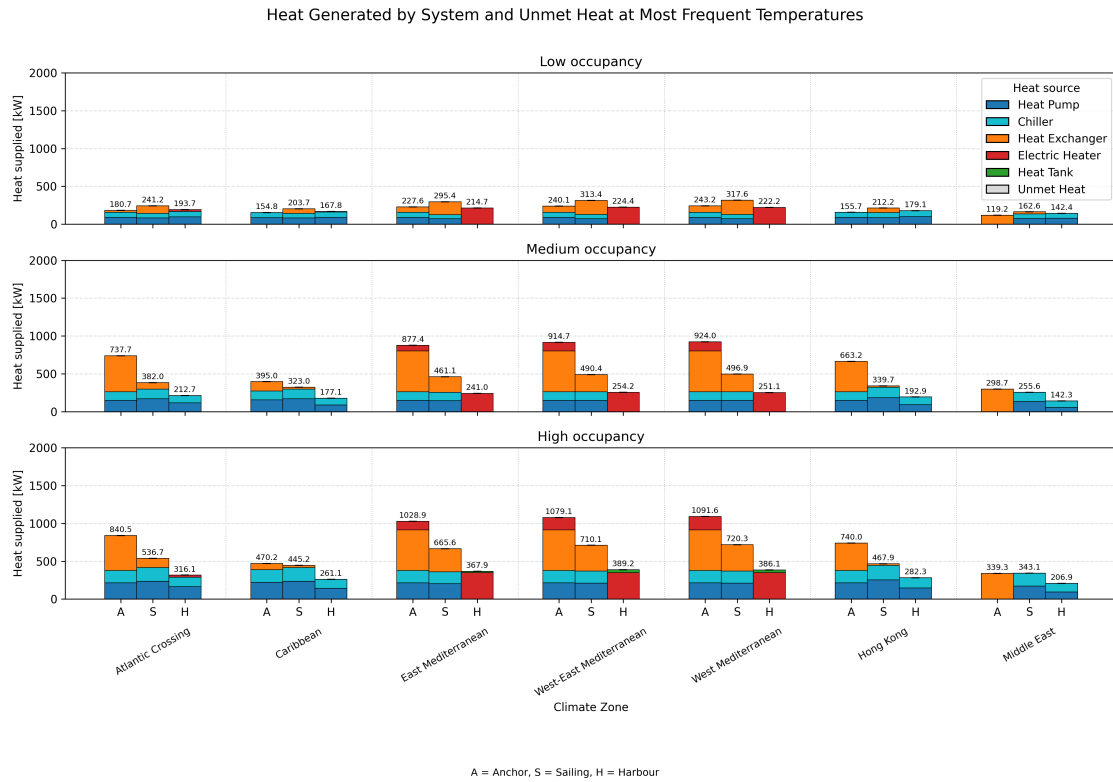


Figure 5.1: Heat supplied by each subsystem and unmet heat for Design 1 under the most frequent temperature conditions.

Figure 5.2 shows the second most frequent temperature conditions. The same overall logic remains visible, which confirms that the patterns discussed above are not limited to a single representative case. Occupancy level is again the strongest driver of the total supplied heat, the Mediterranean climate zones remain among the most demanding, and harbour continues to show the lowest supplied values. Compared with the most frequent case, however, the second most frequent case shows a slightly stronger heating-side contribution in several medium- and high-occupancy scenarios. This is particularly visible in the Caribbean and Mediterranean cases, where the anchor profile becomes more demanding and the electric-heater contribution appears somewhat more pronounced. The second most frequent case therefore confirms the same general behaviour as Figure 5.1, but under a slightly more demanding thermal regime.

The remaining two heat-generation figures, corresponding to the minimum and maximum temperature conditions, are reported in Appendix F. These cases were also analysed in order to verify the behaviour

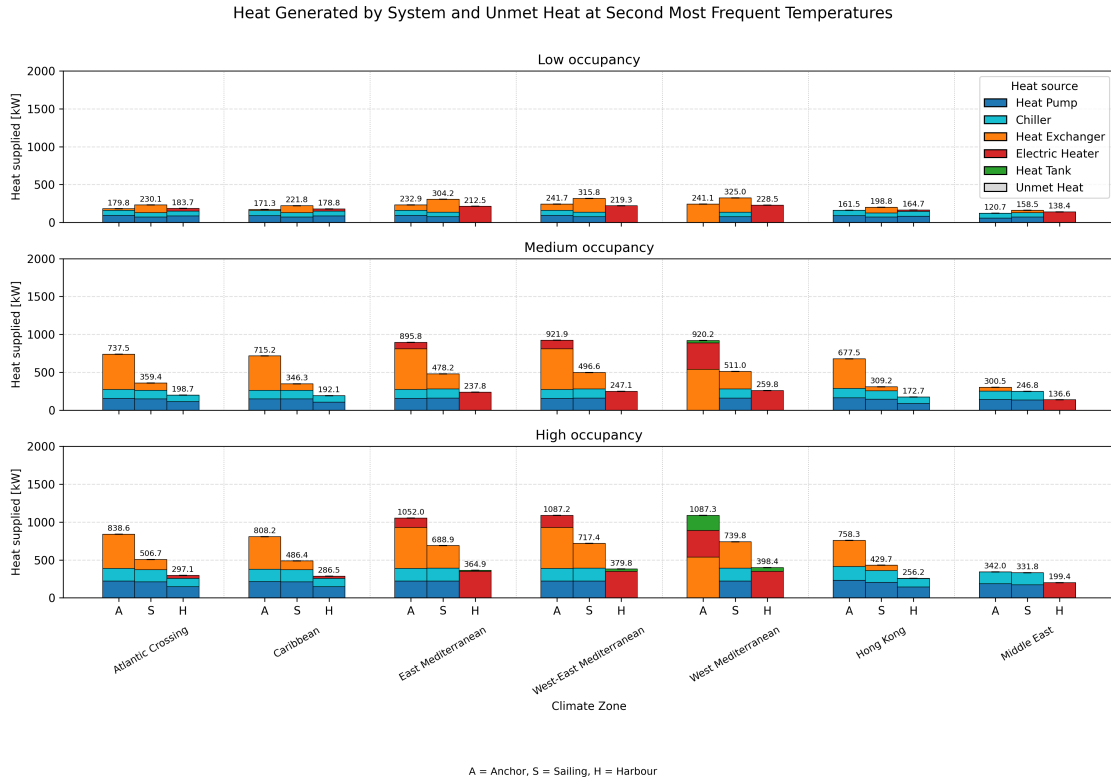


Figure 5.2: Heat supplied by each subsystem and unmet heat for Design 1 under the second most frequent temperature conditions.

of the baseline design under the extreme ends of the considered thermal range. The minimum-temperature case shows a clearly heating-dominated behaviour, in which the heat exchanger and the electric heater become the main contributors and heat-tank support appears in the most demanding anchor cases. The maximum-temperature case shows the opposite extreme, with a much stronger contribution from the electrically driven cooling branch and no visible heat-tank support. These two cases are not discussed here because they represent less frequent operating conditions, but they remain useful for confirming how the system behaves under extreme cold and warm scenarios.

Taken together, the heat-generation results show that occupancy level is the strongest driver of the total supplied heat, while climate zone and operational profile determine how this demand is distributed among the available subsystems. They also show that, under the most representative temperature conditions, Design 1 remains largely recovery-oriented at low demand but increasingly relies on auxiliary support as demand rises.

5.2.3. Performance-KPI Results

KPI I & II: The performance-KPI results confirm that Design 1 is capable of covering the thermal demand in all evaluated scenarios. KPI I indicates that the required demand is met in every case, while KPI II shows that most of these scenarios are covered without the need for storage support. Out of the complete set of evaluated scenarios, 222 are classified as *Unlimited*, whereas the remaining 30 require support from the heat tank. No scenario is classified as *Unable*. The representative temperature cases show the same overall behaviour. Under the most frequent temperature conditions, 60 out of 63 scenarios are *Unlimited*, while only 3 require the intervention of the heat tank. Under the second most frequent temperature conditions, 58 out of 63 scenarios remain *Unlimited*, and the remaining 5 require storage support. These results indicate that the baseline design is generally feasible, but not equally robust in all operating conditions.

Heat-tank support is limited to a small number of high-demand scenarios. Under the most frequent temperature conditions, illustrated in Figure 5.3, it appears only in three high-occupancy harbour cases, namely the East Mediterranean, West-East Mediterranean, and West Mediterranean, where the remaining demand can be sustained for about 423, 194, and 210 minutes, respectively. Under the second most frequent conditions, the same pattern remains but becomes slightly more severe: the same three high-occupancy harbour cases require the support from the heat tank for about 508, 255, and 157 minutes, and additional support appears in the West Mediterranean anchor profile for about 233 minutes at medium occupancy and 38 minutes at high occupancy. These values represent the maximum time for which the tank can sustain the remaining demand in each steady-state scenario, so lower values indicate more critical conditions. However, this does not imply unsafe operation, since the scenarios are treated as steady-state design points rather than as time-varying demands that must persist for the full support duration.

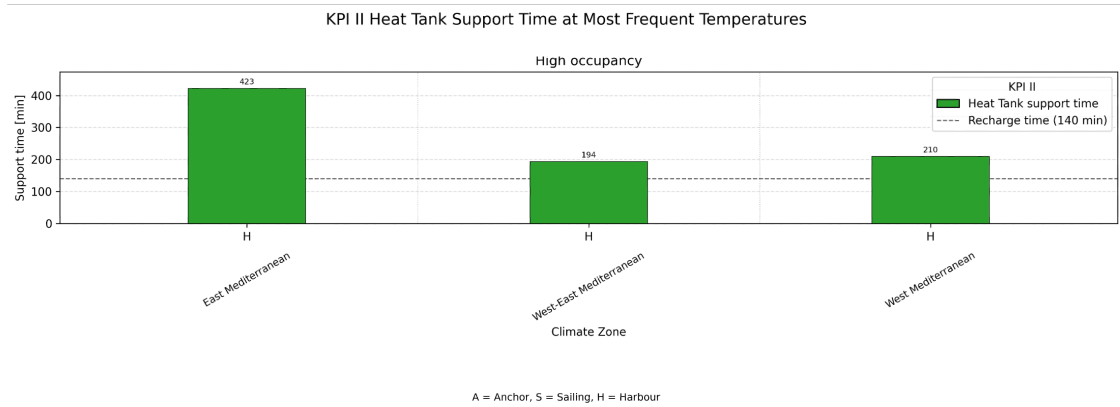


Figure 5.3: KPI II heat tank support time at second most frequent temperatures.

KPI III: The most useful KPI for understanding why these critical cases appear is KPI III, since it shows the utilization level of each subsystem relative to its reference capacity. In this way, KPI III provides the link between the feasibility results from KPI I and KPI II and the subsequent design-improvement process. Figures 5.4 and 5.5 show the KPI III results for the most frequent and second most frequent temperature conditions.

Figure 5.4 shows that, under the most frequent temperature conditions, the utilization of the subsystems increases strongly with occupancy level, as expected. At low occupancy, all systems remain far from saturation, and the design therefore retains a clear operating margin. At medium and high occupancy, however, the Mediterranean cases become significantly more demanding. The heat exchanger reaches very high utilization in the anchor cases, often approaching its full capacity, while the electric heater becomes the critical component in the harbour cases, where it reaches or nearly reaches full utilization. This is particularly visible in the East Mediterranean, West-East Mediterranean, and West Mediterranean, which are the same cases for which storage support becomes necessary or nearly necessary. By contrast, the sailing cases remain more balanced. The heat pump and the heat exchanger are used substantially, but the electric heater is not required, which indicates that the recoverable heat available during sailing is generally sufficient to avoid the strongest bottlenecks.

Figure 5.5 confirms the same general behaviour under the second most frequent temperature conditions. The most demanding scenarios remain concentrated in the Mediterranean climate zones and at medium or high occupancy, and the same two components continue to emerge as the main bottlenecks: the heat exchanger in anchor and the electric heater in harbour. Compared with the most frequent case, the stress on these components becomes slightly broader, which is consistent with the additional tank support observed in the West Mediterranean. Taken together, the KPI III results show that the baseline design is generally capable of meeting the demand, but that its operating margin decreases sharply in the higher-occupancy Mediterranean scenarios.

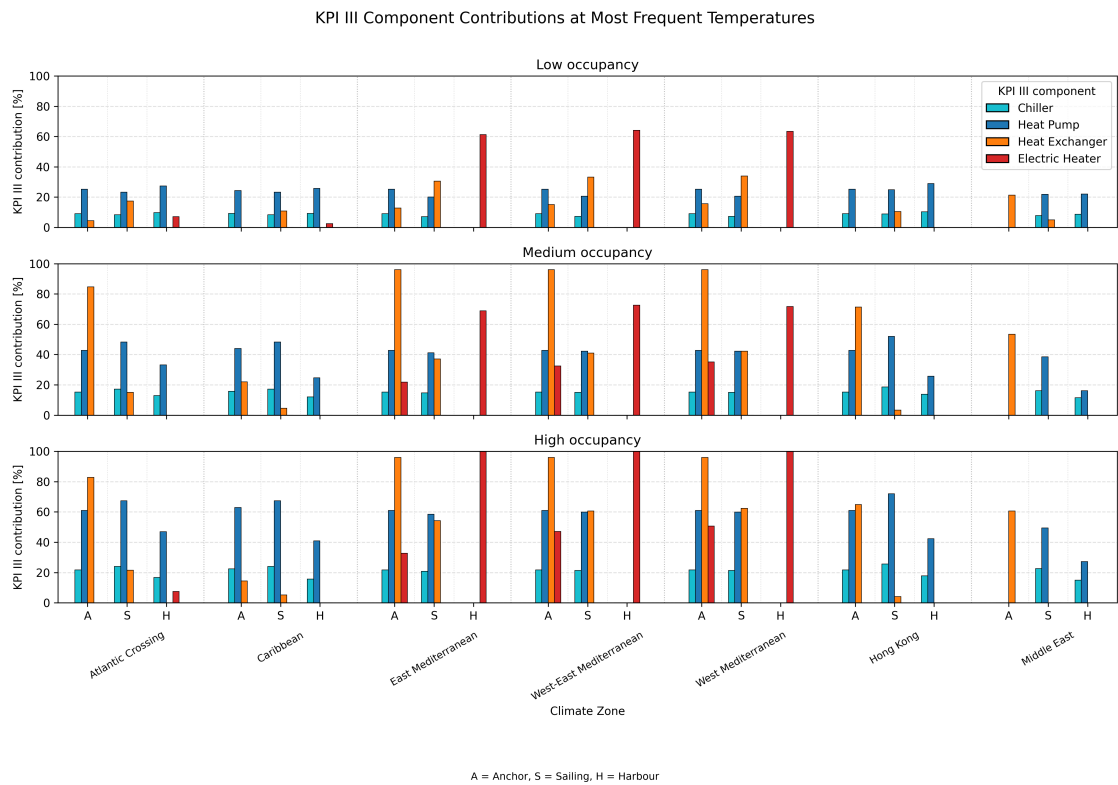


Figure 5.4: KPI III component contributions for Design 1 under the most frequent temperature conditions.

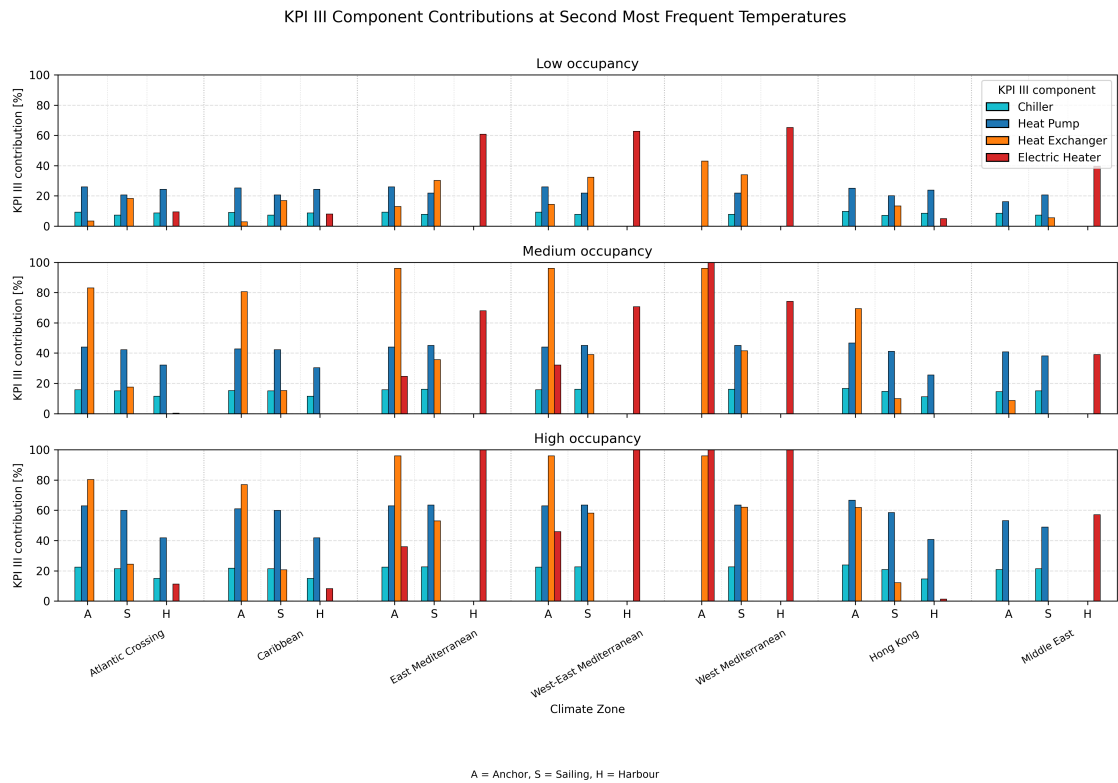


Figure 5.5: KPI III component contributions for Design 1 under the second most frequent temperature conditions.

KPI IV: KPI IV should not be interpreted as a pure efficiency. In the present case, it is better understood as a hybrid performance indicator between an overall efficiency and a coefficient of performance. In anchor and sailing, the formulation relates the useful thermal service to the machinery fuel input and electrical production, so it behaves as a fuel-based system-efficiency indicator. In harbour, however, the formulation reduces to the ratio between useful thermal generation and auxiliary electrical consumption. As a result, when the electrically driven cooling / heat-pump branch dominates, KPI IV behaves more like a COP than like a conventional first-law efficiency. This difference is clearly visible in the results in Appendix H.

Under the most frequent temperature conditions, the anchor profile ranges from 41.9% to 58.6%, with a median of 48.7%. In the Mediterranean climate zones, the median rises to 56.4%, with an average of 53.1%. The sailing profile is lower and more compact, ranging from 41.7% to 47.2%, with a median of 43.3%; in the Mediterranean cases, the median and average are both about 45.0%. Harbour shows a completely different behaviour, with values ranging from 98.0% to 747.9% and a median of 481.2%. However, the Mediterranean harbour cases all remain at about 98.0%, so their median and average are also 98.0%. The reason is that, in these representative Mediterranean harbour scenarios, the useful thermal service is provided mainly by direct electric heating, so the indicator reflects the heater efficiency. By contrast, the very high harbour values occur mainly in the Atlantic Crossing, Caribbean, Hong Kong, and Middle East cases, where the electrically driven cooling / heat-pump branch dominates and the indicator takes on a COP-like character.

The second most frequent temperature conditions show the same general behaviour. Anchor ranges from 41.5% to 58.9%, with a median of 51.2%; in the Mediterranean zones, the median is also 51.2%, with an average of 51.8%. Sailing remains again lower and more stable, ranging from 41.7% to 47.4%, with a median of 43.4%; the Mediterranean median and average are about 45.0% and 45.1%, respectively. Harbour ranges from 98.0% to 728.3%, but its median drops to 98.0%, while the Mediterranean median and average remain 98.0%. Compared with the most frequent case, this indicates that the second most frequent conditions shift more harbour scenarios towards direct electric-heater operation and reduce the number of cases dominated by the cooling / heat-pump branch.

Overall, KPI IV confirms that the energetic quality of Design 1 depends strongly on the operational profile and on the thermal regime. Anchor generally shows the highest values among the fuel-based modes, especially in the more demanding Mediterranean and higher-occupancy scenarios, because the useful thermal service increases while the assumed machinery inputs remain fixed. Sailing is consistently lower, which reflects the larger machinery-energy basis associated with that profile. Harbour must be interpreted separately, since its KPI IV values are governed by the balance between electric-heater operation, which gives values close to 98%, and electrically driven cooling / heat-pump operation, which produces much higher COP-like values. For this reason, KPI IV is useful for comparing patterns within each operational profile, but harbour should not be compared directly in magnitude with anchor and sailing.

The minimum- and maximum-temperature KPI results are also reported in Appendix H. These two cases confirm the boundary behaviour of the baseline design. Under minimum temperatures, the design remains feasible but relies more frequently on the heat exchanger, the electric heater, and, in a larger number of cases, on thermal storage support. Under maximum temperatures, by contrast, the design remains fully feasible without storage support, and the subsystem usage shifts towards the electrically driven cooling branch. These extreme cases are useful to define the limits of the design behaviour, but the most representative evaluation remains the one based on the most frequent and second most frequent temperature conditions.

Overall, the performance-KPI results show that Design 1 is capable of operating in all evaluated scenarios, but they also reveal where its margin becomes limited. The most critical conditions are concentrated in the higher-occupancy Mediterranean scenarios, where subsystem utilization becomes high and storage support is required for limited but relevant durations.

5.2.4. Design-Based KPI Results

Unlike the performance-based KPIs, KPI V, KPI VI, and KPI VII do not depend on the operating scenario. They are instead used to quantify the static design implications of the selected configuration in terms of space, weight, and cost. In the present comparison, these KPIs are calculated only for the systems that directly determine or store useful heating and cooling within the simplified Design 1 model. The engines are not included, since they remain unchanged between the considered design alternatives and would therefore not affect the comparative assessment.

Table 5.3 summarizes the resulting totals and normalized KPI values. The installed volume is determined from simplified geometric envelopes, using a cylindrical approximation for the heat tanks and rectangular envelopes for the other units. The resulting totals are then normalized by the yacht gross tonnage in order to obtain comparable design-level indicators.

Table 5.3: Design-based KPI results for Design 1

Quantity	Value
Total installed volume	18.65 m ³
Total installed weight	8765 kg
Total installed cost	€425,400
KPI V – Volume Ratio	0.00730 m ³ /GT
KPI VI – Mass Ratio	3.43 kg/GT
KPI VII – Cost Ratio	166.56 €/GT

These values define the static burden of Design 1 in terms of onboard integration and capital intensity. On their own, they do not indicate whether the design is preferable, but they establish the baseline against which Design 2 can later be compared. Their main value in this chapter is therefore not in isolated interpretation, but in showing the volumetric, mass-related, and economic consequences of the baseline configuration before the improved design is introduced.

5.2.5. Main Observations

The results confirm that Design 1 provides a workable baseline configuration. As shown in the heat-generation results and the KPI evaluation, the design is capable of covering the thermal demand in all evaluated scenarios, and in most representative cases this is achieved without storage support. In particular, Figures 5.1 and 5.4 show that, under the most frequent temperature conditions, the system performs well whenever recoverable engine heat is available and the overall demand remains moderate. In these cases, the thermal load can be covered mainly through the recovery heat exchanger and the electrically driven heat-pump branch, without requiring significant backup intervention. This indicates that the general recovery-oriented logic of the baseline design is sound.

At the same time, the same figures also show that the design margin is not uniform across the scenario set. The most critical behaviour is concentrated in the higher-occupancy Mediterranean cases. In Figure 5.4, the heat exchanger becomes heavily loaded in the anchor profile, while the electric heater becomes the critical component in harbour, where it reaches or approaches full utilization in the East Mediterranean, West-East Mediterranean, and West Mediterranean. This behaviour remains visible also under the second most frequent temperature conditions in Figure 5.5. The design is therefore feasible, but it becomes increasingly dependent on auxiliary support in the representative high-demand Mediterranean scenarios.

A second important observation is that the electrically driven chiller appears to be oversized for the representative operating conditions considered in the main analysis. This can be seen in Figures 5.4 and 5.5, where the chiller contribution remains comparatively low and far from saturation, while the

real bottlenecks emerge elsewhere in the system. By contrast, the heating side shows much stronger stress, especially in the recovery heat exchanger and, in harbour, in the electric heater. This suggests that the baseline configuration allocates a relatively large installed cooling capacity to a branch that is not the first limiting factor in the most representative scenarios, and that an alternative configuration may therefore be more effective.

A third and more structural limitation is that a considerable share of the heat available from the engines is not reused. This is visible already in Figures 5.1 and 5.2, where the useful contribution of the recovery heat exchanger remains limited even in cases where recoverable engine heat is available and the design still resorts to electric heating. The same conclusion is supported more directly by Figure 5.6, which shows the fraction of available engine HT heat actually passed through the recovery heat exchanger under the most frequent temperature conditions. Under low occupancy, the utilization of available engine HT heat remains very low, generally below about 10%. Even under medium and high occupancy, anchor typically uses only about 30–52% of the available engine HT heat, while sailing remains much lower, generally below about 15%. This indicates that the design does not appear to lack thermal energy at source. Rather, a substantial part of the recoverable engine heat is left unused, while additional electric heating is still required in the more demanding scenarios. In other words, the limitation lies less in the availability of engine heat than in the capacity of the present recovery path to convert and utilize a larger fraction of that heat for useful onboard services.

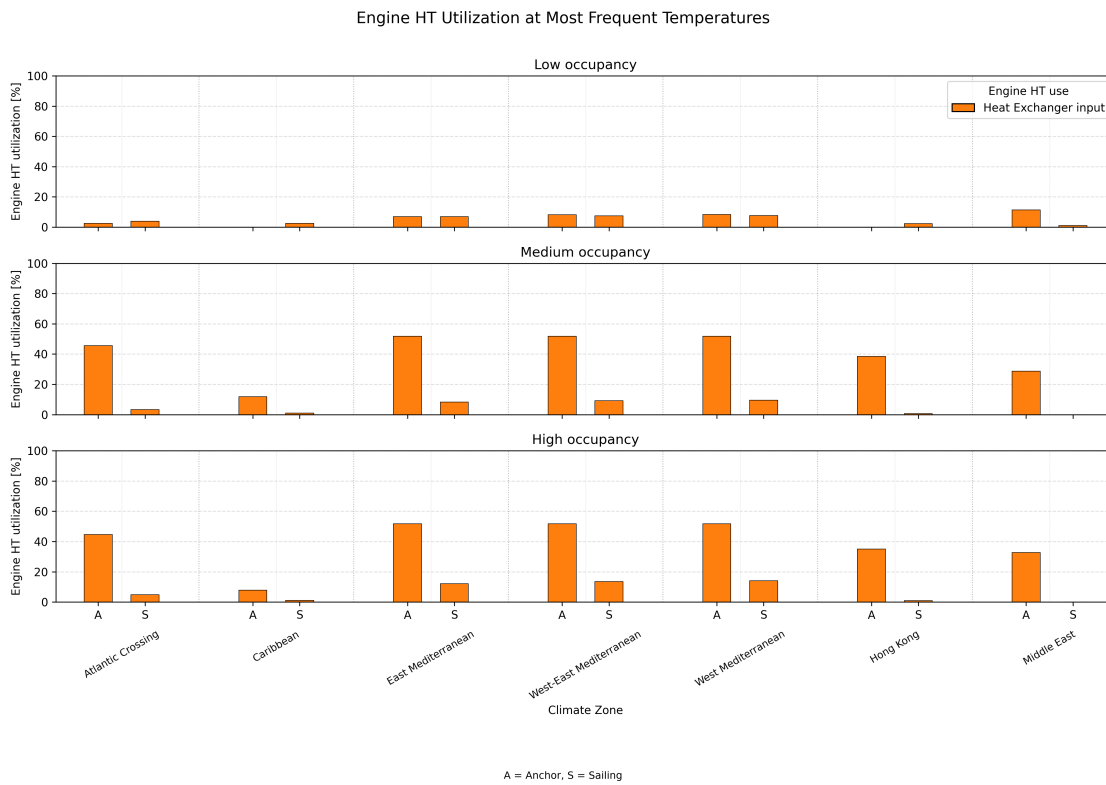


Figure 5.6: Fraction of available engine HT heat used as input to the recovery heat exchanger in Design 1 under the most frequent temperature conditions.

Taken together, these observations indicate that the improvement of Design 1 should not focus on replacing the entire system concept, but on targeting its specific limitations. The main opportunities for improvement are to reduce the dependence on the electric heater in harbour, to reconsider the role and sizing of the electrically driven chiller branch, and to make better use of the recoverable engine heat that is currently not utilized. Within this perspective, increasing the effective recovery capacity of the heat-exchanger branch, or introducing an alternative recovery-based configuration able to exploit the available engine heat more effectively, emerges as the most relevant direction for the next design iteration.

5.3. Design 2

Design 2 is introduced as a targeted improvement of the baseline configuration evaluated in Section 5.2. The purpose of this second iteration is not to redefine the complete TEMS architecture, but to assess whether the main limitations identified for Design 1 can be reduced through a specific modification of the cooling and heat-recovery strategy. The results are therefore evaluated using the same scenario set, KPI structure, and assumptions adopted for the baseline design.

5.3.1. TEMS Configuration

Design 2 is defined as an improved configuration based on the results obtained for Design 1. The general TEMS architecture is kept largely unchanged, so that the comparison focuses on a targeted design modification rather than on a completely different system concept. The main differences are the downsizing of the electrically driven chiller / heat-pump unit and the introduction of an absorption chiller. The resulting configuration is shown in Figure 5.7, while the main specifications for each system are listed in Table 5.4.

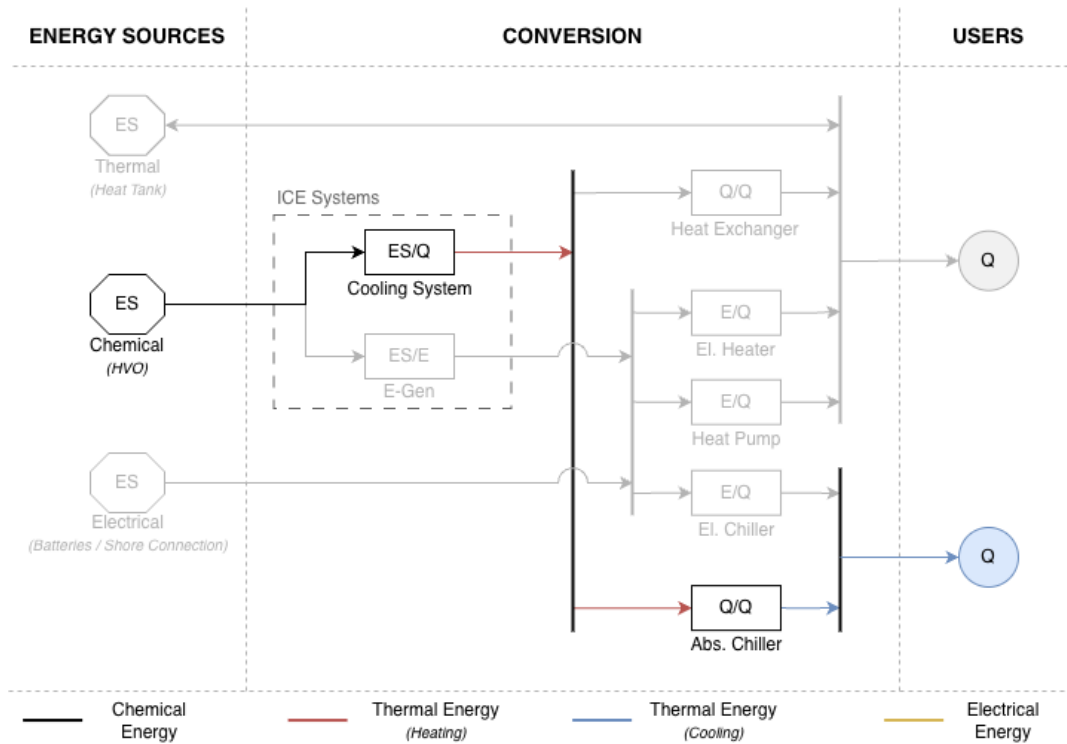


Figure 5.7: Thermal Energy Flow Diagram of Design 2

This modification was selected because the evaluation of Design 1 identified two related improvement opportunities. First, the electrically driven chiller appeared to be oversized under the most representative operating conditions, since its utilisation remained limited while other parts of the system became more critical. Second, a considerable share of the available engine HT heat was not converted into useful thermal service, especially in scenarios where recoverable engine heat was available. Design 2 therefore investigates whether part of the cooling demand can be supplied by using this available heat, instead of relying mainly on electrically driven cooling.

The absorption chiller is introduced for this purpose. In the implemented control logic, it is used as the preferred cooling source when cooling is required and engine HT heat is available, namely during sailing and anchoring. The remaining cooling demand, if any, is then supplied by the electrically driven chiller. At the same time, the HT heat that is not used by the absorption chiller remains available

Table 5.4: Main heat-generation equipment represented explicitly in the Design 2 performance model

System	Length (m)	Width (m)	Height (m)	Mass (kg)	Cost (€)	Maximum Heat Capacity
Heat Tank 1	0.9900	0.9900	2.1350	175.0	700.0	227.6 MJ
Heat Tank 2	0.9900	0.9900	2.1350	175.0	700.0	227.6 MJ
Heat Exchanger	0.3897	0.6300	1.7300	905.0	9000.0	580.0 kW
Electric Heater	1.1660	0.9000	1.3300	310.0	15000.0	350.0 kW
Electrical Chiller / Heat Pump	2.1500	2.0500	2.0650	4800.0	265000.0	500 kW (cooling) 350 kW (heating)
Absorption Chiller	3.8000	2.0000	2.7000	11900.0	235000.0	457.0 kW

for the recovery heat exchanger. This creates a direct interaction between cooling production and heat recovery, and therefore allows the evaluation to assess whether the available engine heat can be used more effectively across the scenario set.

The choice is particularly relevant for the representative warm operating conditions, where cooling demand is significant and where the Mediterranean climate zones have a high weighting in the scenario matrix. At the same time, the modification does not address all limitations of Design 1. In harbour, no engine heat is assumed to be available, so the absorption chiller cannot provide the same benefit. This makes Design 2 a useful improvement case rather than an idealized solution: it tests whether a specific recovery-based addition improves the overall performance, while still exposing the trade-offs in volume, mass, cost, and profile-dependent effectiveness.

5.3.2. Heat-Generation Results

The heat-generation results for Design 2 are presented in Figures 5.8 and 5.9. The same heat-demand matrix and scenario set used for Design 1 are retained. Therefore, the differences observed in this section are caused by the modified TEMS configuration and not by changes in the operating conditions or thermal demand. The complete heat-generation results are reported in Appendix I, while the complete set of heat-generation plots is reported in Appendix J.

Figure 5.8 shows the heat-generation results for the most frequent temperature conditions. Compared with Design 1, the total supplied thermal service remains almost unchanged, since the same scenario demand is being satisfied. The main difference is the distribution between the contributing systems. In Design 2, the absorption chiller introduces an additional heat-driven cooling pathway, shown by the purple contribution in the anchor and sailing cases. As a result, part of the cooling demand that was previously supplied by the electrically driven chiller / heat-pump branch is now supplied through recoverable engine HT heat.

This change is most visible in the anchor and sailing profiles, because these are the profiles in which engine HT heat is available. Under medium and high occupancy, several anchor and sailing cases show a clear absorption-chiller contribution, while the electric chiller contribution is reduced compared with Design 1. This confirms that the added subsystem is active in the operating region for which it was introduced. The recovery heat exchanger remains a major contributor, especially in the higher-demand cases, which indicates that the available engine heat is now distributed between direct heat recovery and heat-driven cooling.

The Mediterranean cases remain important because they have a high weighting in the scenario matrix and because they include some of the largest representative demands. In the most frequent temperature case, the high-occupancy anchor scenarios in the East Mediterranean, West–East Mediterranean, and West Mediterranean all exceed approximately 1 MW of supplied thermal service. In these cases, Design 2 still relies strongly on the recovery heat exchanger and, in some cases, on the electric heater. This shows

that the absorption chiller improves the use of available engine heat for cooling, but it does not remove all heating-side limitations of the system.

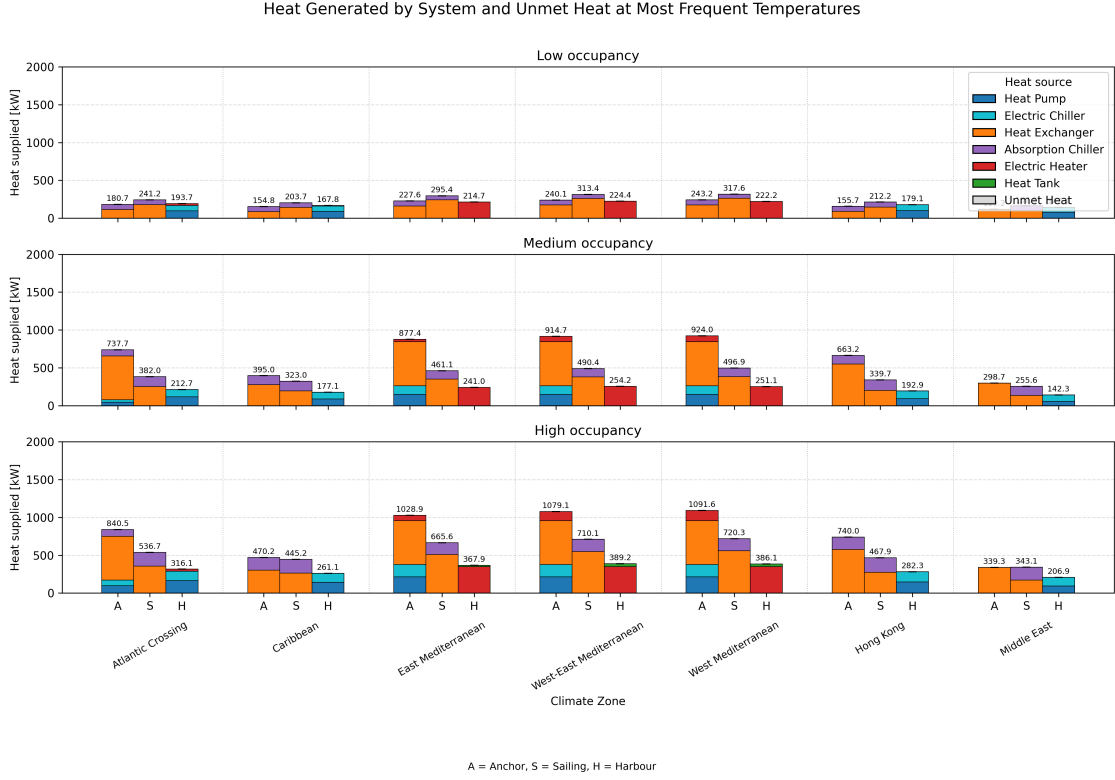


Figure 5.8: Heat supplied by each subsystem and unmet heat for Design 2 under the most frequent temperature conditions.

The harbour profile shows a different behaviour. Since no engine HT heat is assumed to be available in harbour, the absorption chiller cannot contribute in this profile. The harbour results therefore remain governed by the electrically driven chiller / heat-pump branch in cooling-dominated cases and by the electric heater in heating-dominated cases. This is visible in the Mediterranean harbour cases, where the red contribution of the electric heater remains present. Consequently, the modification introduced in Design 2 mainly affects the anchor and sailing profiles, while the harbour behaviour remains close to that of Design 1.

The second most frequent temperature conditions, shown in Figure 5.9, confirm the same general behaviour. The absorption chiller again contributes in several anchor and sailing cases, while the harbour cases remain unaffected by this subsystem. However, the figure also shows that some critical heating cases are still present. In particular, under high occupancy in the West Mediterranean anchor case, the heat tank is still required as backup support. This indicates that the added absorption chiller does not eliminate all peak-demand limitations. Instead, it changes how the available engine HT heat is used across the system.

Overall, the heat-generation results show that Design 2 preserves the load-covering capability of the baseline configuration in the representative temperature cases, while changing the source mix used to meet the demand. The main effect of the design modification is the partial replacement of electrically driven cooling with heat-driven cooling in anchor and sailing conditions. At the same time, the remaining electric-heater and heat-tank contributions show that the heating side of the system can still become critical in demanding scenarios. The performance-KPI results are therefore needed to assess whether this redistribution of thermal energy improves the overall effectiveness of the design.

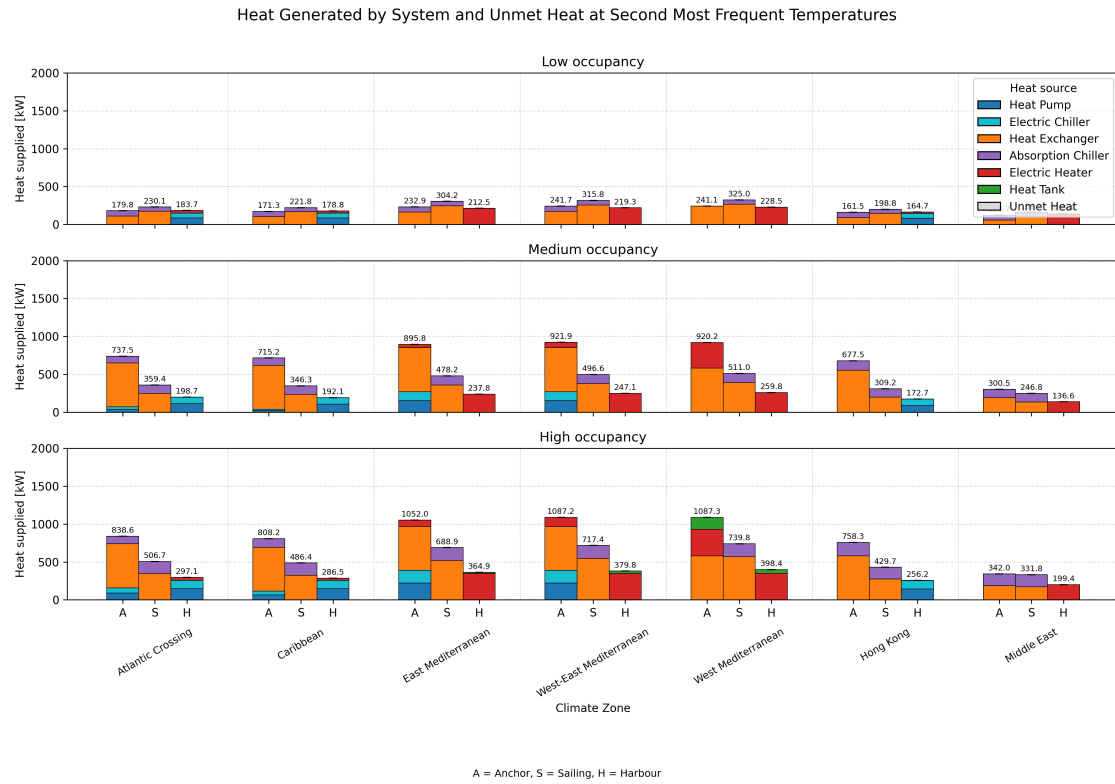


Figure 5.9: Heat supplied by each subsystem and unmet heat for Design 2 under the most frequent temperature conditions.

5.3.3. Performance-KPI Results

KPI I & II: The performance-KPI results show that Design 2 remains capable of covering the thermal demand in the representative temperature cases. As for Design 1, KPI I does not indicate unmet demand in any of the scenarios. The design modification therefore does not change the basic feasibility of the system. The relevant differences are instead found in the way the demand is covered, the use of storage support, and the resulting system efficiency.

KPI II shows that the heat tank remains a backup component rather than a regular source of thermal supply. Under the most frequent temperature conditions, shown in Appendix L, storage support is required only in the high-occupancy harbour cases of the East Mediterranean, West-East Mediterranean, and West Mediterranean. The corresponding support times are approximately 423, 194, and 210 minutes, respectively. These are the same critical harbour cases already observed for Design 1, and show in Figure 5.3, which indicates that the absorption chiller does not affect this limitation. This is expected, since harbour operation does not provide recoverable engine HT heat in the model.

The same behaviour is visible under the second most frequent temperature conditions. The high-occupancy harbour cases in the East Mediterranean, West-East Mediterranean, and West Mediterranean still require storage support for approximately 508, 255, and 157 minutes, respectively. In addition, the West Mediterranean anchor case requires tank support for about 233 minutes at medium occupancy and 38 minutes at high occupancy. Compared with Design 1, the heat-tank pattern is therefore essentially unchanged in the representative cases. This shows that the main effect of Design 2 is not the elimination of storage dependency, but the redistribution of thermal production between electrically driven and heat-driven pathways.

KPI III: KPI III explains how this redistribution takes place at subsystem level. Figures 5.10 and 5.11 show the component utilization for the most frequent and second most frequent temperature conditions. The most visible difference with respect to Design 1 is the appearance of the absorption chiller contribution in the anchor and sailing profiles. This contribution is absent in harbour, because no engine HT heat is assumed to be available in that profile.

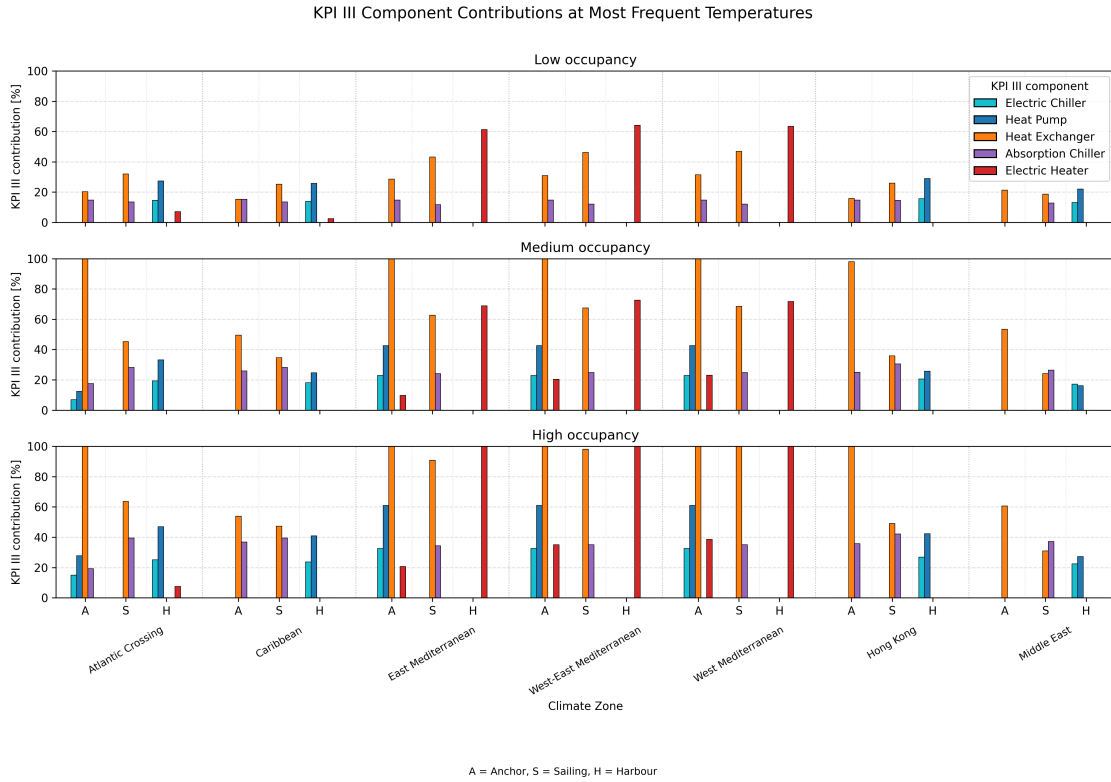


Figure 5.10: KPI III component contributions for Design 2 under the most frequent temperature conditions.

In the most frequent temperature case, shown in Figure 5.10, the absorption chiller is active mainly in the warm anchor and sailing cases. This is particularly clear at medium and high occupancy. For example, in the Mediterranean anchor and sailing cases, the absorption chiller contributes together with the heat exchanger and the electrically driven chiller / heat-pump branch. The same behaviour is visible in the Atlantic Crossing, Caribbean, Hong Kong, and Middle East cases when cooling demand is present. This confirms that the new subsystem is being used in the operating conditions for which it was introduced.

The heat exchanger remains one of the most heavily used components. In several medium- and high-occupancy anchor cases, its utilization reaches or approaches full capacity. This is visible, for example, in the Atlantic Crossing, East Mediterranean, West-East Mediterranean, West Mediterranean, and Hong Kong anchor cases. Compared with Design 1, the heat exchanger is still critical, but it now operates together with the absorption chiller. This indicates that the available engine HT heat is not only used for direct heat recovery, but also partly converted into useful cooling.

The second most frequent temperature case, shown in Figure 5.11, confirms the same pattern. The absorption chiller again contributes in anchor and sailing, while the harbour profile remains unaffected. The high-occupancy Mediterranean cases remain the most demanding: the heat exchanger is still highly utilized in anchor, and the electric heater remains the dominant component in harbour. The electric heater reaches very high utilization in the East Mediterranean, West-East Mediterranean, and West Mediterranean harbour cases, which are the same cases where heat-tank support is required. This confirms that the harbour limitation identified for Design 1 is not solved by the absorption chiller.



Figure 5.11: KPI III component contributions for Design 2 under the most frequent temperature conditions.

KPI IV: KPI IV shows the most important effect of Design 2, since the absorption chiller was introduced to improve the use of recoverable heat and reduce the dependence on electrically driven cooling. As explained for Design 1, KPI IV should not be interpreted as a pure component efficiency. It is a system-level indicator that combines useful thermal service, electrical production, electrical consumption, and fuel-energy input for anchor and sailing. In harbour, it is instead based on the ratio between useful thermal service and electrical consumption. For this reason, harbour values should be interpreted separately from anchor and sailing values.

The KPI IV results show that the efficiency improvement is concentrated in the profiles where engine HT heat is available. Under the most frequent temperature conditions, shown in Appendix L, anchor reaches approximately 56–57% at medium occupancy and up to 60% at high occupancy in the East Mediterranean, West–East Mediterranean, and West Mediterranean. These values are slightly higher than in Design 1, where the same cases were generally around 55–59%. The improvement is modest in absolute terms, but it appears in the same scenarios where the absorption chiller is active in Figure 5.10. This supports the interpretation that part of the efficiency gain comes from replacing electrically driven cooling with heat-driven cooling.

A similar but smaller improvement is visible in sailing. In the most frequent temperature case, Design 2 reaches about 47–48% in the high-occupancy Mediterranean sailing cases, while Design 1 remained around 47% in the same region. The difference is smaller than in anchor because the sailing profile already has a larger engine-power and fuel-input basis, so the effect of the additional thermal recovery pathway is less pronounced in the KPI IV value. Nevertheless, the trend remains consistent: the improvement appears mainly in the warm, higher-occupancy cases where the absorption chiller contributes to the cooling load.

The second most frequent temperature case confirms the same behaviour. In anchor, Design 2 reaches approximately 58–60% in the high-occupancy East Mediterranean and West–East Mediterranean cases, and remains above 50% in most medium- and high-occupancy Mediterranean conditions. These values are again slightly higher than for Design 1. In sailing, the improvement remains limited but visible, with the high-occupancy West–East Mediterranean and West Mediterranean cases reaching about 48%.

The minimum and maximum temperature cases show that the effect of Design 2 depends on the operating condition. At minimum temperatures, the difference with Design 1 is small because the absorption chiller has limited relevance when cooling demand is low. At maximum temperatures, the improvement becomes more visible in anchor and sailing, where the availability of engine HT heat can be used to support cooling production. This confirms that the design change is most useful when recoverable engine heat and cooling demand occur at the same time.

The harbour results do not show the same improvement. In the representative Mediterranean harbour cases, KPI IV remains at approximately 98%, as in Design 1, while other harbour climate zones still show much higher values because of the way the harbour KPI is defined as useful thermal service divided by electrical consumption. These values should not be compared directly with anchor and sailing. More importantly, the harbour pattern remains practically unchanged between the two designs, because the absorption chiller cannot operate without engine HT heat.

Overall, the performance-KPI results show that Design 2 improves the use of recoverable engine heat in the profiles where this heat is available. The absorption chiller introduces a useful heat-driven cooling pathway, and this is reflected in both KPI III and KPI IV. However, the improvement is profile-dependent. Anchor and sailing show a modest but consistent efficiency increase, especially in warm and high-occupancy Mediterranean scenarios, while harbour remains largely unchanged. The heat-tank results also show that the most critical heating-side cases are not removed. Design 2 therefore improves the thermal production strategy, but it does not fully eliminate the limitations identified in the baseline configuration.

5.3.4. Design-Based KPI Results

The design-based KPIs for Design 2 are calculated using the same approach adopted for Design 1. The engines and main power-generation equipment are not included, since they remain unchanged between the two designs. The comparison therefore focuses only on the TEMS components affected by the design modification.

The results are summarized in Table 5.5. Design 2 has a total installed TEMS volume of 34.73 m³, a total installed mass of 18,265 kg, and an estimated component cost of €525,400. Normalized by the yacht gross tonnage of 2,554 GT, this corresponds to a Volume Ratio of 0.01360 m³/GT, a mass ratio of 7.15 kg/GT, and a cost ratio of 205.72 €/GT.

Table 5.5: Design-based KPI results for Design 2

Quantity	Value
Total installed volume	34.73 m ³
Total installed weight	18,265 kg
Total installed cost	€525,400
KPI V – Volume Ratio	0.01360 m ³ /GT
KPI VI – Mass Ratio	7.15 kg/GT
KPI VII – Cost Ratio	205.72 €/GT

Compared with Design 1, the design-based KPIs increase in all three categories. This increase is mainly caused by the absorption chiller, which adds a relatively large volume and mass to the system. The downsizing of the electrically driven chiller improves the operational balance of the TEMS, but it does not compensate for the additional physical and economic impact of the absorption chiller. Design 2 therefore introduces a clear trade-off: it improves the use of recoverable heat and the system efficiency in relevant operating conditions, but it also results in a larger, heavier, and more expensive TEMS configuration.

5.3.5. Effect of the Design Modification

The results of Design 2 show that the absorption chiller changes the way the available engine heat is used, but it does not change all operating profiles equally. The main effect is visible in anchor and sailing conditions, where recoverable engine HT heat is available. In harbour, the design modification has almost no effect, because the engines are assumed to be off and no engine HT heat is available for the absorption chiller.

This behaviour can be seen directly in the KPI III results. In Figures 5.10 and 5.11, the absorption chiller appears in the anchor and sailing cases, while it is absent in harbour. This confirms that the new subsystem operates only when both cooling demand and recoverable engine heat are present. Compared with Figures 5.4 and 5.5, Design 2 therefore introduces an additional pathway for useful thermal production, instead of relying only on the electrically driven chiller / heat-pump unit and the recovery heat exchanger.

The effect is especially visible in the warm representative cases. In the most frequent temperature condition, the absorption chiller contributes in several medium- and high-occupancy anchor and sailing scenarios. This is clear in the Mediterranean cases, but also in Atlantic Crossing, Caribbean, Hong Kong, and Middle East scenarios where cooling demand is present. The second most frequent temperature condition shows the same pattern. The absorption chiller contribution is not constant across all climate zones, but it appears consistently in the cases where engine HT heat can be converted into useful cooling.

The engine-HT-utilization plots show this change more clearly. In Design 1, Figure 5.6 shows that the available engine HT heat is used only through the heat exchanger. In several low-occupancy cases, the utilized share remains very small. Even in medium- and high-occupancy cases, the sailing profile uses only a limited part of the available HT heat. This means that a large amount of recoverable engine heat is still rejected rather than converted into useful thermal service.

Design 2 changes this behaviour, as shown in Figure 5.12. The orange contribution still represents heat used by the recovery heat exchanger, while the purple contribution shows the engine HT heat used by the absorption chiller. The total utilized share of engine HT heat increases in several scenarios. For example, under the most frequent temperature condition, the medium-occupancy Atlantic Crossing anchor case increases from about 45% engine-HT utilization in Design 1 to roughly two thirds in Design 2. A similar increase is visible in the Hong Kong anchor case, where the utilization rises from below 40% to close to 70%. The Caribbean cases also show a clear increase, especially in the second most frequent temperature condition, where the absorption chiller adds a visible contribution in both medium- and high-occupancy anchor operation.

The improvement is not limited to anchor. In Design 1, sailing uses only a small share of the available engine HT heat in most scenarios. In Design 2, the absorption chiller increases the HT utilization in sailing as well, although the total share remains lower than in anchor. This is visible in the high-occupancy Mediterranean sailing cases, where the purple contribution adds to the heat-exchanger input. The same trend appears in Atlantic Crossing, Caribbean, Hong Kong, and Middle East. This confirms that the absorption chiller is not only a component-level addition, but also changes the use of the available waste-heat source.

The impact on KPI IV is positive, but more modest than the change in HT utilization. In the most frequent temperature condition, anchor efficiency increases slightly for the second design. The high-occupancy East Mediterranean, West-East Mediterranean, and West Mediterranean anchor cases reach about 60% in Design 2, compared with about 59% in Design 1. Medium-occupancy anchor cases in the same climate zones increase from about 56% to about 57%. Similar one-percentage-point improvements appear in Atlantic Crossing, Caribbean, and Hong Kong. The improvement is therefore consistent, but not large.

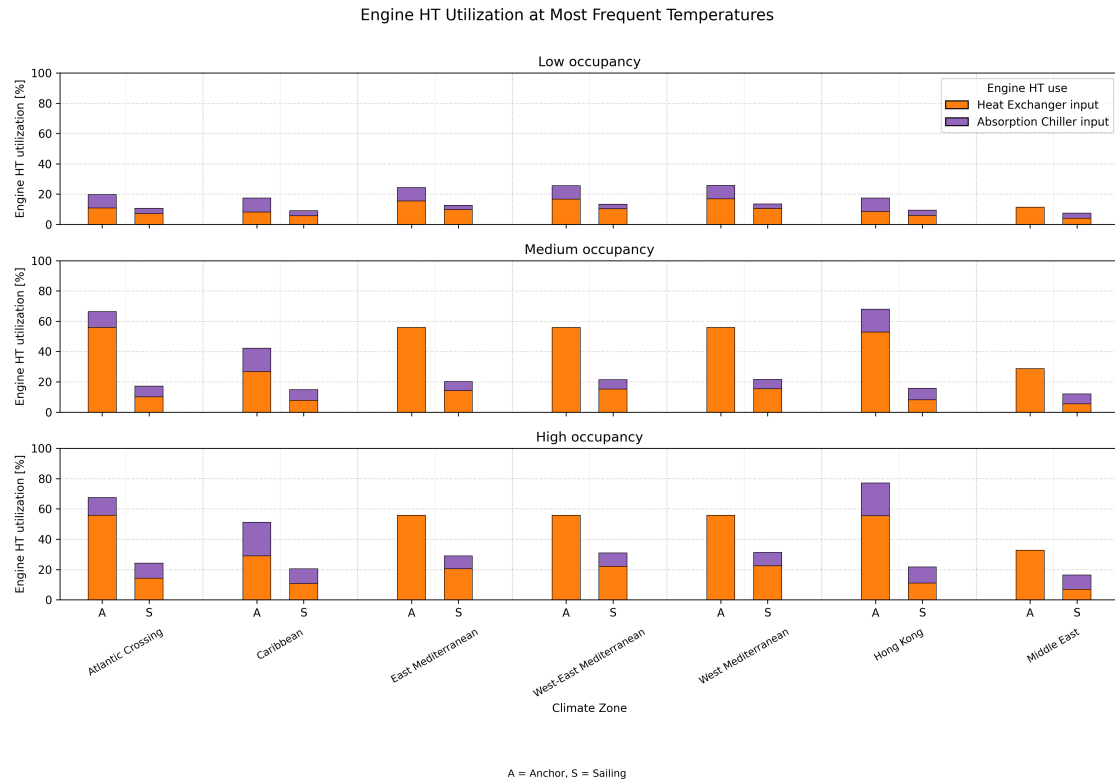


Figure 5.12: Fraction of available engine HT heat used as input to the recovery heat exchanger in Design 2 under the most frequent temperature conditions.

The second most frequent temperature condition shows the same behaviour. The high-occupancy East Mediterranean and West-East Mediterranean anchor cases reach about 60%, while the corresponding Design 1 values are about 59%. The Atlantic Crossing and Caribbean anchor cases also improve slightly. These changes are small in absolute terms, but they occur in the same scenarios where the absorption chiller increases the use of engine HT heat. This supports the interpretation that the efficiency gain is caused by a better use of recoverable heat, rather than by a change in demand.

The sailing improvements are smaller. In the most frequent temperature condition, the high-occupancy West-East Mediterranean and West Mediterranean sailing cases remain around 48%, while some other sailing cases increase by only about one percentage point. This limited change is expected, because KPI IV for sailing is calculated against a larger engine fuel-energy input than in anchor. As a result, the same additional useful thermal output has a smaller effect on the final efficiency value. The absorption chiller still improves the thermal energy use, but this improvement is less visible in the aggregated efficiency indicator.

The design also has clear downsides. First, the absorption chiller uses the same engine HT heat that could otherwise be sent to the recovery heat exchanger. Therefore, the improvement is not simply an addition of free capacity, but a redistribution of the available HT heat between direct heat recovery and heat-driven cooling. Second, the harbour limitation is not solved. The electric heater and heat tank remain necessary in the demanding harbour cases, especially in high-occupancy Mediterranean scenarios. Third, the improved use of recoverable heat comes with a static design penalty. As shown in Table 5.5, Design 2 is larger, heavier, and more expensive than Design 1. The total installed volume increases from 18.65 m³ to 34.73 m³, the installed mass increases from 8,765 kg to 18,265 kg, and the estimated component cost increases from €425,400 to €525,400. This trade-off is mainly caused by the added absorption chiller, whose volume and mass are not compensated by the downsizing of the electrically driven chiller.

Overall, Design 2 improves the use of recoverable engine heat in the conditions for which it was intended. The absorption chiller is active in anchor and sailing, increases the utilized share of engine HT heat, and leads to a small but consistent improvement in KPI IV in the warm representative cases. However, the benefit is profile-dependent. It is strongest when cooling demand and recoverable engine heat occur at the same time, and it disappears in harbour. The design modification therefore improves the operational behaviour of the TEMS, but it does not remove all critical cases and it introduces a clear penalty in space, mass, and cost.

5.4. Final Design Evaluation and Ranking

The previous sections showed that both designs are thermally feasible across the evaluated scenario set, but that they achieve this performance in different ways. The final evaluation therefore has to be read together with the diagnostic performance results. KPI I, KPI II, and KPI III are not included in the final weighted score, because their role is to assess feasibility, storage dependency, and subsystem utilization. They remain essential for identifying where the design has margin for improvement. The final ranking instead uses the selected design-level KPIs: KPI IV, CHPC Efficiency, together with KPI V, Volume Ratio, KPI VI, Mass Ratio, and KPI VII, Cost Ratio.

Since Mode 1 represents the most frequent weather-parameter case, it is used as the main basis for the final comparison. The same ranking procedure was also applied to the remaining weather-parameter cases, and the same overall trend was observed. However, Mode 1 is the most relevant case for the main interpretation because it represents the most recurrent thermal condition in the scenario set. Table 5.6 summarizes the KPI values used for the Mode 1 ranking.

Table 5.6: KPI values used for the final evaluation under Mode 1

Design	KPI IV CHPC Efficiency	KPI V Volume Ratio	KPI VI Mass Ratio	KPI VII Cost Ratio
Design 1	1.820	0.00730	3.43	166.56
Design 2	1.822	0.01360	7.15	205.72

The Mode 1 values show the trade-off created by the design modification. Design 2 achieves a slightly higher KPI IV value, which indicates that the absorption chiller improves the use of recoverable engine heat in the relevant operating profiles. However, the improvement is small. At the same time, the additional subsystem increases the installed volume, mass, and cost of the TEMS, as reflected by KPI V, KPI VI, and KPI VII.

The resulting ranking is shown in Table 5.7. Design 1 is ranked first under the most frequent weather-parameter case. This is because ratio-to-best normalization gives Design 2 the best score only for KPI IV, while Design 1 receives the best score for all three design-based KPIs. Under the equal-weighting assumption adopted in this thesis, the small efficiency improvement of Design 2 is therefore not sufficient to compensate for its larger static design impact.

Table 5.7: Final ranking of Design 1 and Design 2 under Mode 1

Design	Final score	Rank
Design 1	0.9997	1
Design 2	0.7067	2

If a design choice had to be made between the two configurations using the selected weighting factors, Design 1 would therefore be preferred. This does not mean that the modification introduced in Design 2 is ineffective. The diagnostic results showed that the absorption chiller increases the use of recoverable engine HT heat in anchor and sailing conditions. However, KPI II showed that the storage-supported cases are not removed, and KPI III showed that some subsystem bottlenecks remain. The final score therefore confirms that the benefit of Design 2 is not large enough to justify its additional volume, mass, and cost in this specific comparison.

This result illustrates the value of using the full KPI set rather than relying only on the final ranking. The ranking identifies which design is preferable under the selected weighting factors, while the performance KPIs explain why the designs behave as they do and where further improvements should be directed. In this sense, Design 2 should be interpreted as a first improvement iteration rather than as a final optimized solution.

Implications for a next design iteration. The results suggest that a following design iteration should focus on rebalancing the existing system capacities rather than adding another large subsystem. This conclusion follows mainly from the Mode 1 results, which represent the most frequent weather-parameter case. As shown in Figures 5.10 and 5.12, the medium- and high-occupancy anchor scenarios in the Mediterranean still require high thermal output, while less than the full available engine HT heat is used. In these cases, the limitation is therefore not only the availability of recoverable heat, but also the capacity and allocation of the recovery path.

A first modification for Design 3 would be to increase the effective capacity of the HT-to-recovery heat-exchanger path. In the current configuration, the heat exchanger is rated at 580 kW, while the available HT heat at anchor is higher. Increasing this capacity would allow a larger share of the available engine heat to be converted into useful thermal service. This could reduce the need for the electric heater and heat tank in the demanding anchor cases, and could also improve KPI IV by increasing the useful thermal output obtained from the same onboard heat source. The expected penalty is an increase in installed volume, mass, and cost, which would have to be checked through KPI V, KPI VI, and KPI VII.

At the same time, the cooling branches should be reconsidered. In the Mode 1 results, both the absorption chiller and the electrically driven chiller remain below approximately 40% utilization in the analysed representative cases. This suggests that both units may be oversized for the operating conditions that dominate the evaluation. A reduced absorption-chiller capacity could retain the benefit of heat-driven cooling while limiting the static design penalty introduced in Design 2. Similarly, a smaller electrically driven chiller could reduce volume, mass, and cost without necessarily compromising demand coverage, provided that all weather-parameter cases are still satisfied.

The harbour cases require a separate improvement strategy. Since no engine HT heat is assumed to be available in harbour, the absorption chiller cannot address the remaining heating limitation in this profile. If the designer wants to reduce reliance on the heat tanks, the electric heating branch could be increased or replaced by a more efficient electrically driven heating solution, such as a heat-pump-based configuration. For Mode 1, a modest increase of the electric-heater capacity could already reduce the storage-supported harbour cases, but this choice depends on how acceptable thermal-storage reliance is for the client or designer.

Table 5.8 summarizes the main modifications that could be tested in a third design iteration. The values are indicative starting points for a new evaluation cycle, not final design values. Their feasibility would need to be verified across the complete scenario set, including the minimum, maximum, Mode 1, and Mode 2 weather-parameter cases.

The next iteration should therefore be based on the most frequent operating condition, but not validated only against it. Mode 1 can be used to define the main direction of improvement because it represents the most recurrent thermal condition. However, after the Design 3 configuration is defined, the full scenario evaluation must be repeated. If the revised system fails to meet the demand in any minimum, maximum, or Mode 2 scenario, the sizing can then be adjusted in a further iteration. In this way, the performance KPIs guide the design changes, while the final ranking verifies whether the improved performance is sufficient once volume, mass, and cost are also considered.

Table 5.8: Indicative updates to be tested in a possible Design 3 iteration

System	Indicative change	Expected benefit	Main trade-off / check
HT-to-recovery heat exchanger	Upsize from 580 kW toward the available anchor HT heat, approximately 1 MW	More engine heat recovered; less electric-heater and tank support in anchor	Higher volume, mass, and cost
Absorption chiller	Downsize; first test around 50% of current capacity, approximately 230 kW	Keeps heat-driven cooling where useful	Must still cover warm anchor and sailing cases
Electrical chiller / heat pump	Downsize; first test around 50% of current capacity, approximately 250 kW	Reduces volume, mass, and cost	Must still cover maximum cooling cases
Electric heater / harbour heating	Upsize from 350 kW to about 400 kW, or replace with higher-COP heating	Reduces reliance on heat tanks in harbour	Higher electric demand; depends on storage strategy

6. Validation of the Design Method

This chapter validates the proposed TEMS evaluation method using the Validation Square. The method is assessed through four complementary elements: the validity of its theoretical structure, the suitability of the selected case study, its usefulness when applied to that case, and the extent to which this usefulness can be extended to similar design problems. Figure 6.1 summarizes this validation structure as applied in the present thesis.

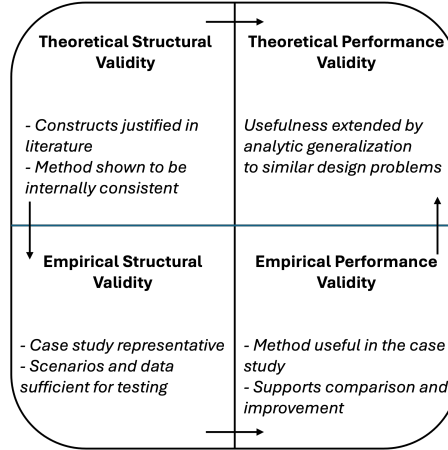


Figure 6.1: Application of the Validation Square to the proposed TEMS evaluation method

6.1. Theoretical Structural Validity

6.1.1. Method constructs

The first step is to assess whether the main constructs of the method are appropriate for the type of problem addressed in this thesis. The proposed framework is intended for the early-stage evaluation, comparison, and iterative improvement of yacht Thermal Energy Management System (TEMS) designs. This problem involves multiple criteria, strong dependence on operating conditions, and limited design-stage information. The method therefore combines several complementary constructs rather than relying on a single model.

At framework level, the method is based on Multi-Criteria Decision Analysis (MCDA), a KPI-based representation of effectiveness, and a distinction between performance-based and design-based indicators. This combination is appropriate because TEMS effectiveness cannot be represented by one variable only. Instead, it must include how the system performs under operating conditions and what the design implies in terms of efficiency, space, weight, and cost. MCDA provides the overall decision-support structure for this type of multi-criteria problem [59], while the KPI architecture ensures that the different dimensions of effectiveness remain explicit and traceable.

For the performance branch, the method uses Scenario-Based Reasoning (SBR) together with scenario weighting and aggregation. This is appropriate because yacht TEMS performance depends on operational profile, climate zone, and occupancy level. A single nominal condition would therefore not represent the actual range of system behaviour. Scenario-based approaches are suitable for design problems in which performance depends on varying contexts [60]. In the present method, SBR captures this variation, while scenario weighting allows the scenario results to be combined into representative design-level information.

For the calculation and ranking steps, the method uses design-stage-feasible steady-state and analytical procedures, followed by ratio-to-best normalization with weighted additive aggregation. This is consistent with the intended application stage. The performance branch remains simple enough to be applied with limited concept-design data, while the design branch evaluates the physical and economic implications from configuration data. Once the selected design-level KPIs have been determined, ratio-to-best normalization and weighted aggregation provide a transparent way to compare alternatives [45].

The final construct is the iterative design-improvement loop. The purpose of the method is not only to rank alternatives, but also to identify weaknesses, propose improvements, and re-evaluate revised configurations within the same framework. This is particularly relevant in early-stage yacht design, where evaluation should guide improvement as well as comparison.

Taken together, these constructs form a suitable basis for the proposed method. MCDA provides the overall structure, SBR captures scenario-dependent performance, the KPI architecture separates operational and design-dependent aspects, and the calculation and aggregation procedures support comparison while preserving traceability. The method can therefore be considered theoretically structurally valid at construct level.

6.1.2. Internal consistency of the method

Theoretical structural validity also requires the method to be internally consistent. In practice, this means that the steps of the framework must form a coherent sequence in which each stage has the required input and produces the output needed by the next stage.

The framework follows four connected steps. First, the problem, the evaluation objective, and the KPIs are defined. Second, the scenarios for the performance-based assessment are established. Third, a selected TEMS design is evaluated and, if needed, improved through iteration. Fourth, the final KPI results are normalized, aggregated, and used to compare the alternative designs. This sequence is logically consistent because each step depends directly on the outcome of the previous one.

As shown in Figure 3.1, the problem definition determines the objective and KPI structure. The KPI structure then determines which indicators require scenario definition and which can be evaluated directly from design data. The scenario definition and collected input data provide the basis for the weather, demand, generation, and KPI calculations. These results support both design interpretation and the proposal of improved configurations. Finally, the selected design-level KPI results are normalized and aggregated to support comparison between alternatives.

The method remains consistent during iteration. The scenario structure, weather-parameter matrix, and demand model are kept fixed because they belong to the case-study definition rather than to a specific TEMS configuration. What changes is the design configuration and the corresponding generation and KPI outcomes. This ensures that differences between iterations can be attributed to the design changes themselves rather than to changes in the evaluation setup.

The method therefore does not contain major structural gaps or redundant branches. Its constructs are not only individually appropriate, but also integrated into a coherent and logically connected procedure.

6.2. Empirical Structural Validity

6.2.1. Appropriateness of the case study

The next step is to verify that the selected case study is appropriate for testing the method. At this stage, the objective is not yet to demonstrate general usefulness, but to show that the vessel, design alternatives, scenarios, and available data represent the type of problem for which the method is intended.

The case study is based on M/Y *Obsidian*, an 84.2 m custom motor yacht previously used in related research within the shipyard. This makes the case suitable for two reasons. First, it ensures continuity

with an existing research context and avoids relying on a purely hypothetical example. Second, the yacht is representative of the class of large custom yachts for which TEMS design involves multiple interacting thermal subsystems, variable operating conditions, and limited design-stage information.

The case setup is also consistent with the purpose of the method. The framework was developed to support both comparison and iterative improvement. In the present application, this is reflected in the use of one reference vessel and two design configurations: an initial baseline design and a revised configuration derived from the evaluation of the first one. This allows the method to be tested not only as a comparison tool, but also as a support tool for structured redesign.

The scenario structure further supports the suitability of the case. The performance-based branch is intended to assess system behaviour under different operating conditions rather than under one nominal case. For this reason, the case study includes scenarios defined by operational profile, climate zone, and occupancy level. These dimensions capture the main sources of variation affecting yacht thermal demand and thermal-generation potential in early-stage design. Both design alternatives are evaluated under the same framework, which isolates the effect of the design changes from the effect of the evaluation setup.

The available data are also sufficient for testing the method. The application relies on environmental data, design-specific technical data, and weighting factors for the expected operating distribution of the yacht. Although these inputs do not all have the same degree of certainty, they are sufficient to construct the weather-parameter matrix, estimate the thermal demand, evaluate the useful heat and cooling generated by the TEMS, and calculate both the performance-based and design-based KPIs. The case study therefore provides enough information to test the full framework rather than only selected parts of it.

The scope of this empirical validation should nevertheless be stated clearly. The use of one yacht and two design alternatives does not provide statistical generalization across the full superyacht sector. However, this is not the purpose of empirical structural validity. At this stage, the requirement is only that the example problem be suitable for testing the method. From that perspective, the selected case study is appropriate and can therefore be considered empirically structurally valid.

6.3. Empirical Performance Validity

6.3.1. Usefulness of the method for the selected case

After establishing that the case study is appropriate, the next step is to assess whether the method is useful when applied to that case. In this thesis, usefulness is judged with respect to the purpose of the method: supporting the early-stage evaluation, comparison, and iterative improvement of alternative yacht TEMS designs through a transparent and traceable framework.

The application of the method shows its usefulness in several ways. First, it evaluates the TEMS through multiple performance dimensions rather than through a single indicator. This makes it possible to assess not only whether the required thermal service can be provided, but also how efficiently this is achieved and what the corresponding implications are in terms of space, weight, and cost. Second, through the scenario-based branch, the method reveals how the system behaves under different operating conditions, rather than under one nominal case. Third, because the same KPI structure, scenario framework, and evaluation logic are applied to each configuration, the comparison between alternatives remains consistent and traceable. Finally, the framework supports design improvement as well as evaluation, since the results of one iteration can be used to identify weaknesses, propose modifications, and re-evaluate the revised design within the same structure.

The method is therefore useful for the selected case study and can be considered to possess empirical performance validity at case-study level.

6.3.2. Contribution of the method to the observed usefulness

A further validation question is whether this usefulness can be attributed to the method itself rather than to the availability of case-specific data alone. In the logic of the Validation Square, this requires examining how the main constructs contribute to the observed usefulness.

A first contribution comes from the overall evaluation structure. MCDA and the KPI architecture turn the assessment into a coherent decision-support process rather than a set of disconnected technical checks. The distinction between performance-based and design-based KPIs is essential here, because it allows the framework to capture both scenario-dependent system behaviour and the physical and economic implications of the design.

A second contribution comes from Scenario-Based Reasoning and the associated scenario weighting. Without this part of the method, the evaluation would collapse to one nominal operating condition and would lose the ability to reveal where the system performs well, where it becomes critical, and which operating situations drive the main weaknesses of the design. Weighting then allows the scenario results to be interpreted at design level without losing their operational meaning.

A third contribution comes from the design-stage-feasible calculation procedures, the final ranking method, and the iterative loop. The steady-state and analytical procedures make the framework applicable during concept development, where detailed information is still limited. Ratio-to-best normalization with weighted aggregation then provides a transparent way to compare alternatives once the selected design-level KPIs have been determined. Finally, the iterative loop extends the method beyond static evaluation by allowing revised designs to be assessed within the same framework.

The usefulness of the method is therefore not accidental. It arises from the combined contribution of its constructs, which means that the observed usefulness can reasonably be linked to applying the method itself. This supports the empirical performance validity of the framework.

6.4. Theoretical Performance Validity

The final step is to assess whether the usefulness demonstrated for the selected case study can reasonably be extended beyond that single application. The question is therefore not whether the method is valid for all possible thermal-energy-system design problems, but whether the previous validation steps support its use for the broader class of problems for which it was developed.

Taken together, the preceding sections show that the method is built on appropriate constructs, organized as a logically consistent procedure, tested on a suitable case study, and capable of producing meaningful and decision-relevant insight. In addition, the observed usefulness was linked to the contribution of the method itself rather than to the availability of case-specific data alone. On this basis, the framework can be considered theoretically valid for the early-stage evaluation, comparison, and iterative improvement of alternative yacht TEMS designs.

This claim remains bounded by the assumptions of the method. The performance branch relies on a steady-state representation and is therefore intended for comparative design evaluation rather than dynamic prediction of transient behaviour or detailed control response. The final comparison also depends on the selected KPI set, the adopted weighting factors, and the chosen aggregation procedure. In addition, the present validation is based on one representative yacht and two design alternatives. The method can therefore be generalized analytically to similar design problems, but it is not statistically validated across a large population of vessels or configurations.

These limitations do not invalidate the method, but define the context within which the claim of validity can be made. Within that context, the proposed framework can be considered to possess theoretical performance validity.

7. Conclusion & Discussion

This chapter answers the main research question on the basis of the method developed and the results obtained in the case study. It then discusses the interpretation, relevance, and limitations of the proposed framework, and outlines the main directions for future work.

7.1. Conclusion

7.1.1. Answer to the Main Research Question

The main research question of this thesis is:

“How can the effectiveness of a Thermal Energy Management System (TEMS) design be evaluated across multiple operational scenarios in order to support design improvement?”

This thesis shows that the effectiveness of a yacht TEMS design can be evaluated through a structured method that combines scenario-based performance assessment with design-based comparison. More specifically, the proposed framework combines MCDA as the overall decision-support structure, an adapted SBR approach for the performance-based KPIs, and direct analytical calculations for the design-dependent KPIs. Within this framework, effectiveness is assessed across a scenario matrix defined by operational profile, climate zone, occupancy level, and representative weather-parameter case, rather than under a single reference condition. In the present case study, this resulted in 252 evaluated scenarios, which made it possible to assess thermal feasibility, robustness, subsystem utilization, energetic effectiveness, and static design impact in terms of volume, mass, and cost.

The application of the method to *M/Y Obsidian* showed that this approach gives a specific and practically useful answer to the design problem identified at the start of the thesis. First, it determines whether a TEMS design can meet the required onboard thermal demand across the considered operating conditions. In the present application, Design 1 was found to cover the thermal demand in all evaluated scenarios. Of the 252 scenarios, 222 were classified as *Unlimited*, 30 required support from thermal storage, and none were classified as *Unable*. Second, the method identifies where the design becomes critical. For the baseline design, the most demanding cases were concentrated in the higher-occupancy Mediterranean scenarios, where the recovery heat exchanger became highly utilized in anchor operation and the electric heater became the main bottleneck in harbour. Third, the method explains why these critical cases appear. The results showed that a significant share of the available engine HT heat remained unused, while the electrically driven chiller was relatively underutilized in the most representative conditions. This means that the baseline design did not mainly suffer from a lack of thermal energy at source, but from limited ability to recover and use that energy effectively.

The method also showed how TEMS evaluation can support design improvement rather than only design judgement. Based on the weaknesses identified in Design 1, a second configuration was developed in which an absorption chiller was introduced and the electrically driven chiller was downsized. The results showed that this modification improved the use of recoverable engine HT heat in the profiles where such heat was available, namely anchor and sailing, and led to a small but consistent improvement in KPI IV. However, the same evaluation also showed the limits of this improvement. The benefit was largely absent in harbour, where no engine HT heat was assumed to be available, and the added absorption chiller caused a substantial increase in installed volume, mass, and cost. As a result, the final ranking showed that Design 1 remained the preferred solution under the selected equal weighting factors. The two designs performed very similarly in weighted KPI IV, but Design 1 performed substantially better in the three design-based KPIs. This shows that the proposed method does not simply reward the addition of new technology, but reveals the actual trade-off between operational improvement and design penalty.

The main research question can therefore be answered as follows. The effectiveness of a yacht TEMS

design can be evaluated across multiple operational scenarios by combining scenario-based thermal-demand and heat-generation modelling with a KPI-based comparison framework that distinguishes between operational behaviour and static design impact. Within the scope of this thesis, this method proved capable of identifying whether a design is feasible, where its main bottlenecks are located, how effectively it uses the available energy sources, and whether a proposed design modification leads to a more favourable overall solution. The main contribution of this thesis is therefore the development and demonstration of a structured design-support method for the early-stage evaluation, comparison, and improvement of yacht TEMS concepts.

7.1.2. Answers to the Sub-questions

The main research question was addressed through five sub-questions. Their answers can now be summarized on the basis of the findings presented in Chapters 2 to 6.

Sub-question 1: “How do the DVNA design process and the configuration of yacht TEMS shape the requirements for a methodology to evaluate TEMS effectiveness?”

The analysis of the DVNA design process showed that early-stage TEMS decisions are still based largely on worst-case assumptions, spreadsheet-based load balances, and separated subsystem sizing. At the same time, the analysis of yacht TEMS configurations showed that thermal demand and recoverable heat vary strongly with operational profile, climate zone, occupancy, and subsystem arrangement. Together, these findings led directly to the definition of the eight method requirements: the method had to be multi-KPI, flexible, comparative, traceable, data-driven, feasible at design stage, steady-state based, and capable of evaluating performance across multiple scenarios while producing both scenario-specific and design-level outputs.

Sub-question 2: “Which KPIs and associated evaluation methods are most appropriate for assessing yacht TEMS effectiveness across multiple operational scenarios?”

The thesis showed that no single KPI is sufficient to represent TEMS effectiveness. A suitable evaluation requires both performance-based and design-dependent indicators. For this reason, the final KPI set consisted of Load Coverage, Coverage Durability, Usage Ratio, and CHPC Efficiency on the performance side, and Volume Ratio, Mass Ratio, and Cost Ratio on the design side. MCDA was selected as the overall comparison framework, adapted SBR was selected for the performance-based KPIs, and direct analytical calculations were used for the design-dependent KPIs. This combination was shown to satisfy the methodological requirements more effectively than any of the approaches on their own.

Sub-question 3: “How can the selected KPI framework and evaluation methods be translated into an operational model for TEMS effectiveness evaluation, and what input data, scenario definitions, and assumptions are required for its implementation?”

The selected KPI framework was translated into an operational model through a four-step procedure: problem, objective, and KPI definition; scenario definition; design evaluation and improvement loop; and final normalization and ranking. In the implemented case study, the scenario space was defined by operational profile, climate zone, occupancy level, and representative weather-parameter case, resulting in 252 scenarios. The required inputs included fleet-based weather data, seawater temperatures, technical specifications of the TEMS components, and scenario weighting factors. The operational model itself consisted of a weather-parameter matrix, a scenario-based demand model using the domestic hot water, HVAC, and pool workbooks, a steady-state heat-generation model, and a KPI post-processing step.

Sub-question 4: “What results are obtained when the proposed evaluation method is applied to the selected yacht, and how do the baseline and improved TEMS designs compare?”

The application to *M/Y Obsidian* showed first that the baseline design, Design 1, was thermally feasible across the full evaluated scenario space. However, the method also revealed that the design margin was not uniform. The most critical cases were concentrated in the higher-occupancy Mediterranean scenarios, where the recovery heat exchanger became highly utilized in anchor operation and the electric heater

became the limiting component in harbour. These findings motivated the development of Design 2, in which an absorption chiller was introduced and the electric chiller was downsized. Design 2 improved the use of recoverable engine HT heat in anchor and sailing and produced a small but consistent increase in KPI IV, but this benefit remained profile-dependent and was largely absent in harbour. At the same time, the absorption chiller introduced a clear penalty in installed volume, mass, and cost. As a result, the final ranking showed that Design 1 remained the preferred configuration under the selected equal weighting factors.

Sub-question 5: “How can the accuracy of the proposed evaluation method be validated?”

The thesis addressed this question through the Validation Square. The validation showed, first, that the method is theoretically structurally valid because its main constructs are appropriate for the problem and internally consistent when combined into the four-step procedure. Second, the case study was shown to be empirically structurally valid, since *M/Y Obsidian* and the two design alternatives represent a realistic example of the type of early-stage yacht TEMS problem for which the method is intended. Third, the method was shown to possess empirical performance validity, because its application produced useful engineering insight, enabled transparent comparison between alternatives, and guided a concrete design-improvement iteration. Finally, the method was argued to possess theoretical performance validity within its intended domain, namely the early-stage evaluation, comparison, and iterative improvement of yacht TEMS concepts under multiple operational scenarios.

7.2. Discussion

7.2.1. Interpretation and Relevance

The results show that the proposed framework is useful because it separates three questions that would otherwise be difficult to distinguish. First, it checks whether a TEMS design is thermally feasible across the scenario set. Second, it identifies how the system achieves this feasibility, including storage use and subsystem loading. Third, it compares design alternatives by combining the selected design-level KPIs into a final ranking. This distinction is important because the case study showed that thermal feasibility does not automatically imply a better overall design.

Both evaluated configurations were able to cover the thermal demand in all considered scenarios. However, the two designs did not perform equally from a design perspective. Design 2 improved the use of recoverable engine HT heat in anchor and sailing conditions and produced a small increase in KPI IV. At the same time, the added absorption chiller increased the installed volume, mass, and cost of the TEMS. Under the selected weighting factors, this penalty was larger than the efficiency benefit, so Design 1 remained the preferred option in the final ranking. The main outcome is therefore not only that Design 1 ranked higher, but that the method explained why the improvement introduced in Design 2 was not sufficient.

The scenario-based results also showed that yacht TEMS performance cannot be understood from a single nominal design point. The most critical conditions were concentrated in specific parts of the scenario space, especially higher-occupancy Mediterranean cases. In these scenarios, the recovery heat exchanger, electric heater, and heat tank became more relevant, while other components remained far from their installed capacity. This information is not captured by the final ranking alone. It is provided by the performance KPIs, especially KPI II and KPI III, which show where storage support is required and which subsystems operate close to their limits.

The case study also showed that design improvements are profile-dependent. The absorption chiller improved the use of recoverable heat only when cooling demand and engine HT heat were available at the same time. This occurred mainly in anchor and sailing conditions. In harbour, where no engine HT heat was assumed to be available, the same modification did not address the remaining limitation. This confirms that a TEMS modification should not be judged only by its component-level potential, but by its effect across the operating profiles in which the yacht is expected to operate.

From a practical design perspective, the framework addresses a relevant gap in the current process. Chapter 2 showed that yacht thermal systems are often sized from conservative boundary conditions and developed through separated subsystem calculations. The proposed framework adds an internal evaluation step before detailed design choices are fixed. It allows alternative configurations to be compared under the same scenario set, while also indicating which parts of the system should be reconsidered in the next design iteration. Its value therefore lies both in supporting design selection and in guiding design improvement.

7.2.2. Strengths and Limitations of the Method

The main strength of the method is its multi-output structure. The final score is not the only result of the evaluation. Load Coverage, Coverage Durability, and Usage Ratio first provide information on feasibility, robustness, and subsystem loading. CHPC Efficiency and the design-dependent KPIs are then used to compare alternatives at design level. This prevents the evaluation from reducing TEMS effectiveness to one indicator too early, while still allowing a final ranking when a decision between alternatives is required.

A second strength is the combination of MCDA, adapted SBR, and analytical calculations. MCDA provides the structure for comparing alternatives across multiple KPIs. The adapted scenario-based approach captures the dependence of performance on operational profile, climate zone, occupancy level, and weather-parameter case. Analytical calculations allow the design-dependent KPIs to be determined from available component data. Together, these elements make the method traceable and repeatable, while keeping it feasible for early-stage design work.

The method also supports iterative design. This was shown by the transition from Design 1 to Design 2. The first evaluation identified unused engine HT heat and limited use of the electrically driven chiller as improvement opportunities. The second design then tested a recovery-based modification by adding an absorption chiller. Although this modification did not improve the final ranking, the method still showed where the change was beneficial and where it introduced new penalties. This is a useful outcome for design development, because it turns the evaluation into a structured feedback loop rather than a one-time comparison.

The main limitation of the method is its steady-state representation of performance. Each scenario is evaluated as a design condition, without modelling transient demand, control actions, storage charging and discharging, or part-load behaviour over time. This choice is consistent with the intended design-stage use of the framework, but it limits the level of operational detail that can be captured. The method should therefore be interpreted as a comparative design-support tool, not as a high-fidelity simulation of onboard operation.

A second limitation is the dependence on scenario definition and weighting. The scenario set makes the evaluation more representative than a single design point, but the aggregated results depend on how the operational profiles, climate zones, occupancy levels, and weather-parameter cases are selected and weighted. If these assumptions change, the aggregated KPI values and final ranking may also change. This is not a weakness of the scenario-based approach itself, but it means that the quality of the evaluation depends on the quality and representativeness of the scenario data.

A third limitation concerns the final ranking method. Ratio-to-best normalization is transparent and suitable for comparing two alternatives, but it is relative to the evaluated design set. The final score therefore depends on the alternatives included in the comparison and on the selected weighting factors. For this reason, the ranking should always be interpreted together with the raw KPI values and the diagnostic scenario results. In this thesis, the equal-weighting assumption was useful to keep the comparison neutral, but it does not represent the preference structure of a specific owner, designer, or shipyard.

7.2.3. Limitations of the Case-Study Application

The application to M/Y Obsidian demonstrates the method on a realistic and relevant yacht, but the implemented model remains an approximation of the actual system. Design 1 was defined to represent the baseline TEMS as closely as possible using the available information, manufacturer data, and engineering estimates. However, it is not a complete one-to-one reproduction of the real yacht. The results should therefore be interpreted as a structured case-study evaluation rather than as a detailed performance assessment of the actual vessel.

The representation of the onboard power-generation system is another important limitation. In the implemented model, the recoverable engine heat is prescribed for each operational profile. The engine configuration is fixed for sailing, anchor, and harbour operation, and is not determined dynamically from propulsion demand, hotel load, battery state, or hybrid operating strategy. In reality, recoverable heat depends on engine dispatch and load, and is coupled to the wider electrical and propulsion system. This simplification is acceptable for a first comparative application, but it limits the accuracy of the absolute heat-availability results.

The electrical side of the system is also simplified. KPI IV includes electrical production and consumption terms, but the model does not include a full onboard electrical-load balance. It therefore does not determine how generated electrical energy is distributed between propulsion, hotel load, batteries, thermal equipment, and auxiliary systems. This affects the interpretation of the CHPC Efficiency results, especially in hybrid operating conditions where thermal and electrical performance are strongly coupled.

The heat-demand model also depends on the quality of the existing subsystem workbooks. The domestic hot water, HVAC, and swimming-pool workbooks were used as calculation modules and were assumed to be suitable for the scenario-based evaluation. Some operational assumptions, such as active systems, use patterns, and the heating or cooling classification of the HVAC demand, were based on engineering judgement. In addition, constant efficiencies and coefficients of performance were used where detailed performance maps were not available. These choices are reasonable for the intended scope, but they mean that the numerical results depend on the representativeness of the input models and assumptions.

Finally, the design-based KPIs are concept-level indicators. Component volumes were estimated using simplified geometric envelopes, and mass and cost values were based on available component data and estimates. These values are sufficient for comparing the two modelled configurations, but they do not replace a detailed integration, arrangement, or cost study. The final ranking should therefore be understood as a comparative design-stage result, not as a final procurement or integration decision.

7.3. Recommendations for Future Work

Future work should first improve the representation of the onboard energy system. The most important extension would be to include an explicit electrical-load and power-generation model. This would allow engine operation, electrical production, battery interaction, and recoverable heat availability to be calculated together within each scenario. Such an extension would be especially relevant for hybrid yachts, where the thermal system is strongly connected to the electrical and propulsion architecture.

A second recommendation is to extend the performance model beyond steady-state evaluation. A dynamic or quasi-dynamic layer would make it possible to study storage charging and discharging, part-load operation, equipment control, and transitions between operating conditions. This would be particularly useful for evaluating the heat tanks, since the current method determines whether storage support is needed and for how long, but does not model how the tanks are charged, depleted, or recovered over an operating period.

A third recommendation is to improve the input data used for scenario weighting and subsystem operation. The operational-profile weights were based on Feadship fleet-average AIS data, but the climate-zone and occupancy distributions relied partly on engineering assumptions supported by sector evidence. Future work could refine these values using more vessel-specific operational data, charter schedules, owner-use profiles, or long-term monitoring data. This would improve the representativeness

of the aggregated KPI results.

The framework should also be applied to a larger set of yachts and design alternatives. In this thesis, the method was demonstrated on one reference yacht and two TEMS configurations. Applying the same method to additional vessels would test whether the selected KPI structure and scenario logic remain suitable across different yacht sizes, operating patterns, and system architectures. Evaluating more than two alternatives would also make it possible to apply and compare ranking methods such as TOPSIS in a more meaningful way.

Further work should also include sensitivity analysis. The final ranking depends on KPI weighting factors, scenario weights, component assumptions, and normalization method. Testing the sensitivity of the ranking to these choices would show which assumptions have the strongest influence on the design decision. This would be useful in practical design work, where different stakeholders may assign different importance to efficiency, space, mass, cost, and robustness.

Finally, the design-improvement direction identified in Chapter 5 should be developed further. The next iteration should focus on rebalancing the recovery, cooling, and harbour-heating pathways, rather than simply adding another subsystem. In particular, the HT-to-recovery heat-exchanger capacity, the sizing of the absorption and electrical chillers, and the harbour heating strategy should be evaluated in a new design cycle. The same framework can then be used to test whether these modifications improve the diagnostic performance KPIs while still producing a favourable final ranking once volume, mass, and cost are included.

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Appendix

A. Weather Parameters

Table A.1: Weather boundary conditions for the Anchor operational profile by climate zone and parameter set^a.

Climate Zone	Parameter	Air T @ 10 m [°C]	RH @ 10 m [%]	h @ 10 m [kJ/kg]	Seawater T [°C]
Atlantic Crossing	Min	2.50	25.00	5.33	-2.00
	Max	37.50	35.00	74.13	31.60
	Mode 1	22.50	85.00	59.57	25.50
	Mode 2	27.50	65.00	65.88	26.00
Caribbean	Min	2.50	55.00	8.72	17.50
	Max	32.50	95.00	109.16	34.30
	Mode 1	27.50	65.00	65.88	30.00
	Mode 2	22.50	85.00	59.57	27.00
East Mediterranean	Min	2.50	25.00	5.33	13.30
	Max	37.50	45.00	84.84	32.50
	Mode 1	22.50	85.00	59.57	18.00
	Mode 2	27.50	65.00	65.88	17.50
West-East Mediterranean	Min	2.50	25.00	5.33	7.70
	Max	37.50	45.00	84.84	32.80
	Mode 1	22.50	85.00	59.57	16.00
	Mode 2	27.50	65.00	65.88	16.10
West Mediterranean	Min	2.50	65.00	9.86	9.30
	Max	32.50	75.00	92.46	31.00
	Mode 1	22.50	85.00	59.57	15.50
	Mode 2	17.50	85.00	44.44	15.00
Hong Kong	Min	7.50	45.00	14.77	13.10
	Max	32.50	85.00	100.77	32.50
	Mode 1	22.50	85.00	59.57	29.50
	Mode 2	27.50	85.00	78.02	29.60
Middle East	Min	12.50	55.00	25.00	13.10
	Max	32.50	75.00	92.46	36.70
	Mode 1	17.50	85.00	44.44	34.50
	Mode 2	22.50	65.00	50.72	34.60

^a Min = lowest observed combination of air and seawater temperatures; Max = highest observed combination; Mode 1 = most frequent combination; Mode 2 = second most frequent combination.

Table A.2: Weather boundary conditions for the Sailing operational profile by climate zone and parameter set^a.

Climate Zone	Parameter	Air T @ 10 m [°C]	RH @ 10 m [%]	h @ 10 m [kJ/kg]	Seawater T [°C]
Atlantic Crossing	Min	2.50	25.00	5.33	-2.00
	Max	37.50	25.00	63.56	31.60
	Mode 1	27.50	85.00	78.02	25.50
	Mode 2	22.50	75.00	55.13	26.00
Caribbean	Min	7.50	55.00	16.39	17.50
	Max	32.50	85.00	100.77	34.30
	Mode 1	27.50	85.00	78.02	30.00
	Mode 2	22.50	75.00	55.13	27.00
East Mediterranean	Min	2.50	45.00	7.59	13.30
	Max	37.50	35.00	74.13	32.50
	Mode 1	22.50	65.00	50.72	18.00
	Mode 2	27.50	65.00	65.88	17.50
West-East Mediterranean	Min	2.50	45.00	7.59	7.70
	Max	37.50	35.00	74.13	32.80
	Mode 1	22.50	75.00	55.13	16.00
	Mode 2	27.50	65.00	65.88	16.10
West Mediterranean	Min	2.50	55.00	8.72	9.30
	Max	37.50	25.00	63.56	31.00
	Mode 1	22.50	75.00	55.13	15.50
	Mode 2	27.50	65.00	65.88	15.00
Hong Kong	Min	12.50	25.00	18.20	13.10
	Max	32.50	85.00	100.77	32.50
	Mode 1	22.50	75.00	92.46	29.50
	Mode 2	22.50	65.00	50.72	29.60
Middle East	Min	17.50	45.00	31.70	13.10
	Max	37.50	45.00	84.84	36.70
	Mode 1	27.50	65.00	65.88	34.50
	Mode 2	22.50	75.00	55.13	34.60

^a Min = lowest observed combination of air and seawater temperatures; Max = highest observed combination; Mode 1 = most frequent combination; Mode 2 = second most frequent combination.

Table A.3: Weather boundary conditions for the Harbour operational profile by climate zone and parameter set^a.

Climate Zone	Parameter	Air T @ 10 m [°C]	RH @ 10 m [%]	h @ 10 m [kJ/kg]	Seawater T [°C]
Atlantic Crossing	Min	2.50	25.00	5.33	-2.00
	Max	32.50	95.00	109.16	31.60
	Mode 1	27.50	85.00	78.02	25.50
	Mode 2	22.50	75.00	55.13	26.00
Caribbean	Min	7.50	55.00	16.39	17.50
	Max	32.50	95.00	109.16	34.30
	Mode 1	27.50	65.00	65.88	30.00
	Mode 2	22.50	75.00	55.13	27.00
East Mediterranean	Min	2.50	15.00	4.20	13.30
	Max	32.50	85.00	100.77	32.50
	Mode 1	12.50	85.00	31.87	18.00
	Mode 2	7.50	65.00	18.01	17.50
West-East Mediterranean	Min	2.50	15.00	4.20	7.70
	Max	32.50	85.00	100.77	32.80
	Mode 1	12.50	85.00	31.87	16.00
	Mode 2	7.50	65.00	18.01	16.10
West Mediterranean	Min	2.50	25.00	5.33	9.30
	Max	32.50	85.00	100.77	31.00
	Mode 1	7.50	65.00	18.01	15.50
	Mode 2	12.50	75.00	29.57	15.00
Hong Kong	Min	7.50	25.00	11.55	13.10
	Max	32.50	85.00	100.77	32.50
	Mode 1	32.50	75.00	92.46	29.50
	Mode 2	22.50	65.00	50.72	29.60
Middle East	Min	12.50	65.00	27.28	13.10
	Max	37.50	35.00	74.13	36.70
	Mode 1	22.50	75.00	55.13	34.50
	Mode 2	17.50	85.00	44.44	34.60

^a Min = lowest observed combination of air and seawater temperatures; Max = highest observed combination; Mode 1 = most frequent combination; Mode 2 = second most frequent combination.

B. Temperature Profiles by Climate Zone and Operational Profile

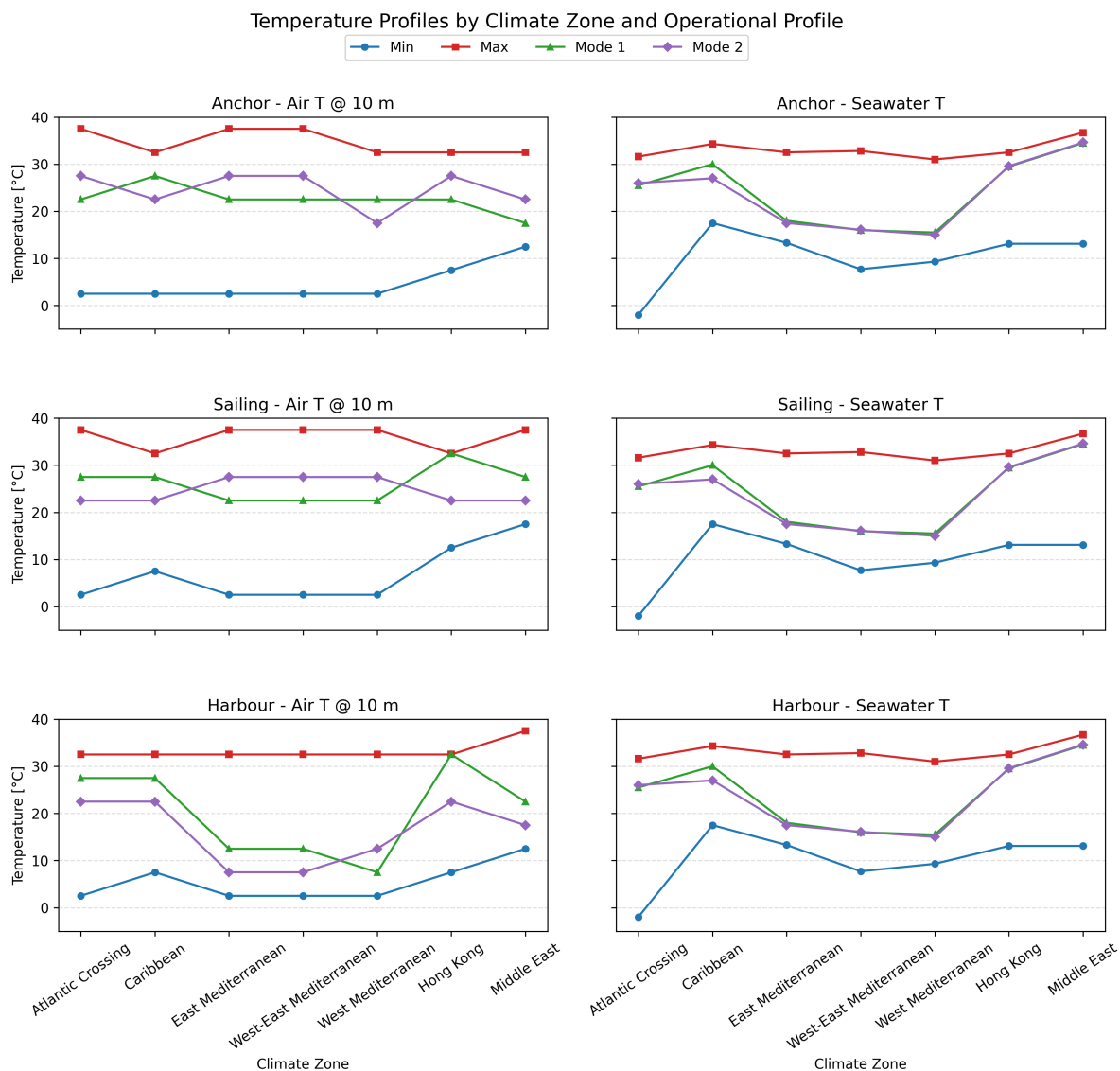


Figure B.1: Temperature Profiles by Climate Zone and Operational Profile

C. Heat Demand Matrix

Table C.1: Heat demand matrix for low-occupancy scenarios^a.

Climate Zone	Parameter	Anchor				Sailing				Harbour			
		DWS	HVAC	Pool	Total	DWS	HVAC	Pool	Total	DWS	HVAC	Pool	Total
Atlantic Crossing	Min	285.22	48.44	0	333.66	408.11	40.28	0	448.39	254.04	48.79	0	302.83
	Max	75.16	72.52	0	147.68	128.29	57.75	0	186.03	91.10	83.40	0	174.50
	Mode 1	113.29	67.43	0	180.72	179.09	62.08	0	241.17	120.68	73.02	0	193.70
	Mode 2	110.17	69.64	0	179.80	174.92	55.22	0	230.14	118.26	65.39	0	183.65
Caribbean	Min	163.31	49.63	0	212.94	245.71	43.59	0	289.31	159.48	52.48	0	211.95
	Max	58.28	84.79	0	143.06	105.80	68.91	0	174.71	78.01	83.40	0	161.41
	Mode 1	85.16	69.64	0	154.80	141.61	62.08	0	203.70	98.86	68.97	0	167.84
	Mode 2	103.91	67.43	0	171.34	166.60	55.22	0	221.82	113.41	65.39	0	178.80
East Mediterranean	Min	189.57	48.44	0	238.01	280.69	40.96	0	321.65	179.85	48.41	0	228.26
	Max	69.53	76.27	0	145.80	120.79	60.92	0	181.71	86.74	80.60	0	167.34
	Mode 1	160.18	67.43	0	227.61	241.55	53.90	0	295.45	157.05	57.64	0	214.69
	Mode 2	163.31	69.64	0	232.95	245.71	58.44	0	304.16	159.48	53.02	0	212.49
West-East Mediterranean	Min	224.58	48.44	0	273.02	327.33	40.96	0	368.29	207.00	48.41	0	255.42
	Max	67.65	76.27	0	143.93	118.29	60.92	0	179.21	85.28	80.60	0	165.89
	Mode 1	172.69	67.43	0	240.11	258.21	55.22	0	313.42	166.75	57.64	0	224.39
	Mode 2	172.06	69.64	0	241.70	257.37	58.44	0	315.82	166.27	53.02	0	219.28
West Mediterranean	Min	214.57	50.03	0	264.60	314.00	41.30	0	355.30	199.24	48.79	0	248.03
	Max	78.91	78.94	0	157.85	133.28	57.75	0	191.03	94.01	80.60	0	174.62
	Mode 1	175.81	67.43	0	243.24	262.37	55.22	0	317.59	169.18	53.02	0	222.19
	Mode 2	178.94	62.13	0	241.07	266.53	58.44	0	324.98	171.60	56.87	0	228.47
Hong Kong	Min	190.82	51.75	0	242.57	282.36	44.14	0	326.50	180.82	50.86	0	231.68
	Max	69.53	81.85	0	151.38	120.79	68.91	0	189.70	86.74	80.60	0	167.34
	Mode 1	88.29	67.43	0	155.71	145.78	66.42	0	212.19	101.29	77.83	0	179.12
	Mode 2	87.66	73.88	0	161.54	144.94	53.90	0	198.84	100.80	63.92	0	164.72
Middle East	Min	190.82	55.33	0	246.15	282.36	48.19	0	330.55	180.82	56.11	0	236.92
	Max	43.27	78.94	0	122.21	85.81	64.13	0	149.94	66.37	71.72	0	138.09
	Mode 1	57.03	62.13	0	119.16	104.14	58.44	0	162.58	77.04	65.39	0	142.43
	Mode 2	56.40	64.33	0	120.73	103.30	55.22	0	158.52	76.56	61.83	0	138.38

^a Min = lowest observed combination of air and seawater temperatures; Max = highest observed combination; Mode 1 = most frequent combination; Mode 2 = second most frequent combination.

Table C.2: Heat demand matrix for medium-occupancy scenarios^a.

Climate Zone	Parameter	Anchor				Sailing				Harbour			
		DWS	HVAC	Pool	Total	DWS	HVAC	Pool	Total	DWS	HVAC	Pool	Total
Atlantic Crossing	Min	873.17	82.59	249.60	1,205.35	613.03	78.22	0	691.25	298.90	62.46	0	361.37
	Max	247.33	122.72	0	370.05	172.97	118.98	0	291.96	75.80	110.92	0	186.72
	Mode 1	360.95	114.23	262.57	737.75	252.86	129.10	0	381.97	116.31	96.38	0	212.69
	Mode 2	351.63	117.91	267.91	737.46	246.31	113.09	0	359.40	112.99	85.70	0	198.69
Caribbean	Min	509.96	84.57	249.60	844.12	357.64	85.96	0	443.60	169.43	67.62	0	237.05
	Max	197.04	143.16	0	340.20	137.61	145.03	0	282.64	57.88	110.92	0	168.79
	Mode 1	277.13	117.91	0	395.04	193.93	129.10	0	323.03	86.43	90.72	0	177.15
	Mode 2	333.01	114.23	267.91	715.15	233.22	113.09	0	346.30	106.35	85.70	0	192.05
East Mediterranean	Min	588.19	82.59	249.60	920.37	412.64	79.81	0	492.45	197.31	61.94	0	259.25
	Max	230.56	128.97	0	359.53	161.18	126.38	0	287.57	69.83	107.00	0	176.83
	Mode 1	500.64	114.23	262.57	877.45	351.09	110.00	0	461.09	166.11	74.84	0	240.95
	Mode 2	509.96	117.91	267.91	895.78	357.64	120.61	0	478.25	169.43	68.38	0	237.80
West-East Mediterranean	Min	692.49	82.59	249.60	1,024.68	485.99	79.81	0	565.79	234.50	61.94	0	296.43
	Max	224.98	128.97	0	353.94	157.26	126.38	0	283.64	67.84	107.00	0	174.84
	Mode 1	537.90	114.23	262.57	914.70	377.28	113.09	0	490.37	179.39	74.84	0	254.23
	Mode 2	536.03	117.91	267.91	921.86	375.97	120.61	0	496.59	178.72	68.38	0	247.10
West Mediterranean	Min	662.69	85.23	249.60	997.52	465.03	80.60	0	545.63	223.87	62.46	0	286.34
	Max	258.50	133.42	0	391.92	180.83	118.98	0	299.81	79.79	107.00	0	186.79
	Mode 1	547.21	114.23	262.57	924.01	383.83	113.09	0	496.92	182.71	68.38	0	251.08
	Mode 2	556.52	105.40	258.27	920.20	390.38	120.61	0	510.99	186.03	73.77	0	259.80
Hong Kong	Min	591.91	88.10	249.60	929.61	415.26	87.23	0	502.50	198.64	65.36	0	264.01
	Max	230.56	138.26	0	368.83	161.18	145.03	0	306.22	69.83	107.00	0	176.83
	Mode 1	286.44	114.23	262.57	663.25	200.47	139.22	0	339.69	89.75	103.12	0	192.87
	Mode 2	284.58	124.99	267.91	677.48	199.17	110.00	0	309.16	89.08	83.65	0	172.73
Middle East	Min	591.91	94.07	258.27	944.25	415.26	96.68	0	511.95	198.64	72.71	0	271.35
	Max	152.33	133.42	0	285.75	106.18	133.88	0	240.06	41.94	94.57	0	136.51
	Mode 1	193.31	105.40	0	298.71	134.99	120.61	0	255.60	56.55	85.70	0	142.25
	Mode 2	191.45	109.07	0	300.52	133.68	113.09	0	246.77	55.88	80.71	0	136.60

^a Min = lowest observed combination of air and seawater temperatures; Max = highest observed combination; Mode 1 = most frequent combination; Mode 2 = second most frequent combination.

C. Heat Demand Matrix (continued)

Table C.3: Heat demand matrix for high-occupancy scenarios^a.

Climate Zone	Parameter	Anchor				Sailing				Harbour			
		DWS	HVAC	Pool	Total	DWS	HVAC	Pool	Total	DWS	HVAC	Pool	Total
Atlantic Crossing	Min	1,105.33	118.06	249.60	1,472.98	915.69	117.36	0	1,033.05	482.27	81.86	0	564.13
	Max	261.48	175.39	0	436.87	232.29	167.83	0	400.12	125.93	144.16	0	270.10
	Mode 1	414.68	163.25	262.57	840.51	356.36	180.36	0	536.72	190.63	125.47	0	316.10
	Mode 2	402.12	168.52	267.91	838.55	346.19	160.53	0	506.72	185.32	111.74	0	297.07
Caribbean	Min	615.59	120.88	249.60	986.07	519.07	126.94	0	646.02	275.47	88.50	0	363.96
	Max	193.67	204.58	0	398.25	177.37	200.08	0	377.45	97.30	144.16	0	241.46
	Mode 1	301.66	168.52	0	470.18	264.83	180.36	0	445.19	142.90	118.19	0	261.10
	Mode 2	377.01	163.25	267.91	808.17	325.85	160.53	0	486.38	174.72	111.74	0	286.46
East Mediterranean	Min	721.07	118.06	249.60	1,088.73	604.50	119.32	0	723.82	320.01	81.19	0	401.20
	Max	238.88	184.31	0	423.19	213.98	176.99	0	390.97	116.39	139.13	0	255.52
	Mode 1	603.04	163.25	262.57	1,028.86	508.90	156.70	0	665.61	270.16	97.78	0	367.95
	Mode 2	615.59	168.52	267.91	1,052.02	519.07	169.84	0	688.92	275.47	89.47	0	364.93
West-East Mediterranean	Min	861.72	118.06	249.60	1,229.37	718.40	119.32	0	837.72	379.40	81.19	0	460.58
	Max	231.34	184.31	0	415.65	207.88	176.99	0	384.87	113.21	139.13	0	252.33
	Mode 1	653.27	163.25	262.57	1,079.09	549.58	160.53	0	710.11	291.38	97.78	0	389.16
	Mode 2	650.75	168.52	267.91	1,087.19	547.55	169.84	0	717.39	290.31	89.47	0	379.78
West Mediterranean	Min	821.53	121.83	249.60	1,192.96	685.86	120.30	0	806.16	362.43	81.86	0	444.29
	Max	276.55	190.66	0	467.21	244.49	167.83	0	412.32	132.30	139.13	0	271.42
	Mode 1	665.82	163.25	262.57	1,091.65	559.75	160.53	0	720.28	296.68	89.47	0	386.14
	Mode 2	678.38	150.65	258.27	1,087.30	569.92	169.84	0	739.76	301.98	96.41	0	398.39
Hong Kong	Min	726.10	125.92	249.60	1,101.62	608.57	128.52	0	737.08	322.13	85.59	0	407.73
	Max	238.88	197.59	0	436.46	213.98	200.08	0	414.06	116.39	139.13	0	255.52
	Mode 1	314.22	163.25	262.57	740.05	275.00	192.88	0	467.88	148.21	134.14	0	282.35
	Mode 2	311.71	178.63	267.91	758.25	272.97	156.70	0	429.67	147.14	109.10	0	256.24
Middle East	Min	726.10	134.45	258.27	1,118.82	608.57	140.21	0	748.78	322.13	95.03	0	417.16
	Max	133.40	190.66	0	324.06	128.56	186.27	0	314.83	71.85	123.14	0	194.99
	Mode 1	188.65	150.65	0	339.29	173.31	169.84	0	343.15	95.18	111.74	0	206.92
	Mode 2	186.14	155.88	0	342.02	171.27	160.53	0	331.80	94.12	105.33	0	199.45

^a Min = lowest observed combination of air and seawater temperatures; Max = highest observed combination; Mode 1 = most frequent combination; Mode 2 = second most frequent combination.

D. Heat Demand Plots

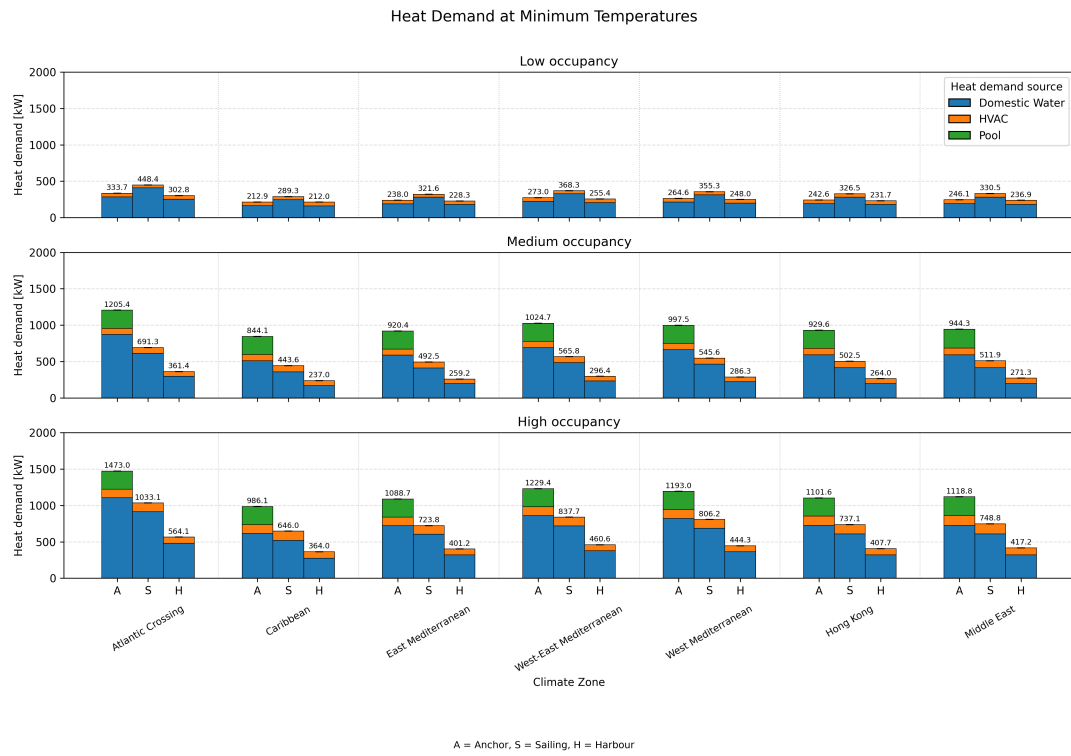


Figure D.1: Heat demand at minimum temperatures.

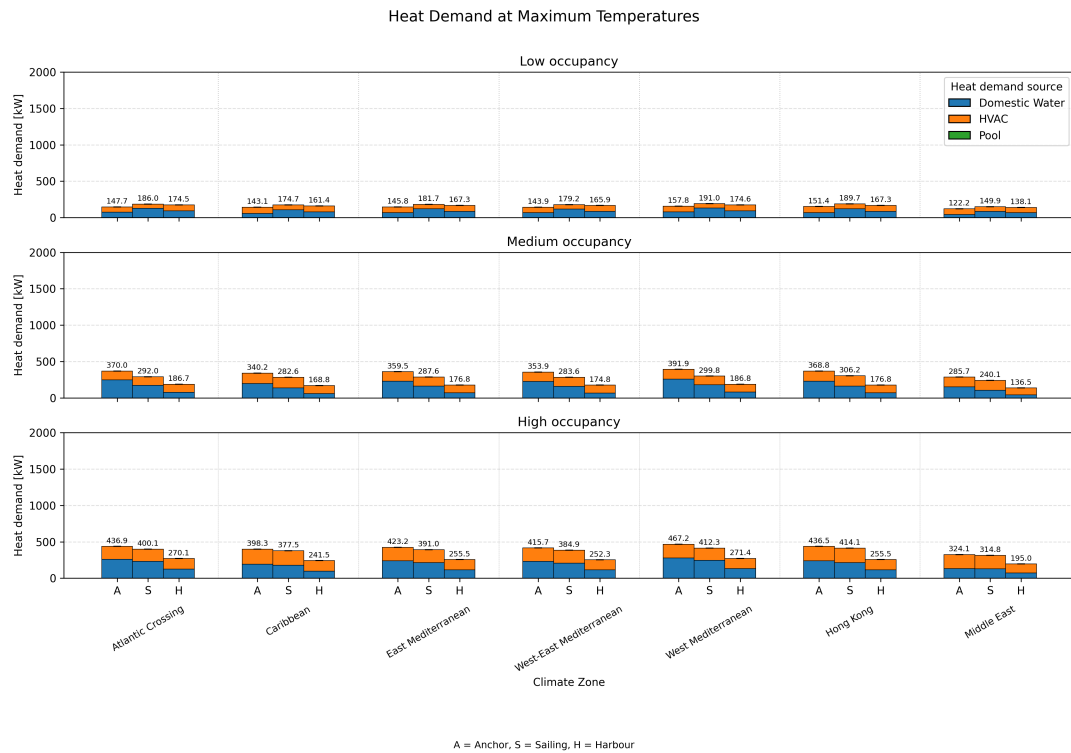


Figure D.2: Heat demand at maximum temperatures.

D. Heat Demand Plots (continued)

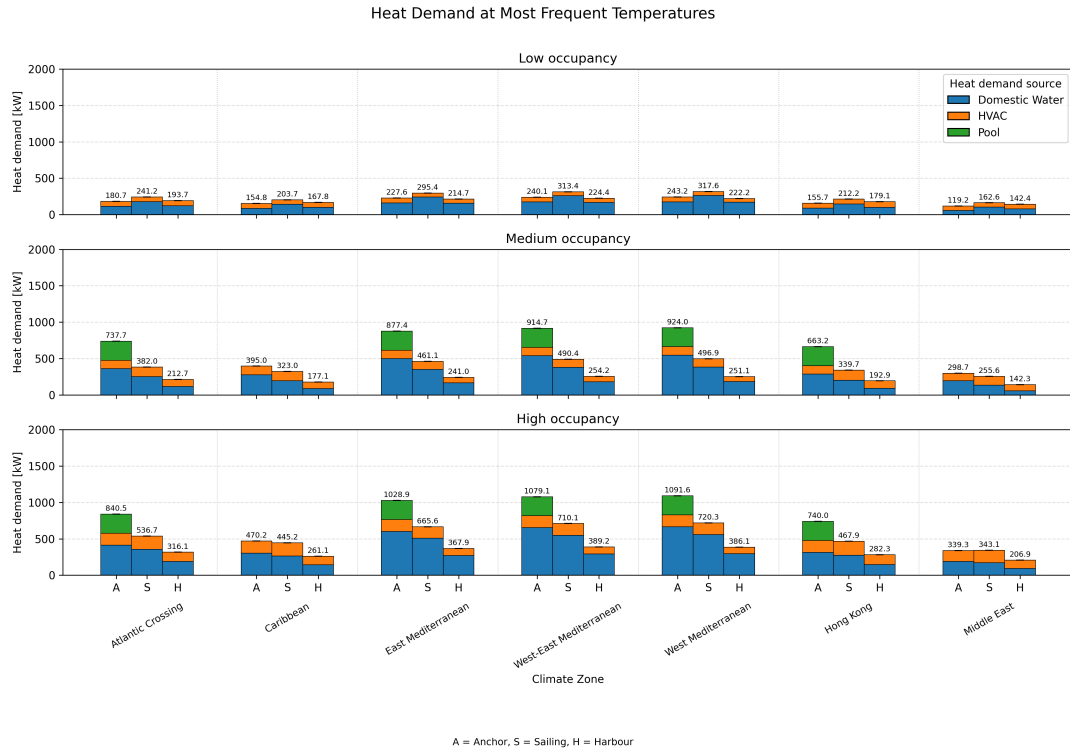


Figure D.3: Heat demand at most frequent temperatures.

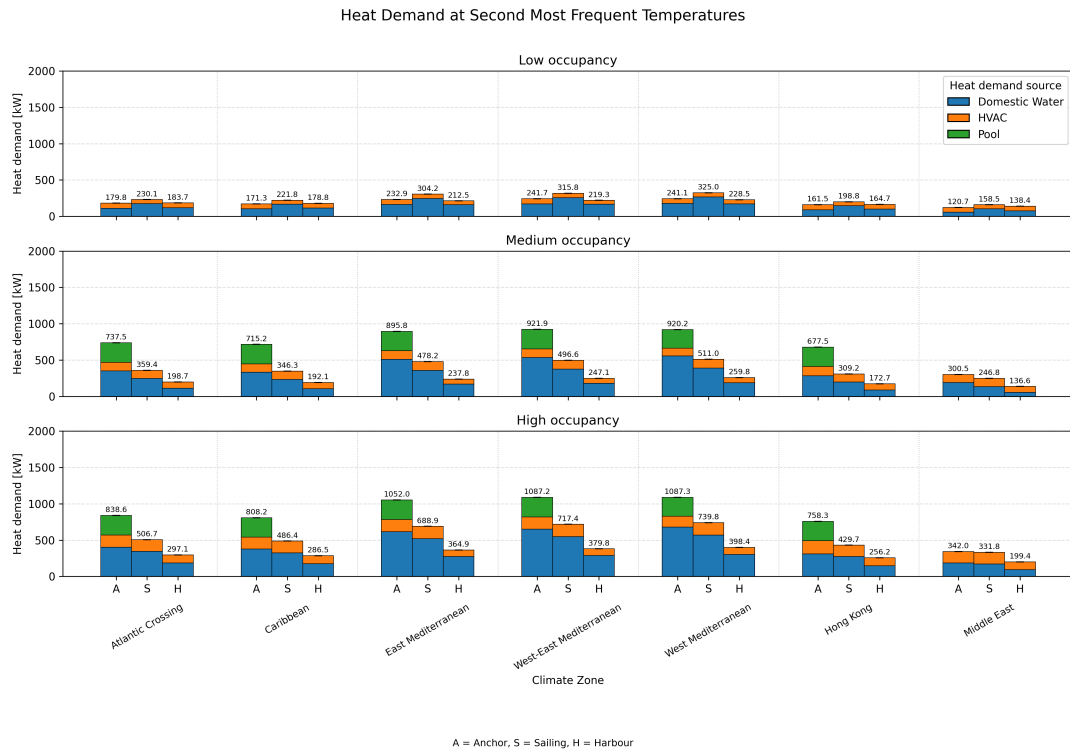


Figure D.4: Heat demand at second most frequent temperatures.

E. Heat Generated Results for Design 1

Table E.1: Heat generation results for the anchor operational profile under low occupancy^a.

Climate Zone	Parameter	Electrical Chiller / Heat Pump					Heat Exchanger		Electrical Heater			Heat Tank	
		Q_H [kW]	Q_C [kW]	Q_L [kW]	P_E [kW]	COP [-]	Q [kW]	Q_L [kW]	Q [kW]	Q_L [kW]	P_E [kW]	Q [kW]	t [min]
Atlantic Crossing	Min	0.0	0.0	0.0	0.0	0.0	333.7	13.9	0.0	0.0	0.0	0.0	0.0
	Max	75.2	72.5	0.0	22.3	6.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Mode 1	88.2	67.4	0.0	20.7	7.5	25.1	1.0	0.0	0.0	0.0	0.0	0.0
Caribbean	Mode 2	91.1	69.6	0.0	21.4	7.5	19.1	0.8	0.0	0.0	0.0	0.0	0.0
	Min	0.0	0.0	0.0	0.0	0.0	212.9	8.9	0.0	0.0	0.0	0.0	0.0
	Max	58.3	84.8	0.0	26.1	5.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
East Mediterranean	Mode 1	85.2	69.6	0.0	21.4	7.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Mode 2	88.2	67.4	0.0	20.7	7.5	15.7	0.7	0.0	0.0	0.0	0.0	0.0
	Min	0.0	0.0	0.0	0.0	0.0	238.0	9.9	0.0	0.0	0.0	0.0	0.0
West-East Mediterranean	Max	69.5	76.3	0.0	23.5	6.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Mode 1	88.2	67.4	0.0	20.7	7.5	72.0	3.0	0.0	0.0	0.0	0.0	0.0
	Mode 2	91.1	69.6	0.0	21.4	7.5	72.2	3.0	0.0	0.0	0.0	0.0	0.0
West Mediterranean	Min	0.0	0.0	0.0	0.0	0.0	273.0	11.4	0.0	0.0	0.0	0.0	0.0
	Max	67.7	76.3	0.0	23.5	6.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Mode 1	88.2	67.4	0.0	20.7	7.5	84.5	3.5	0.0	0.0	0.0	0.0	0.0
Hong Kong	Mode 2	91.1	69.6	0.0	21.4	7.5	81.0	3.4	0.0	0.0	0.0	0.0	0.0
	Min	0.0	0.0	0.0	0.0	0.0	264.6	11.0	0.0	0.0	0.0	0.0	0.0
	Max	78.9	78.9	0.0	24.3	6.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Middle East	Mode 1	88.2	67.4	0.0	20.7	7.5	87.6	3.7	0.0	0.0	0.0	0.0	0.0
	Mode 2	0.0	0.0	0.0	0.0	0.0	241.1	10.0	0.0	0.0	0.0	0.0	0.0
	Min	0.0	0.0	0.0	0.0	0.0	242.6	10.1	0.0	0.0	0.0	0.0	0.0
Middle East	Max	69.5	81.8	0.0	25.2	6.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Mode 1	88.2	67.4	0.0	20.7	7.5	0.1	0.0	0.0	0.0	0.0	0.0	0.0
	Mode 2	87.7	73.9	0.0	22.7	7.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Middle East	Min	0.0	0.0	0.0	0.0	0.0	246.1	10.3	0.0	0.0	0.0	0.0	0.0
	Max	43.3	78.9	0.0	24.3	5.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Mode 1	0.0	0.0	0.0	0.0	0.0	119.2	5.0	0.0	0.0	0.0	0.0	0.0
	Mode 2	56.4	64.3	0.0	19.8	6.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0

^a Min = lowest observed combination of air and seawater temperatures; Max = highest observed combination; Mode 1 = most frequent combination; Mode 2 = second most frequent combination.

Table E.2: Heat generation results for the sailing operational profile under low occupancy^a.

Climate Zone	Parameter	Electrical Chiller / Heat Pump					Heat Exchanger		Electrical Heater			Heat Tank	
		Q_H [kW]	Q_C [kW]	Q_L [kW]	P_E [kW]	COP [-]	Q [kW]	Q_L [kW]	Q [kW]	Q_L [kW]	P_E [kW]	Q [kW]	t [min]
Atlantic Crossing	Min	0.0	0.0	0.0	0.0	0.0	448.4	18.7	0.0	0.0	0.0	0.0	0.0
	Max	75.5	57.7	0.0	17.8	7.5	52.8	2.2	0.0	0.0	0.0	0.0	0.0
	Mode 1	81.2	62.1	0.0	19.1	7.5	97.9	4.1	0.0	0.0	0.0	0.0	0.0
Caribbean	Mode 2	72.2	55.2	0.0	17.0	7.5	102.7	4.3	0.0	0.0	0.0	0.0	0.0
	Min	0.0	0.0	0.0	0.0	0.0	289.3	12.1	0.0	0.0	0.0	0.0	0.0
	Max	90.1	68.9	0.0	21.2	7.5	15.7	0.7	0.0	0.0	0.0	0.0	0.0
East Mediterranean	Mode 1	81.2	62.1	0.0	19.1	7.5	60.4	2.5	0.0	0.0	0.0	0.0	0.0
	Mode 2	72.2	55.2	0.0	17.0	7.5	94.4	3.9	0.0	0.0	0.0	0.0	0.0
	Min	0.0	0.0	0.0	0.0	0.0	321.6	13.4	0.0	0.0	0.0	0.0	0.0
West-East Mediterranean	Max	79.7	60.9	0.0	18.7	7.5	41.1	1.7	0.0	0.0	0.0	0.0	0.0
	Mode 1	70.5	53.9	0.0	16.6	7.5	171.1	7.1	0.0	0.0	0.0	0.0	0.0
	Mode 2	76.4	58.4	0.0	18.0	7.5	169.3	7.1	0.0	0.0	0.0	0.0	0.0
West Mediterranean	Min	0.0	0.0	0.0	0.0	0.0	368.3	15.3	0.0	0.0	0.0	0.0	0.0
	Max	79.7	60.9	0.0	18.7	7.5	38.6	1.6	0.0	0.0	0.0	0.0	0.0
	Mode 1	72.2	55.2	0.0	17.0	7.5	186.0	7.7	0.0	0.0	0.0	0.0	0.0
Hong Kong	Mode 2	76.4	58.4	0.0	18.0	7.5	180.9	7.5	0.0	0.0	0.0	0.0	0.0
	Min	0.0	0.0	0.0	0.0	0.0	355.3	14.8	0.0	0.0	0.0	0.0	0.0
	Max	75.5	57.7	0.0	17.8	7.5	57.8	2.4	0.0	0.0	0.0	0.0	0.0
Middle East	Mode 1	72.2	55.2	0.0	17.0	7.5	190.2	7.9	0.0	0.0	0.0	0.0	0.0
	Mode 2	76.4	58.4	0.0	18.0	7.5	190.1	7.9	0.0	0.0	0.0	0.0	0.0
	Min	0.0	0.0	0.0	0.0	0.0	326.5	13.6	0.0	0.0	0.0	0.0	0.0
Middle East	Max	90.1	68.9	0.0	21.2	7.5	30.7	1.3	0.0	0.0	0.0	0.0	0.0
	Mode 1	86.9	66.4	0.0	20.4	7.5	58.9	2.5	0.0	0.0	0.0	0.0	0.0
	Mode 2	70.5	53.9	0.0	16.6	7.5	74.5	3.1	0.0	0.0	0.0	0.0	0.0
Middle East	Min	0.0	0.0	0.0	0.0	0.0	330.5	13.8	0.0	0.0	0.0	0.0	0.0
	Max	83.9	64.1	0.0	19.7	7.5	2.0	0.1	0.0	0.0	0.0	0.0	0.0
	Mode 1	76.4	58.4	0.0	18.0	7.5	27.7	1.2	0.0	0.0	0.0	0.0	0.0
	Mode 2	72.2	55.2	0.0	17.0	7.5	31.1	1.3	0.0	0.0	0.0	0.0	0.0

^a Min = lowest observed combination of air and seawater temperatures; Max = highest observed combination; Mode 1 = most frequent combination; Mode 2 = second most frequent combination.

Table E.3: Heat generation results for the harbour operational profile under low occupancy^a.

Climate Zone	Parameter	Electrical Chiller / Heat Pump					Heat Exchanger		Electrical Heater			Heat Tank	
		Q_H [kW]	Q_C [kW]	Q_L [kW]	P_E [kW]	COP [-]	Q [kW]	Q_L [kW]	Q [kW]	Q_L [kW]	P_E [kW]	Q [kW]	t [min]
Atlantic Crossing	Min	0.0	0.0	0.0	0.0	0.0	0.0	0.0	302.8	6.2	309.0	0.0	0.0
	Max	91.1	83.4	0.0	25.7	6.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Mode 1	95.5	73.0	0.0	22.5	7.5	0.0	0.0	25.2	0.5	25.7	0.0	0.0
Caribbean	Mode 2	85.5	65.4	0.0	20.1	7.5	0.0	0.0	32.7	0.7	33.4	0.0	0.0
	Min	0.0	0.0	0.0	0.0	0.0	0.0	0.0	212.0	4.3	216.3	0.0	0.0
	Max	78.0	83.4	0.0	25.7	6.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
East Mediterranean	Mode 1	90.2	69.0	0.0	21.2	7.5	0.0	0.0	8.7	0.2	8.8	0.0	0.0
	Mode 2	85.5	65.4	0.0	20.1	7.5	0.0	0.0	27.9	0.6	28.5	0.0	0.0
	Min	0.0	0.0	0.0	0.0	0.0	0.0	0.0	228.3	4.7	232.9	0.0	0.0
West-East Mediterranean	Max	86.7	80.6	0.0	24.8	6.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Mode 1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	214.7	4.4	219.1	0.0	0.0
	Mode 2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	212.5	4.3	216.8	0.0	0.0
West Mediterranean	Min	0.0	0.0	0.0	0.0	0.0	0.0	0.0	255.4	5.2	260.6	0.0	0.0
	Max	85.3	80.6	0.0	24.8	6.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Mode 1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	224.4	4.6	229.0	0.0	0.0
Hong Kong	Mode 2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	219.3	4.5	223.8	0.0	0.0
	Min	0.0	0.0	0.0	0.0	0.0	0.0	0.0	248.0	5.1	253.1	0.0	0.0
	Max	94.0	80.6	0.0	24.8	7.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Middle East	Mode 1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	222.2	4.5	226.7	0.0	0.0
	Mode 2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	228.5	4.7	233.1	0.0	0.0
	Min	0.0	0.0	0.0	0.0	0.0	0.0	0.0	231.7	4.7	236.4	0.0	0.0
	Max	86.7	80.6	0.0	24.8	6.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Mode 1	101.3	77.8	0.0	23.9	7.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Mode 2	83.6	63.9	0.0	19.7	7.5	0.0	0.0	17.2	0.4	17.6	0.0	0.0
	Min	0.0	0.0	0.0	0.0	0.0	0.0	0.0	236.9	4.8	241.8	0.0	0.0
	Max	66.4	71.7	0.0	22.1	6.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Mode 1	77.0	65.4	0.0	20.1	7.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Mode 2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	138.4	2.8	141.2	0.0	0.0

^a Min = lowest observed combination of air and seawater temperatures; Max = highest observed combination; Mode 1 = most frequent combination; Mode 2 = second most frequent combination.

Table E.4: Heat generation results for the anchor operational profile under medium occupancy^a.

Climate Zone	Parameter	Electrical Chiller / Heat Pump					Heat Exchanger		Electrical Heater			Heat Tank	
		Q_H [kW]	Q_C [kW]	Q_L [kW]	P_E [kW]	COP [-]	Q [kW]	Q_L [kW]	Q [kW]	Q_L [kW]	P_E [kW]	Q [kW]	t [min]
Atlantic Crossing	Min	0.0	0.0	0.0	0.0	0.0	537.6	22.4	350.0	7.1	357.1	317.8	23.9
	Max	160.5	122.7	0.0	37.8	7.5	86.8	3.6	0.0	0.0	0.0	0.0	0.0
	Mode 1	149.4	114.2	0.0	35.1	7.5	474.1	19.8	0.0	0.0	0.0	0.0	0.0
Caribbean	Mode 2	154.2	117.9	0.0	36.3	7.5	465.4	19.4	0.0	0.0	0.0	0.0	0.0
	Min	0.0	0.0	0.0	0.0	0.0	537.6	22.4	306.5	6.3	312.8	0.0	0.0
	Max	187.2	143.2	0.0	44.0	7.5	9.8	0.4	0.0	0.0	0.0	0.0	0.0
East Mediterranean	Mode 1	154.2	117.9	0.0	36.3	7.5	122.9	5.1	0.0	0.0	0.0	0.0	0.0
	Mode 2	149.4	114.2	0.0	35.1	7.5	451.5	18.8	0.0	0.0	0.0	0.0	0.0
	Min	0.0	0.0	0.0	0.0	0.0	537.6	22.4	350.0	7.1	357.1	32.8	231.5
West-East Mediterranean	Max	168.7	129.0	0.0	39.7	7.5	61.9	2.6	0.0	0.0	0.0	0.0	0.0
	Mode 1	149.4	114.2	0.0	35.1	7.5	537.6	22.4	76.2	1.6	77.8	0.0	0.0
	Mode 2	154.2	117.9	0.0	36.3	7.5	537.6	22.4	86.1	1.8	87.8	0.0	0.0
West Mediterranean	Min	0.0	0.0	0.0	0.0	0.0	537.6	22.4	350.0	7.1	357.1	137.1	55.3
	Max	168.7	129.0	0.0	39.7	7.5	56.3	2.3	0.0	0.0	0.0	0.0	0.0
	Mode 1	149.4	114.2	0.0	35.1	7.5	537.6	22.4	113.5	2.3	115.8	0.0	0.0
Hong Kong	Mode 2	154.2	117.9	0.0	36.3	7.5	537.6	22.4	112.2	2.3	114.4	0.0	0.0
	Min	0.0	0.0	0.0	0.0	0.0	537.6	22.4	350.0	7.1	357.1	109.9	69.0
	Max	174.5	133.4	0.0	41.1	7.5	84.0	3.5	0.0	0.0	0.0	0.0	0.0
Middle East	Mode 1	149.4	114.2	0.0	35.1	7.5	537.6	22.4	122.8	2.5	125.3	0.0	0.0
	Mode 2	0.0	0.0	0.0	0.0	0.0	537.6	22.4	350.0	7.1	357.1	32.6	232.7
	Min	0.0	0.0	0.0	0.0	0.0	537.6	22.4	350.0	7.1	357.1	42.0	180.6
	Max	180.8	138.3	0.0	42.5	7.5	49.8	2.1	0.0	0.0	0.0	0.0	0.0
	Mode 1	149.4	114.2	0.0	35.1	7.5	399.6	16.7	0.0	0.0	0.0	0.0	0.0
	Mode 2	163.4	125.0	0.0	38.5	7.5	389.0	16.2	0.0	0.0	0.0	0.0	0.0
	Min	0.0	0.0	0.0	0.0	0.0	537.6	22.4	350.0	7.1	357.1	56.7	133.9
	Max	152.3	133.4	0.0	41.1	7.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Mode 1	0.0	0.0	0.0	0.0	0.0	298.7	12.4	0.0	0.0	0.0	0.0	0.0
	Mode 2	142.6	109.1	0.0	33.6	7.5	48.8	2.0	0.0	0.0	0.0	0.0	0.0

^a Min = lowest observed combination of air and seawater temperatures; Max = highest observed combination; Mode 1 = most frequent combination; Mode 2 = second most frequent combination.

Table E.5: Heat generation results for the sailing operational profile under medium occupancy^a.

Climate Zone	Parameter	Electrical Chiller / Heat Pump					Heat Exchanger		Electrical Heater			Heat Tank	
		Q_H [kW]	Q_C [kW]	Q_L [kW]	P_E [kW]	COP [-]	Q [kW]	Q_L [kW]	Q [kW]	Q_L [kW]	P_E [kW]	Q [kW]	t [min]
Atlantic Crossing	Min	0.0	0.0	0.0	0.0	0.0	537.6	22.4	153.7	3.1	156.8	0.0	0.0
	Max	155.6	119.0	0.0	36.6	7.5	17.4	0.7	0.0	0.0	0.0	0.0	0.0
	Mode 1	168.8	129.1	0.0	39.7	7.5	84.0	3.5	0.0	0.0	0.0	0.0	0.0
Caribbean	Mode 2	147.9	113.1	0.0	34.8	7.5	98.4	4.1	0.0	0.0	0.0	0.0	0.0
	Min	0.0	0.0	0.0	0.0	0.0	443.6	18.5	0.0	0.0	0.0	0.0	0.0
	Max	137.6	145.0	0.0	44.6	6.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
East Mediterranean	Mode 1	168.8	129.1	0.0	39.7	7.5	25.1	1.0	0.0	0.0	0.0	0.0	0.0
	Mode 2	147.9	113.1	0.0	34.8	7.5	85.3	3.6	0.0	0.0	0.0	0.0	0.0
	Min	0.0	0.0	0.0	0.0	0.0	492.5	20.5	0.0	0.0	0.0	0.0	0.0
West-East Mediterranean	Max	161.2	126.4	0.0	38.9	7.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Mode 1	143.8	110.0	0.0	33.8	7.5	207.2	8.6	0.0	0.0	0.0	0.0	0.0
	Mode 2	157.7	120.6	0.0	37.1	7.5	199.9	8.3	0.0	0.0	0.0	0.0	0.0
West Mediterranean	Min	0.0	0.0	0.0	0.0	0.0	537.6	22.4	28.2	0.6	28.8	0.0	0.0
	Max	157.3	126.4	0.0	38.9	7.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Mode 1	147.9	113.1	0.0	34.8	7.5	229.4	9.6	0.0	0.0	0.0	0.0	0.0
Hong Kong	Mode 2	157.7	120.6	0.0	37.1	7.5	218.3	9.1	0.0	0.0	0.0	0.0	0.0
	Min	0.0	0.0	0.0	0.0	0.0	537.6	22.4	8.0	0.2	8.2	0.0	0.0
	Max	155.6	119.0	0.0	36.6	7.5	25.2	1.1	0.0	0.0	0.0	0.0	0.0
Middle East	Mode 1	147.9	113.1	0.0	34.8	7.5	235.9	9.8	0.0	0.0	0.0	0.0	0.0
	Mode 2	157.7	120.6	0.0	37.1	7.5	232.7	9.7	0.0	0.0	0.0	0.0	0.0
	Min	0.0	0.0	0.0	0.0	0.0	502.5	20.9	0.0	0.0	0.0	0.0	0.0
	Max	161.2	145.0	0.0	44.6	6.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Mode 1	182.1	139.2	0.0	42.8	7.5	18.4	0.8	0.0	0.0	0.0	0.0	0.0
	Mode 2	143.8	110.0	0.0	33.8	7.5	55.3	2.3	0.0	0.0	0.0	0.0	0.0
	Min	0.0	0.0	0.0	0.0	0.0	511.9	21.3	0.0	0.0	0.0	0.0	0.0
	Max	106.2	133.9	0.0	41.2	5.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Mode 1	135.0	120.6	0.0	37.1	6.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Mode 2	133.7	113.1	0.0	34.8	7.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0

^a Min = lowest observed combination of air and seawater temperatures; Max = highest observed combination; Mode 1 = most frequent combination; Mode 2 = second most frequent combination.

Table E.6: Heat generation results for the harbour operational profile under medium occupancy^a.

Climate Zone	Parameter	Electrical Chiller / Heat Pump					Heat Exchanger		Electrical Heater			Heat Tank	
		Q_H [kW]	Q_C [kW]	Q_L [kW]	P_E [kW]	COP [-]	Q [kW]	Q_L [kW]	Q [kW]	Q_L [kW]	P_E [kW]	Q [kW]	t [min]
Atlantic Crossing	Min	0.0	0.0	0.0	0.0	0.0	0.0	0.0	350.0	7.1	357.1	11.4	667.5
	Max	75.8	110.9	0.0	34.1	5.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Mode 1	116.3	96.4	0.0	29.7	7.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Caribbean	Mode 2	112.1	85.7	0.0	26.4	7.5	0.0	0.0	0.9	0.0	0.9	0.0	0.0
	Min	0.0	0.0	0.0	0.0	0.0	0.0	0.0	237.0	4.8	241.9	0.0	0.0
	Max	57.9	110.9	0.0	34.1	4.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0
East Mediterranean	Mode 1	86.4	90.7	0.0	27.9	6.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Mode 2	106.3	85.7	0.0	26.4	7.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Min	0.0	0.0	0.0	0.0	0.0	0.0	0.0	259.2	5.3	264.5	0.0	0.0
West-East Mediterranean	Max	69.8	107.0	0.0	32.9	5.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Mode 1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	241.0	4.9	245.9	0.0	0.0
	Mode 2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	237.8	4.9	242.7	0.0	0.0
West Mediterranean	Min	0.0	0.0	0.0	0.0	0.0	0.0	0.0	296.4	6.0	302.5	0.0	0.0
	Max	67.8	107.0	0.0	32.9	5.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Mode 1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	254.2	5.2	259.4	0.0	0.0
Hong Kong	Mode 2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	247.1	5.0	252.1	0.0	0.0
	Min	0.0	0.0	0.0	0.0	0.0	0.0	0.0	286.3	5.8	292.2	0.0	0.0
	Max	79.8	107.0	0.0	32.9	5.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Middle East	Mode 1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	251.1	5.1	256.2	0.0	0.0
	Mode 2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	259.8	5.3	265.1	0.0	0.0
	Min	0.0	0.0	0.0	0.0	0.0	0.0	0.0	264.0	5.4	269.4	0.0	0.0
	Max	69.8	107.0	0.0	32.9	5.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Mode 1	89.7	103.1	0.0	31.7	6.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Mode 2	89.1	83.6	0.0	25.7	6.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Min	0.0	0.0	0.0	0.0	0.0	0.0	0.0	271.3	5.5	276.9	0.0	0.0
	Max	41.9	94.6	0.0	29.1	4.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Mode 1	56.5	85.7	0.0	26.4	5.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Mode 2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	136.6	2.8	139.4	0.0	0.0

^a Min = lowest observed combination of air and seawater temperatures; Max = highest observed combination; Mode 1 = most frequent combination; Mode 2 = second most frequent combination.

Table E.7: Heat generation results for the anchor operational profile under high occupancy^a.

Climate Zone	Parameter	Electrical Chiller / Heat Pump					Heat Exchanger		Electrical Heater			Heat Tank	
		Q_H [kW]	Q_C [kW]	Q_L [kW]	P_E [kW]	COP [-]	Q [kW]	Q_L [kW]	Q [kW]	Q_L [kW]	P_E [kW]	Q [kW]	t [min]
Atlantic Crossing	Min	0.0	0.0	0.0	0.0	0.0	537.6	22.4	350.0	7.1	357.1	585.4	13.0
	Max	229.4	175.4	0.0	54.0	7.5	32.1	1.3	0.0	0.0	0.0	0.0	0.0
	Mode 1	213.5	163.3	0.0	50.2	7.5	463.8	19.3	0.0	0.0	0.0	0.0	0.0
	Mode 2	220.4	168.5	0.0	51.9	7.5	449.7	18.7	0.0	0.0	0.0	0.0	0.0
Caribbean	Min	0.0	0.0	0.0	0.0	0.0	537.6	22.4	350.0	7.1	357.1	98.5	77.0
	Max	193.7	204.6	0.0	62.9	6.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Mode 1	220.4	168.5	0.0	51.9	7.5	81.3	3.4	0.0	0.0	0.0	0.0	0.0
	Mode 2	213.5	163.3	0.0	50.2	7.5	431.4	18.0	0.0	0.0	0.0	0.0	0.0
East Mediterranean	Min	0.0	0.0	0.0	0.0	0.0	537.6	22.4	350.0	7.1	357.1	201.1	37.7
	Max	238.9	184.3	0.0	56.7	7.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Mode 1	213.5	163.3	0.0	50.2	7.5	537.6	22.4	114.5	2.3	116.9	0.0	0.0
	Mode 2	220.4	168.5	0.0	51.9	7.5	537.6	22.4	125.5	2.6	128.1	0.0	0.0
West-East Mediterranean	Min	0.0	0.0	0.0	0.0	0.0	537.6	22.4	350.0	7.1	357.1	341.8	22.2
	Max	231.3	184.3	0.0	56.7	7.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Mode 1	213.5	163.3	0.0	50.2	7.5	537.6	22.4	164.8	3.4	168.1	0.0	0.0
	Mode 2	220.4	168.5	0.0	51.9	7.5	537.6	22.4	160.7	3.3	164.0	0.0	0.0
West Mediterranean	Min	0.0	0.0	0.0	0.0	0.0	537.6	22.4	350.0	7.1	357.1	305.4	24.8
	Max	249.3	190.7	0.0	58.7	7.5	27.2	1.1	0.0	0.0	0.0	0.0	0.0
	Mode 1	213.5	163.3	0.0	50.2	7.5	537.6	22.4	177.3	3.6	180.9	0.0	0.0
	Mode 2	0.0	0.0	0.0	0.0	0.0	537.6	22.4	350.0	7.1	357.1	199.7	38.0
Hong Kong	Min	0.0	0.0	0.0	0.0	0.0	537.6	22.4	350.0	7.1	357.1	214.0	35.4
	Max	238.9	197.6	0.0	60.8	7.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Mode 1	213.5	163.3	0.0	50.2	7.5	363.3	15.1	0.0	0.0	0.0	0.0	0.0
	Mode 2	233.6	178.6	0.0	55.0	7.5	346.0	14.4	0.0	0.0	0.0	0.0	0.0
Middle East	Min	0.0	0.0	0.0	0.0	0.0	537.6	22.4	350.0	7.1	357.1	231.2	32.8
	Max	133.4	190.7	0.0	58.7	5.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Mode 1	0.0	0.0	0.0	0.0	0.0	339.3	14.1	0.0	0.0	0.0	0.0	0.0
	Mode 2	186.1	155.9	0.0	48.0	7.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0

^a Min = lowest observed combination of air and seawater temperatures; Max = highest observed combination; Mode 1 = most frequent combination; Mode 2 = second most frequent combination.

Table E.8: Heat generation results for the sailing operational profile under high occupancy^a.

Climate Zone	Parameter	Electrical Chiller / Heat Pump					Heat Exchanger		Electrical Heater			Heat Tank	
		Q_H [kW]	Q_C [kW]	Q_L [kW]	P_E [kW]	COP [-]	Q [kW]	Q_L [kW]	Q [kW]	Q_L [kW]	P_E [kW]	Q [kW]	t [min]
Atlantic Crossing	Min	0.0	0.0	0.0	0.0	0.0	537.6	22.4	350.0	7.1	357.1	145.5	52.2
	Max	219.5	167.8	0.0	51.6	7.5	12.8	0.5	0.0	0.0	0.0	0.0	0.0
	Mode 1	235.9	180.4	0.0	55.5	7.5	120.5	5.0	0.0	0.0	0.0	0.0	0.0
	Mode 2	209.9	160.5	0.0	49.4	7.5	136.3	5.7	0.0	0.0	0.0	0.0	0.0
Caribbean	Min	0.0	0.0	0.0	0.0	0.0	537.6	22.4	108.4	2.2	110.6	0.0	0.0
	Max	177.4	200.1	0.0	61.6	6.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Mode 1	235.9	180.4	0.0	55.5	7.5	29.0	1.2	0.0	0.0	0.0	0.0	0.0
	Mode 2	209.9	160.5	0.0	49.4	7.5	115.9	4.8	0.0	0.0	0.0	0.0	0.0
East Mediterranean	Min	0.0	0.0	0.0	0.0	0.0	537.6	22.4	186.2	3.8	190.0	0.0	0.0
	Max	214.0	177.0	0.0	54.5	7.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Mode 1	204.9	156.7	0.0	48.2	7.5	304.0	12.7	0.0	0.0	0.0	0.0	0.0
	Mode 2	222.1	169.8	0.0	52.3	7.5	297.0	12.4	0.0	0.0	0.0	0.0	0.0
West-East Mediterranean	Min	0.0	0.0	0.0	0.0	0.0	537.6	22.4	300.1	6.1	306.2	0.0	0.0
	Max	207.9	177.0	0.0	54.5	7.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Mode 1	209.9	160.5	0.0	49.4	7.5	339.7	14.2	0.0	0.0	0.0	0.0	0.0
	Mode 2	222.1	169.8	0.0	52.3	7.5	325.4	13.6	0.0	0.0	0.0	0.0	0.0
West Mediterranean	Min	0.0	0.0	0.0	0.0	0.0	537.6	22.4	268.6	5.5	274.0	0.0	0.0
	Max	219.5	167.8	0.0	51.6	7.5	25.0	1.0	0.0	0.0	0.0	0.0	0.0
	Mode 1	209.9	160.5	0.0	49.4	7.5	349.8	14.6	0.0	0.0	0.0	0.0	0.0
	Mode 2	222.1	169.8	0.0	52.3	7.5	347.8	14.5	0.0	0.0	0.0	0.0	0.0
Hong Kong	Min	0.0	0.0	0.0	0.0	0.0	537.6	22.4	199.5	4.1	203.6	0.0	0.0
	Max	214.0	200.1	0.0	61.6	6.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Mode 1	252.2	192.9	0.0	59.3	7.5	22.8	0.9	0.0	0.0	0.0	0.0	0.0
	Mode 2	204.9	156.7	0.0	48.2	7.5	68.0	2.8	0.0	0.0	0.0	0.0	0.0
Middle East	Min	0.0	0.0	0.0	0.0	0.0	537.6	22.4	211.2	4.3	215.5	0.0	0.0
	Max	128.6	186.3	0.0	57.3	5.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Mode 1	173.3	169.8	0.0	52.3	6.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Mode 2	171.3	160.5	0.0	49.4	6.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0

^a Min = lowest observed combination of air and seawater temperatures; Max = highest observed combination; Mode 1 = most frequent combination; Mode 2 = second most frequent combination.

Table E.9: Heat generation results for the harbour operational profile under high occupancy^a.

Climate Zone	Parameter	Electrical Chiller / Heat Pump					Heat Exchanger		Electrical Heater			Heat Tank	
		Q_H [kW]	Q_C [kW]	Q_L [kW]	P_E [kW]	COP [-]	Q [kW]	Q_L [kW]	Q [kW]	Q_L [kW]	P_E [kW]	Q [kW]	t [min]
Atlantic Crossing	Min	0.0	0.0	0.0	0.0	0.0	0.0	0.0	350.0	7.1	357.1	214.1	35.4
	Max	125.9	144.2	0.0	44.4	6.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Mode 1	164.1	125.5	0.0	38.6	7.5	0.0	0.0	26.5	0.5	27.1	0.0	0.0
Caribbean	Mode 2	146.1	111.7	0.0	34.4	7.5	0.0	0.0	39.2	0.8	40.0	0.0	0.0
	Min	0.0	0.0	0.0	0.0	0.0	0.0	0.0	350.0	7.1	357.1	14.0	543.3
	Max	97.3	144.2	0.0	44.4	5.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0
East Mediterranean	Mode 1	142.9	118.2	0.0	36.4	7.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Mode 2	146.1	111.7	0.0	34.4	7.5	0.0	0.0	28.6	0.6	29.2	0.0	0.0
	Min	0.0	0.0	0.0	0.0	0.0	0.0	0.0	350.0	7.1	357.1	51.2	148.2
West-East Mediterranean	Max	116.4	139.1	0.0	42.8	6.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Mode 1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	350.0	7.1	357.1	17.9	422.7
	Mode 2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	350.0	7.1	357.1	14.9	508.0
West Mediterranean	Min	0.0	0.0	0.0	0.0	0.0	0.0	0.0	350.0	7.1	357.1	110.6	68.6
	Max	113.2	139.1	0.0	42.8	5.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Mode 1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	350.0	7.1	357.1	39.2	193.7
Hong Kong	Mode 2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	350.0	7.1	357.1	29.8	254.7
	Min	0.0	0.0	0.0	0.0	0.0	0.0	0.0	350.0	7.1	357.1	94.3	80.5
	Max	132.3	139.1	0.0	42.8	6.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Middle East	Mode 1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	350.0	7.1	357.1	36.1	209.9
	Mode 2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	350.0	7.1	357.1	48.4	156.8
	Min	0.0	0.0	0.0	0.0	0.0	0.0	0.0	350.0	7.1	357.1	57.7	131.4
	Max	116.4	139.1	0.0	42.8	6.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Mode 1	148.2	134.1	0.0	41.3	6.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Mode 2	142.7	109.1	0.0	33.6	7.5	0.0	0.0	4.5	0.1	4.6	0.0	0.0
	Min	0.0	0.0	0.0	0.0	0.0	0.0	0.0	350.0	7.1	357.1	67.2	113.0
	Max	71.8	123.1	0.0	37.9	5.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Mode 1	95.2	111.7	0.0	34.4	6.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Mode 2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	199.4	4.1	203.5	0.0	0.0

^a Min = lowest observed combination of air and seawater temperatures; Max = highest observed combination; Mode 1 = most frequent combination; Mode 2 = second most frequent combination.

F. Heat Generated Plots for Design 1

Heat Generated by System and Unmet Heat at Minimum Temperatures

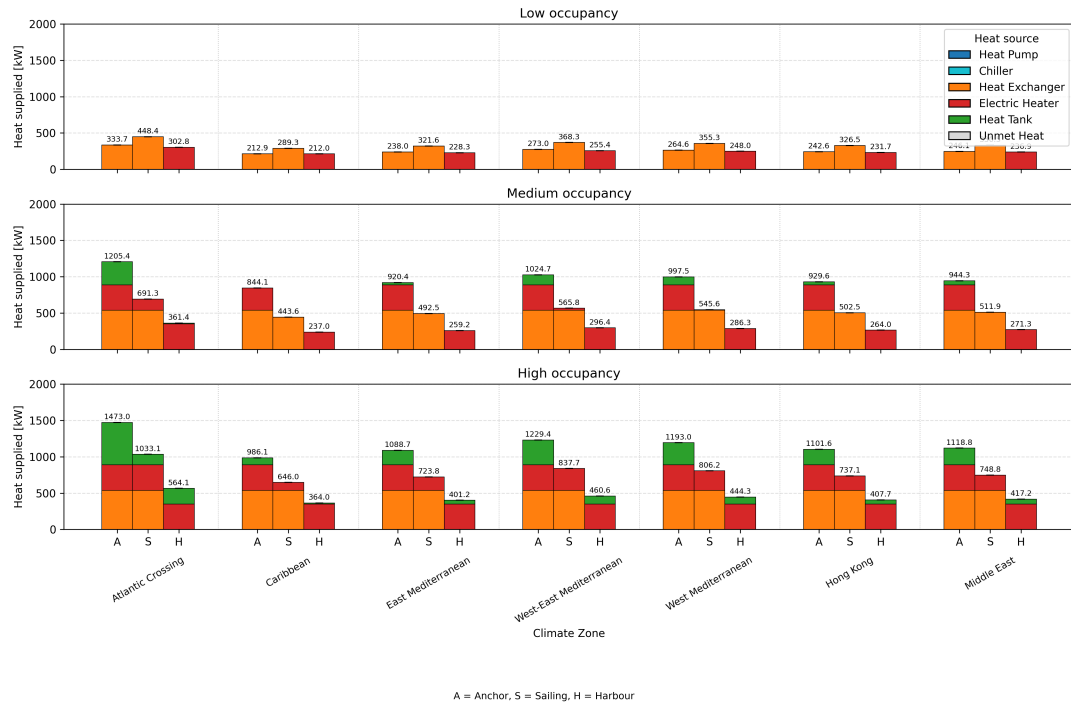


Figure F.1: Heat generated at minimum temperatures.

Heat Generated by System and Unmet Heat at Maximum Temperatures

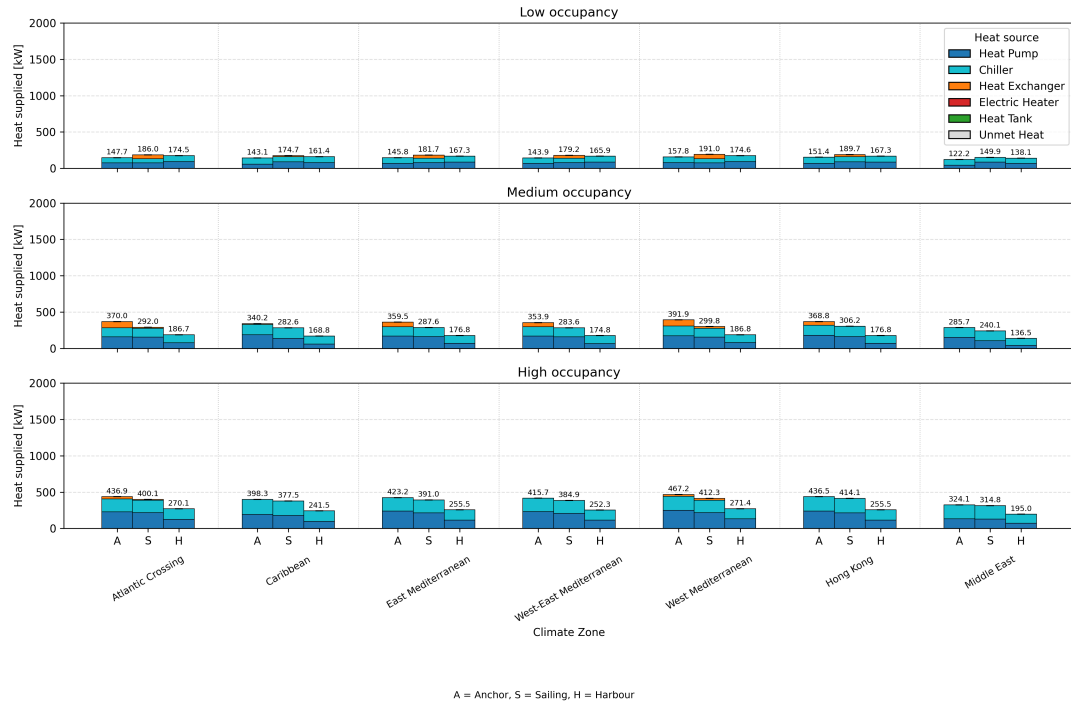


Figure F.2: Heat generated at maximum temperatures.

F. Heat Generated Plots for Design 1 (continued)

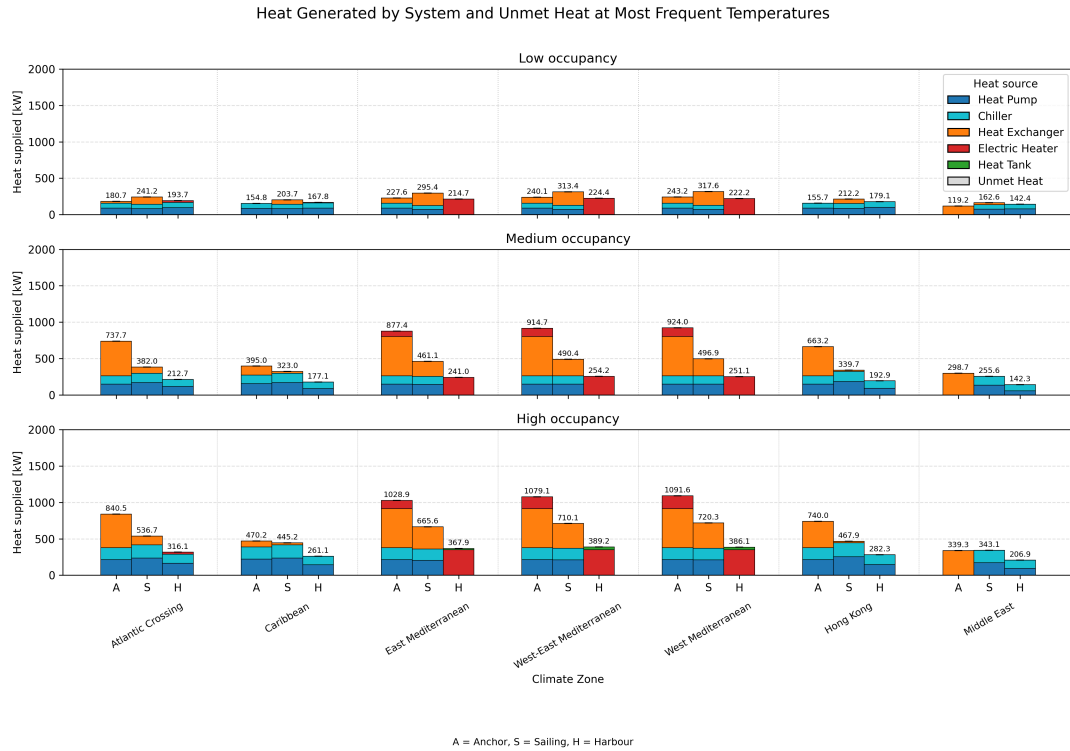


Figure F.3: Heat generated at most frequent temperatures.
Heat Generated by System and Unmet Heat at Second Most Frequent Temperatures

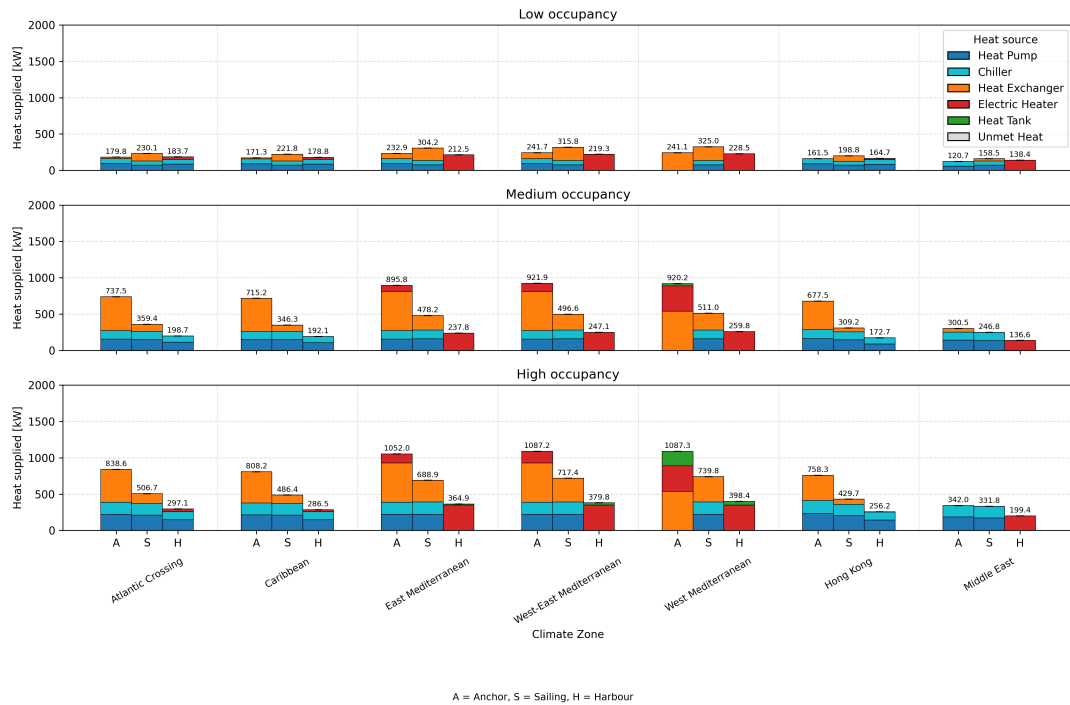


Figure F.4: Heat generated at second most frequent temperatures.

G. KPI Results for Design 1

Table G.1: KPI results for the anchor operational profile under low-occupancy scenarios^a.

Climate Zone	Parameter	KPI I		KPI II		KPI III					KPI IV		KPI V		KPI VI		KPI VII	
		[-]	[hh:mm:ss / -]	[-]	[hh:mm:ss / -]	E. Chiller / HP C		E. Chiller / HP H		Heat Exch. E. Heater	Heat Tank	[-]	[-]	[-]	[-]	[-]	[-]	[-]
						[-]	[-]	[-]	[-]									
Atlantic Crossing	Min	1.000	Unlimited	0.000	0.000	0.596	0.000	0.000	0.000	0.000	0.468	0.015	10.129	282.459				
	Max	1.000	Unlimited	0.097	0.215	0.000	0.000	0.000	0.000	0.000	0.421	0.015	10.129	282.459				
	Mode 1	1.000	Unlimited	0.090	0.252	0.045	0.000	0.000	0.000	0.000	0.429	0.015	10.129	282.459				
Caribbean	Mode 2	1.000	Unlimited	0.093	0.260	0.034	0.000	0.000	0.000	0.000	0.428	0.015	10.129	282.459				
	Min	1.000	Unlimited	0.000	0.000	0.380	0.000	0.000	0.000	0.440	0.015	10.129	282.459					
	Max	1.000	Unlimited	0.113	0.167	0.000	0.000	0.000	0.000	0.419	0.015	10.129	282.459					
East Mediterranean	Mode 1	1.000	Unlimited	0.093	0.243	0.000	0.000	0.000	0.000	0.423	0.015	10.129	282.459					
	Mode 2	1.000	Unlimited	0.090	0.252	0.028	0.000	0.000	0.000	0.426	0.015	10.129	282.459					
	Min	1.000	Unlimited	0.000	0.000	0.425	0.000	0.000	0.000	0.446	0.015	10.129	282.459					
West-East Mediterranean	Max	1.000	Unlimited	0.102	0.199	0.000	0.000	0.000	0.000	0.420	0.015	10.129	282.459					
	Mode 1	1.000	Unlimited	0.090	0.252	0.129	0.000	0.000	0.000	0.439	0.015	10.129	282.459					
	Mode 2	1.000	Unlimited	0.093	0.260	0.129	0.000	0.000	0.000	0.440	0.015	10.129	282.459					
West Mediterranean	Min	1.000	Unlimited	0.000	0.000	0.488	0.000	0.000	0.000	0.454	0.015	10.129	282.459					
	Max	1.000	Unlimited	0.102	0.193	0.000	0.000	0.000	0.000	0.420	0.015	10.129	282.459					
	Mode 1	1.000	Unlimited	0.090	0.252	0.151	0.000	0.000	0.000	0.442	0.015	10.129	282.459					
Hong Kong	Mode 2	1.000	Unlimited	0.093	0.260	0.145	0.000	0.000	0.000	0.442	0.015	10.129	282.459					
	Min	1.000	Unlimited	0.000	0.000	0.473	0.000	0.000	0.000	0.452	0.015	10.129	282.459					
	Max	1.000	Unlimited	0.105	0.225	0.000	0.000	0.000	0.000	0.423	0.015	10.129	282.459					
Middle East	Mode 1	1.000	Unlimited	0.090	0.252	0.156	0.000	0.000	0.000	0.443	0.015	10.129	282.459					
	Mode 2	1.000	Unlimited	0.000	0.000	0.430	0.000	0.000	0.000	0.447	0.015	10.129	282.459					
	Min	1.000	Unlimited	0.000	0.000	0.433	0.000	0.000	0.000	0.447	0.015	10.129	282.459					
	Max	1.000	Unlimited	0.109	0.199	0.000	0.000	0.000	0.000	0.421	0.015	10.129	282.459					
	Mode 1	1.000	Unlimited	0.090	0.252	0.000	0.000	0.000	0.000	0.423	0.015	10.129	282.459					
	Mode 2	1.000	Unlimited	0.099	0.250	0.000	0.000	0.000	0.000	0.424	0.015	10.129	282.459					
	Min	1.000	Unlimited	0.000	0.000	0.440	0.000	0.000	0.000	0.448	0.015	10.129	282.459					
	Max	1.000	Unlimited	0.105	0.124	0.000	0.000	0.000	0.000	0.415	0.015	10.129	282.459					
	Mode 1	1.000	Unlimited	0.000	0.000	0.213	0.000	0.000	0.000	0.419	0.015	10.129	282.459					
	Mode 2	1.000	Unlimited	0.086	0.161	0.000	0.000	0.000	0.000	0.415	0.015	10.129	282.459					

^a Min = lowest observed combination of air and seawater temperatures; Max = highest observed combination; Mode 1 = most frequent combination; Mode 2 = second most frequent combination.

Table G.2: KPI results for the sailing operational profile under low-occupancy scenarios^a.

Climate Zone	Parameter	KPI I		KPI II		KPI III					KPI IV		KPI V		KPI VI		KPI VII	
		[-]	[hh:mm:ss / -]	[-]	[hh:mm:ss / -]	E. Chiller / HP C		E. Chiller / HP H		Heat Exch. E. Heater	Heat Tank	[-]	[-]	[-]	[-]	[-]	[-]	[-]
						[-]	[-]	[-]	[-]									
Atlantic Crossing	Min	1.000	Unlimited	0.000	0.000	0.801	0.000	0.000	0.000	0.449	0.015	10.129	282.459					
	Max	1.000	Unlimited	0.077	0.216	0.094	0.000	0.000	0.000	0.420	0.015	10.129	282.459					
	Mode 1	1.000	Unlimited	0.083	0.232	0.175	0.000	0.000	0.000	0.425	0.015	10.129	282.459					
Caribbean	Mode 2	1.000	Unlimited	0.074	0.206	0.183	0.000	0.000	0.000	0.424	0.015	10.129	282.459					
	Min	1.000	Unlimited	0.000	0.000	0.517	0.000	0.000	0.000	0.432	0.015	10.129	282.459					
	Max	1.000	Unlimited	0.092	0.257	0.028	0.000	0.000	0.000	0.418	0.015	10.129	282.459					
East Mediterranean	Mode 1	1.000	Unlimited	0.083	0.232	0.108	0.000	0.000	0.000	0.421	0.015	10.129	282.459					
	Mode 2	1.000	Unlimited	0.074	0.206	0.169	0.000	0.000	0.000	0.423	0.015	10.129	282.459					
	Min	1.000	Unlimited	0.000	0.000	0.574	0.000	0.000	0.000	0.436	0.015	10.129	282.459					
West-East Mediterranean	Max	1.000	Unlimited	0.081	0.228	0.073	0.000	0.000	0.000	0.419	0.015	10.129	282.459					
	Mode 1	1.000	Unlimited	0.072	0.201	0.305	0.000	0.000	0.000	0.431	0.015	10.129	282.459					
	Mode 2	1.000	Unlimited	0.078	0.218	0.302	0.000	0.000	0.000	0.432	0.015	10.129	282.459					
West Mediterranean	Min	1.000	Unlimited	0.000	0.000	0.658	0.000	0.000	0.000	0.440	0.015	10.129	282.459					
	Max	1.000	Unlimited	0.081	0.228	0.069	0.000	0.000	0.000	0.419	0.015	10.129	282.459					
	Mode 1	1.000	Unlimited	0.074	0.206	0.332	0.000	0.000	0.000	0.433	0.015	10.129	282.459					
Hong Kong	Mode 2	1.000	Unlimited	0.078	0.218	0.323	0.000	0.000	0.000	0.433	0.015	10.129	282.459					
	Min	1.000	Unlimited	0.000	0.000	0.634	0.000	0.000	0.000	0.439	0.015	10.129	282.459					
	Max	1.000	Unlimited	0.077	0.216	0.103	0.000	0.000	0.000	0.420	0.015	10.129	282.459					
Middle East	Mode 1	1.000	Unlimited	0.074	0.206	0.340	0.000	0.000	0.000	0.433	0.015	10.129	282.459					
	Mode 2	1.000	Unlimited	0.078	0.218	0.339	0.000	0.000	0.000	0.434	0.015	10.129	282.459					
	Min	1.000	Unlimited	0.000	0.000	0.583	0.000	0.000	0.000	0.436	0.015	10.129	282.459					
	Max	1.000	Unlimited	0.092	0.257	0.055	0.000	0.000	0.000	0.420	0.015	10.129	282.459					
	Mode 1	1.000	Unlimited	0.089	0.248	0.105	0.000	0.000	0.000	0.422	0.015	10.129	282.459					
	Mode 2	1.000	Unlimited	0.072	0.201	0.133	0.000	0.000	0.000	0.421	0.015	10.129	282.459					
	Min	1.000	Unlimited	0.000	0.000	0.590	0.000	0.000	0.000	0.436	0.015	10.129	282.459					
	Max	1.000	Unlimited	0.086	0.240	0.003	0.000	0.000	0.000	0.416	0.015	10.129	282.459					
	Mode 1	1.000	Unlimited	0.078	0.218	0.049	0.000	0.000	0.000	0.417	0.015	10.129	282.459					
	Mode 2	1.000	Unlimited	0.074	0.206	0.056	0.000	0.000	0.000	0.417	0.015	10.129	282.459					

^a Min = lowest observed combination of air and seawater temperatures; Max = highest observed combination; Mode 1 = most frequent combination; Mode 2 = second most frequent combination.

Table G.3: KPI results for the harbour operational profile under low-occupancy scenarios^a.

Climate Zone	Parameter	KPI I		KPI II		KPI III						KPI IV	KPI V	KPI VI	KPI VII
		[-]	[hh:mm:ss / -]	E. Chiller / HP C		E. Chiller / HP H		Heat Exch.	E. Heater	Heat Tank	[-]	[-]	[-]	[-]	
				[-]	[-]	[-]	[-]	[-]	[-]	[-]					
Atlantic Crossing	Min	1.000	Unlimited	0.000	0.000	0.000	0.000	0.000	0.865	0.000	0.980	0.015	10.129	282.459	
	Max	1.000	Unlimited	0.111	0.260	0.000	0.260	0.000	0.000	0.000	6.800	0.015	10.129	282.459	
	Mode 1	1.000	Unlimited	0.097	0.273	0.000	0.273	0.000	0.072	0.000	4.020	0.015	10.129	282.459	
Caribbean	Mode 2	1.000	Unlimited	0.087	0.244	0.000	0.244	0.000	0.000	0.000	3.430	0.015	10.129	282.459	
	Min	1.000	Unlimited	0.000	0.000	0.000	0.000	0.000	0.606	0.000	0.980	0.015	10.129	282.459	
	Max	1.000	Unlimited	0.111	0.223	0.000	0.223	0.000	0.000	0.000	6.290	0.015	10.129	282.459	
East Mediterranean	Mode 1	1.000	Unlimited	0.092	0.258	0.000	0.258	0.000	0.025	0.000	5.583	0.015	10.129	282.459	
	Mode 2	1.000	Unlimited	0.087	0.244	0.000	0.244	0.000	0.080	0.000	3.680	0.015	10.129	282.459	
	Min	1.000	Unlimited	0.000	0.000	0.000	0.000	0.000	0.652	0.000	0.980	0.015	10.129	282.459	
West-East Mediterranean	Max	1.000	Unlimited	0.107	0.248	0.000	0.248	0.000	0.000	0.000	6.747	0.015	10.129	282.459	
	Mode 1	1.000	Unlimited	0.000	0.000	0.000	0.000	0.000	0.613	0.000	0.980	0.015	10.129	282.459	
	Mode 2	1.000	Unlimited	0.000	0.000	0.000	0.000	0.000	0.607	0.000	0.980	0.015	10.129	282.459	
West Mediterranean	Min	1.000	Unlimited	0.000	0.000	0.000	0.000	0.000	0.730	0.000	0.980	0.015	10.129	282.459	
	Max	1.000	Unlimited	0.107	0.244	0.000	0.244	0.000	0.000	0.000	6.689	0.015	10.129	282.459	
	Mode 1	1.000	Unlimited	0.000	0.000	0.000	0.000	0.000	0.641	0.000	0.980	0.015	10.129	282.459	
Hong Kong	Mode 2	1.000	Unlimited	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.980	0.015	10.129	282.459	
	Min	1.000	Unlimited	0.000	0.000	0.000	0.000	0.000	0.709	0.000	0.980	0.015	10.129	282.459	
	Max	1.000	Unlimited	0.107	0.269	0.000	0.269	0.000	0.000	0.000	7.041	0.015	10.129	282.459	
Middle East	Mode 1	1.000	Unlimited	0.000	0.000	0.000	0.000	0.000	0.635	0.000	0.980	0.015	10.129	282.459	
	Mode 2	1.000	Unlimited	0.000	0.000	0.000	0.000	0.000	0.653	0.000	0.980	0.015	10.129	282.459	
	Min	1.000	Unlimited	0.000	0.000	0.000	0.000	0.000	0.662	0.000	0.980	0.015	10.129	282.459	
Hong Kong	Max	1.000	Unlimited	0.107	0.248	0.000	0.248	0.000	0.000	0.000	6.747	0.015	10.129	282.459	
	Mode 1	1.000	Unlimited	0.104	0.289	0.000	0.289	0.000	0.000	0.000	7.479	0.015	10.129	282.459	
	Mode 2	1.000	Unlimited	0.085	0.239	0.000	0.239	0.000	0.049	0.000	4.424	0.015	10.129	282.459	
Middle East	Min	1.000	Unlimited	0.000	0.000	0.000	0.000	0.000	0.677	0.000	0.980	0.015	10.129	282.459	
	Max	1.000	Unlimited	0.096	0.190	0.000	0.190	0.000	0.000	0.000	6.258	0.015	10.129	282.459	
	Mode 1	1.000	Unlimited	0.087	0.220	0.000	0.220	0.000	0.000	0.000	7.079	0.015	10.129	282.459	
	Mode 2	1.000	Unlimited	0.000	0.000	0.000	0.000	0.000	0.395	0.000	0.980	0.015	10.129	282.459	

^a Min = lowest observed combination of air and seawater temperatures; Max = highest observed combination; Mode 1 = most frequent combination; Mode 2 = second most frequent combination.

Table G.4: KPI results for the anchor operational profile under medium-occupancy scenarios^a.

Climate Zone	Parameter	KPI I		KPI II		KPI III						KPI IV	KPI V	KPI VI	KPI VII
		[-]	[hh:mm:ss / -]	E. Chiller / HP C		E. Chiller / HP H		Heat Exch.	E. Heater	Heat Tank	[-]	[-]	[-]	[-]	
				[-]	[-]	[-]	[-]	[-]	[-]						
Atlantic Crossing	Min	1.000	00:23:53	0.000	0.000	0.960	1.000	0.171	0.512	0.015	10.129	282.459			
	Max	1.000	Unlimited	0.164	0.459	0.155	0.000	0.000	0.467	0.015	10.129	282.459			
	Mode 1	1.000	Unlimited	0.152	0.427	0.847	0.000	0.000	0.550	0.015	10.129	282.459			
Caribbean	Mode 2	1.000	Unlimited	0.157	0.441	0.831	0.000	0.000	0.550	0.015	10.129	282.459			
	Min	1.000	Unlimited	0.000	0.000	0.960	0.876	0.000	0.512	0.015	10.129	282.459			
	Max	1.000	Unlimited	0.191	0.535	0.018	0.000	0.000	0.459	0.015	10.129	282.459			
East Mediterranean	Mode 1	1.000	Unlimited	0.157	0.441	0.220	0.000	0.000	0.473	0.015	10.129	282.459			
	Mode 2	1.000	Unlimited	0.152	0.427	0.806	0.000	0.000	0.545	0.015	10.129	282.459			
	Min	1.000	03:51:29	0.000	0.000	0.960	1.000	1.653	0.512	0.015	10.129	282.459			
West-East Mediterranean	Max	1.000	Unlimited	0.172	0.482	0.111	0.000	0.000	0.464	0.015	10.129	282.459			
	Mode 1	1.000	Unlimited	0.152	0.427	0.960	0.218	0.000	0.564	0.015	10.129	282.459			
	Mode 2	1.000	Unlimited	0.157	0.441	0.960	0.246	0.000	0.566	0.015	10.129	282.459			
West Mediterranean	Min	1.000	00:55:21	0.000	0.000	0.960	1.000	0.395	0.512	0.015	10.129	282.459			
	Max	1.000	Unlimited	0.172	0.482	0.101	0.000	0.000	0.463	0.015	10.129	282.459			
	Mode 1	1.000	Unlimited	0.152	0.427	0.960	0.324	0.000	0.564	0.015	10.129	282.459			
Hong Kong	Mode 2	1.000	Unlimited	0.157	0.441	0.960	0.320	0.000	0.566	0.015	10.129	282.459			
	Min	1.000	01:09:01	0.000	0.000	0.960	1.000	0.493	0.512	0.015	10.129	282.459			
	Max	1.000	Unlimited	0.178	0.498	0.150	0.000	0.000	0.471	0.015	10.129	282.459			
Middle East	Mode 1	1.000	Unlimited	0.152	0.427	0.960	0.351	0.000	0.564	0.015	10.129	282.459			
	Mode 2	1.000	03:52:43	0.000	0.000	0.960	1.000	1.662	0.512	0.015	10.129	282.459			
	Min	1.000	03:00:37	0.000	0.000	0.960	1.000	1.290	0.512	0.015	10.129	282.459			
Middle East	Max	1.000	Unlimited	0.184	0.517	0.089	0.000	0.000	0.466	0.015	10.129	282.459			
	Mode 1	1.000	Unlimited	0.152	0.427	0.714	0.000	0.000	0.534	0.015	10.129	282.459			
	Mode 2	1.000	Unlimited	0.167	0.467	0.695	0.000	0.000	0.536	0.015	10.129	282.459			
	Min	1.000	02:13:55	0.000	0.000	0.960	1.000	0.957	0.512	0.015	10.129	282.459			
Middle East	Max	1.000	Unlimited	0.178	0.435	0.000	0.000	0.000	0.448	0.015	10.129	282.459			
	Mode 1	1.000	Unlimited	0.000	0.000	0.533	0.000	0.000	0.460	0.015	10.129	282.459			
	Mode 2	1.000	Unlimited	0.145	0.408	0.087	0.000	0.000	0.453	0.015	10.129	282.459			

^a Min = lowest observed combination of air and seawater temperatures; Max = highest observed combination; Mode 1 = most frequent combination; Mode 2 = second most frequent combination.

Table G.5: KPI results for the sailing operational profile under medium-occupancy scenarios^a.

Climate Zone	Parameter	KPI I		KPI II		KPI III						KPI IV	KPI V	KPI VI	KPI VII
		[-]	[hh:mm:ss / -]	E. Chiller / HP C		E. Chiller / HP H		Heat Exch.	E. Heater	Heat Tank	[-]	[-]	[-]	[-]	
				[-]	[-]	[-]	[-]	[-]	[-]						
Atlantic Crossing	Min	1.000	Unlimited	0.000	0.000	0.960	0.439	0.000	0.458	0.015	10.129	282.459			
	Max	1.000	Unlimited	0.159	0.445	0.031	0.000	0.000	0.429	0.015	10.129	282.459			
	Mode 1	1.000	Unlimited	0.172	0.482	0.150	0.000	0.000	0.438	0.015	10.129	282.459			
Caribbean	Mode 2	1.000	Unlimited	0.151	0.423	0.176	0.000	0.000	0.436	0.015	10.129	282.459			
	Min	1.000	Unlimited	0.000	0.000	0.792	0.000	0.000	0.448	0.015	10.129	282.459			
	Max	1.000	Unlimited	0.193	0.393	0.000	0.000	0.000	0.427	0.015	10.129	282.459			
East Mediterranean	Mode 1	1.000	Unlimited	0.172	0.482	0.045	0.000	0.000	0.432	0.015	10.129	282.459			
	Mode 2	1.000	Unlimited	0.151	0.423	0.152	0.000	0.000	0.434	0.015	10.129	282.459			
	Min	1.000	Unlimited	0.000	0.000	0.879	0.000	0.000	0.453	0.015	10.129	282.459			
West-East Mediterranean	Max	1.000	Unlimited	0.169	0.461	0.000	0.000	0.000	0.428	0.015	10.129	282.459			
	Mode 1	1.000	Unlimited	0.147	0.411	0.370	0.000	0.000	0.447	0.015	10.129	282.459			
	Mode 2	1.000	Unlimited	0.161	0.451	0.357	0.000	0.000	0.448	0.015	10.129	282.459			
West Mediterranean	Min	1.000	Unlimited	0.000	0.000	0.960	0.081	0.000	0.458	0.015	10.129	282.459			
	Max	1.000	Unlimited	0.169	0.449	0.000	0.000	0.000	0.428	0.015	10.129	282.459			
	Mode 1	1.000	Unlimited	0.151	0.423	0.410	0.000	0.000	0.450	0.015	10.129	282.459			
Hong Kong	Mode 2	1.000	Unlimited	0.161	0.451	0.390	0.000	0.000	0.450	0.015	10.129	282.459			
	Min	1.000	Unlimited	0.000	0.000	0.960	0.023	0.000	0.458	0.015	10.129	282.459			
	Max	1.000	Unlimited	0.193	0.461	0.000	0.000	0.000	0.429	0.015	10.129	282.459			
Middle East	Mode 1	1.000	Unlimited	0.186	0.520	0.033	0.000	0.000	0.433	0.015	10.129	282.459			
	Mode 2	1.000	Unlimited	0.147	0.411	0.099	0.000	0.000	0.431	0.015	10.129	282.459			
	Min	1.000	Unlimited	0.000	0.000	0.914	0.000	0.000	0.455	0.015	10.129	282.459			
	Max	1.000	Unlimited	0.179	0.303	0.000	0.000	0.000	0.423	0.015	10.129	282.459			
	Mode 1	1.000	Unlimited	0.161	0.386	0.000	0.000	0.000	0.425	0.015	10.129	282.459			
	Mode 2	1.000	Unlimited	0.151	0.382	0.000	0.000	0.000	0.424	0.015	10.129	282.459			

^a Min = lowest observed combination of air and seawater temperatures; Max = highest observed combination; Mode 1 = most frequent combination; Mode 2 = second most frequent combination.

Table G.6: KPI results for the harbour operational profile under medium-occupancy scenarios^a.

Climate Zone	Parameter	KPI I		KPI II		KPI III						KPI IV	KPI V	KPI VI	KPI VII
		[-]	[hh:mm:ss / -]	E. Chiller / HP C		E. Chiller / HP H		Heat Exch.	E. Heater	Heat Tank	[-]	[-]	[-]	[-]	
				[-]	[-]	[-]	[-]	[-]	[-]						
Atlantic Crossing	Min	1.000	11:07:27	0.000	0.000	0.000	0.000	0.000	1.000	4.768	0.980	0.015	10.129	282.459	
	Max	1.000	Unlimited	0.148	0.217	0.000	0.000	0.000	0.000	0.000	5.471	0.015	10.129	282.459	
	Mode 1	1.000	Unlimited	0.129	0.332	0.000	0.000	0.000	0.000	0.000	7.172	0.015	10.129	282.459	
Caribbean	Mode 2	1.000	Unlimited	0.114	0.320	0.000	0.000	0.003	0.000	0.000	7.277	0.015	10.129	282.459	
	Min	1.000	Unlimited	0.000	0.000	0.000	0.677	0.000	0.980	0.000	0.980	0.015	10.129	282.459	
	Max	1.000	Unlimited	0.148	0.165	0.000	0.000	0.000	0.000	0.000	4.946	0.015	10.129	282.459	
East Mediterranean	Mode 1	1.000	Unlimited	0.121	0.247	0.000	0.000	0.000	0.000	0.000	6.346	0.015	10.129	282.459	
	Mode 2	1.000	Unlimited	0.114	0.304	0.000	0.000	0.000	0.000	0.000	7.283	0.015	10.129	282.459	
	Min	1.000	Unlimited	0.000	0.000	0.000	0.000	0.741	0.000	0.000	0.980	0.015	10.129	282.459	
West-East Mediterranean	Max	1.000	Unlimited	0.143	0.200	0.000	0.000	0.000	0.000	0.000	5.371	0.015	10.129	282.459	
	Mode 1	1.000	Unlimited	0.000	0.000	0.000	0.000	0.688	0.000	0.000	0.980	0.015	10.129	282.459	
	Mode 2	1.000	Unlimited	0.000	0.000	0.000	0.000	0.679	0.000	0.000	0.980	0.015	10.129	282.459	
West Mediterranean	Min	1.000	Unlimited	0.000	0.000	0.000	0.000	0.847	0.000	0.000	0.980	0.015	10.129	282.459	
	Max	1.000	Unlimited	0.143	0.194	0.000	0.000	0.000	0.000	0.000	5.310	0.015	10.129	282.459	
	Mode 1	1.000	Unlimited	0.000	0.000	0.000	0.000	0.726	0.000	0.000	0.980	0.015	10.129	282.459	
Hong Kong	Mode 2	1.000	Unlimited	0.000	0.000	0.000	0.000	0.706	0.000	0.000	0.980	0.015	10.129	282.459	
	Min	1.000	Unlimited	0.000	0.000	0.000	0.000	0.818	0.000	0.000	0.980	0.015	10.129	282.459	
	Max	1.000	Unlimited	0.143	0.228	0.000	0.000	0.000	0.000	0.000	5.673	0.015	10.129	282.459	
Middle East	Mode 1	1.000	Unlimited	0.000	0.000	0.000	0.000	0.717	0.000	0.000	0.980	0.015	10.129	282.459	
	Mode 2	1.000	Unlimited	0.000	0.000	0.000	0.000	0.742	0.000	0.000	0.980	0.015	10.129	282.459	
	Min	1.000	Unlimited	0.000	0.000	0.000	0.000	0.754	0.000	0.000	0.980	0.015	10.129	282.459	
Middle East	Max	1.000	Unlimited	0.143	0.200	0.000	0.000	0.000	0.000	0.000	5.371	0.015	10.129	282.459	
	Mode 1	1.000	Unlimited	0.137	0.256	0.000	0.000	0.000	0.000	0.000	6.078	0.015	10.129	282.459	
	Mode 2	1.000	Unlimited	0.112	0.255	0.000	0.000	0.000	0.000	0.000	6.711	0.015	10.129	282.459	
Middle East	Min	1.000	Unlimited	0.000	0.000	0.000	0.000	0.775	0.000	0.000	0.980	0.015	10.129	282.459	
	Max	1.000	Unlimited	0.126	0.120	0.000	0.000	0.000	0.000	0.000	4.691	0.015	10.129	282.459	
	Mode 1	1.000	Unlimited	0.114	0.162	0.000	0.000	0.000	0.000	0.000	5.394	0.015	10.129	282.459	
Mode 2	1.000	Unlimited	0.000	0.000	0.000	0.000	0.390	0.000	0.000	0.980	0.015	10.129	282.459		

^a Min = lowest observed combination of air and seawater temperatures; Max = highest observed combination; Mode 1 = most frequent combination; Mode 2 = second most frequent combination.

Table G.7: KPI results for the anchor operational profile under high-occupancy scenarios^a.

Climate Zone	Parameter	KPI I	KPI II	KPI III						KPI IV	KPI V	KPI VI	KPI VII	
		[-]	[hh:mm:ss / -]	E. Chiller / HP C		E. Chiller / HP H		Heat Exch.	E. Heater	Heat Tank	[-]	[-]	[-]	[-]
				[-]	[-]	[-]	[-]	[-]	[-]					
Atlantic Crossing	Min	1.000	00:12:58	0.000	0.000	0.960	1.000	0.093	0.512	0.015	10.129	282.459		
	Max	1.000	Unlimited	0.234	0.655	0.057	0.000	0.000	0.479	0.015	10.129	282.459		
	Mode 1	1.000	Unlimited	0.218	0.610	0.828	0.000	0.000	0.570	0.015	10.129	282.459		
Caribbean	Mode 2	1.000	Unlimited	0.225	0.630	0.803	0.000	0.500	0.569	0.015	10.129	282.459		
	Min	1.000	01:17:03	0.000	0.000	0.960	1.000	0.550	0.512	0.015	10.129	282.459		
	Max	1.000	Unlimited	0.273	0.553	0.000	0.000	0.000	0.468	0.015	10.129	282.459		
East Mediterranean	Mode 1	1.000	Unlimited	0.225	0.630	0.145	0.000	0.000	0.487	0.015	10.129	282.459		
	Mode 2	1.000	Unlimited	0.218	0.610	0.770	0.000	0.000	0.563	0.015	10.129	282.459		
	Min	1.000	00:37:43	0.000	0.000	0.960	1.000	0.269	0.512	0.015	10.129	282.459		
West-East Mediterranean	Max	1.000	Unlimited	0.246	0.683	0.000	0.000	0.000	0.475	0.015	10.129	282.459		
	Mode 1	1.000	Unlimited	0.218	0.610	0.960	0.327	0.000	0.586	0.015	10.129	282.459		
	Mode 2	1.000	Unlimited	0.225	0.630	0.960	0.359	0.000	0.589	0.015	10.129	282.459		
West Mediterranean	Min	1.000	00:22:12	0.000	0.000	0.960	1.000	0.159	0.512	0.015	10.129	282.459		
	Max	1.000	Unlimited	0.246	0.661	0.000	0.000	0.000	0.473	0.015	10.129	282.459		
	Mode 1	1.000	Unlimited	0.218	0.610	0.960	0.471	0.000	0.586	0.015	10.129	282.459		
Hong Kong	Mode 2	1.000	Unlimited	0.225	0.630	0.960	0.459	0.000	0.588	0.015	10.129	282.459		
	Min	1.000	00:24:51	0.000	0.000	0.960	1.000	0.177	0.512	0.015	10.129	282.459		
	Max	1.000	Unlimited	0.254	0.712	0.049	0.000	0.000	0.484	0.015	10.129	282.459		
Middle East	Mode 1	1.000	Unlimited	0.218	0.610	0.960	0.507	0.000	0.586	0.015	10.129	282.459		
	Mode 2	1.000	00:37:59	0.000	0.000	0.960	1.000	0.271	0.512	0.015	10.129	282.459		
	Min	1.000	00:35:27	0.000	0.000	0.960	1.000	0.253	0.512	0.015	10.129	282.459		
Hong Kong	Max	1.000	Unlimited	0.263	0.683	0.000	0.000	0.000	0.477	0.015	10.129	282.459		
	Mode 1	1.000	Unlimited	0.218	0.610	0.649	0.000	0.000	0.548	0.015	10.129	282.459		
	Mode 2	1.000	Unlimited	0.238	0.667	0.618	0.000	0.000	0.551	0.015	10.129	282.459		
Middle East	Min	1.000	00:32:49	0.000	0.000	0.960	1.000	0.234	0.512	0.015	10.129	282.459		
	Max	1.000	Unlimited	0.254	0.381	0.000	0.000	0.000	0.452	0.015	10.129	282.459		
	Mode 1	1.000	Unlimited	0.000	0.000	0.606	0.000	0.000	0.469	0.015	10.129	282.459		
Mode 2	1.000	Unlimited	0.208	0.532	0.000	0.000	0.000	0.459	0.015	10.129	282.459			

^a Min = lowest observed combination of air and seawater temperatures; Max = highest observed combination; Mode 1 = most frequent combination; Mode 2 = second most frequent combination.

Table G.8: KPI results for the sailing operational profile under high-occupancy scenarios^a.

Climate Zone	Parameter	KPI I		KPI II		KPI III						KPI IV	KPI V	KPI VI	KPI VII
		[-]	[hh:mm:ss / -]	E. Chiller / HP C		E. Chiller / HP H		Heat Exch.	E. Heater	Heat Tank	[-]	[-]	[-]	[-]	
				[-]	[-]	[-]	[-]	[-]	[-]						
Atlantic Crossing	Min	1.000	00:52:10	0.000	0.000	0.960	1.000	0.373	0.457	0.015	10.129	282.459			
	Max	1.000	Unlimited	0.224	0.627	0.023	0.000	0.000	0.438	0.015	10.129	282.459			
	Mode 1	1.000	Unlimited	0.240	0.674	0.215	0.000	0.000	0.452	0.015	10.129	282.459			
Caribbean	Mode 2	1.000	Unlimited	0.214	0.600	0.243	0.000	0.000	0.450	0.015	10.129	282.459			
	Min	1.000	Unlimited	0.000	0.000	0.960	0.310	0.000	0.458	0.015	10.129	282.459			
	Max	1.000	Unlimited	0.267	0.507	0.000	0.000	0.000	0.435	0.015	10.129	282.459			
East Mediterranean	Mode 1	1.000	Unlimited	0.240	0.674	0.052	0.000	0.000	0.443	0.015	10.129	282.459			
	Mode 2	1.000	Unlimited	0.214	0.600	0.207	0.000	0.000	0.448	0.015	10.129	282.459			
	Min	1.000	Unlimited	0.000	0.000	0.960	0.532	0.000	0.458	0.015	10.129	282.459			
West-East Mediterranean	Max	1.000	Unlimited	0.236	0.611	0.000	0.000	0.000	0.437	0.015	10.129	282.459			
	Mode 1	1.000	Unlimited	0.209	0.585	0.543	0.000	0.000	0.466	0.015	10.129	282.459			
	Mode 2	1.000	Unlimited	0.226	0.635	0.530	0.000	0.000	0.468	0.015	10.129	282.459			
West Mediterranean	Min	1.000	Unlimited	0.000	0.000	0.960	0.857	0.000	0.457	0.015	10.129	282.459			
	Max	1.000	Unlimited	0.236	0.594	0.000	0.000	0.000	0.436	0.015	10.129	282.459			
	Mode 1	1.000	Unlimited	0.214	0.600	0.607	0.000	0.000	0.471	0.015	10.129	282.459			
Hong Kong	Mode 2	1.000	Unlimited	0.226	0.635	0.581	0.000	0.000	0.471	0.015	10.129	282.459			
	Min	1.000	Unlimited	0.000	0.000	0.960	0.767	0.000	0.458	0.015	10.129	282.459			
	Max	1.000	Unlimited	0.224	0.627	0.045	0.000	0.000	0.440	0.015	10.129	282.459			
Middle East	Mode 1	1.000	Unlimited	0.214	0.600	0.625	0.000	0.000	0.472	0.015	10.129	282.459			
	Mode 2	1.000	Unlimited	0.226	0.635	0.621	0.000	0.000	0.474	0.015	10.129	282.459			
	Min	1.000	Unlimited	0.000	0.000	0.960	0.570	0.000	0.458	0.015	10.129	282.459			
	Max	1.000	Unlimited	0.267	0.611	0.000	0.000	0.000	0.439	0.015	10.129	282.459			
	Mode 1	1.000	Unlimited	0.257	0.721	0.041	0.000	0.000	0.445	0.015	10.129	282.459			
	Mode 2	1.000	Unlimited	0.209	0.585	0.122	0.000	0.000	0.442	0.015	10.129	282.459			
	Min	1.000	Unlimited	0.000	0.000	0.960	0.603	0.000	0.458	0.015	10.129	282.459			
	Max	1.000	Unlimited	0.248	0.367	0.000	0.000	0.000	0.429	0.015	10.129	282.459			
	Mode 1	1.000	Unlimited	0.226	0.495	0.000	0.000	0.000	0.432	0.015	10.129	282.459			
	Mode 2	1.000	Unlimited	0.214	0.489	0.000	0.000	0.000	0.431	0.015	10.129	282.459			

^a Min = lowest observed combination of air and seawater temperatures; Max = highest observed combination; Mode 1 = most frequent combination; Mode 2 = second most frequent combination.

Table G.9: KPI results for the harbour operational profile under high-occupancy scenarios^a.

Climate Zone	Parameter	KPI I	KPI II	KPI III						KPI IV	KPI V	KPI VI	KPI VII	
		[-]	[hh:mm:ss / -]	E. Chiller / HP C		E. Chiller / HP H		Heat Exch.	E. Heater	Heat Tank	[-]	[-]	[-]	[-]
				[-]	[-]	[-]	[-]	[-]	[-]					
Atlantic Crossing	Min	1.000	00:35:26	0.000	0.000	0.000	1.000	0.253	0.980	0.015	10.129	282.459		
	Max	1.000	Unlimited	0.192	0.360	0.000	0.000	0.000	6.089	0.015	10.129	282.459		
	Mode 1	1.000	Unlimited	0.167	0.469	0.000	0.076	0.000	4.812	0.015	10.129	282.459		
Caribbean	Mode 2	1.000	Unlimited	0.149	0.418	0.000	0.112	0.000	3.994	0.015	10.129	282.459		
	Min	1.000	09:03:19	0.000	0.000	0.000	1.000	3.881	0.980	0.015	10.129	282.459		
	Max	1.000	Unlimited	0.192	0.278	0.000	0.000	0.000	5.444	0.015	10.129	282.459		
East Mediterranean	Mode 1	1.000	Unlimited	0.158	0.408	0.000	0.000	0.000	7.179	0.015	10.129	282.459		
	Mode 2	1.000	Unlimited	0.149	0.418	0.000	0.000	0.082	0.000	4.507	0.015	10.129	282.459	
	Min	1.000	02:28:12	0.000	0.000	0.000	1.000	1.059	0.980	0.015	10.129	282.459		
West-East Mediterranean	Max	1.000	Unlimited	0.186	0.333	0.000	0.000	0.000	5.969	0.015	10.129	282.459		
	Mode 1	1.000	07:02:42	0.000	0.000	0.000	1.000	3.019	0.980	0.015	10.129	282.459		
	Mode 2	1.000	08:28:00	0.000	0.000	0.000	1.000	3.629	0.980	0.015	10.129	282.459		
West Mediterranean	Min	1.000	01:08:36	0.000	0.000	0.000	1.000	0.490	0.980	0.015	10.129	282.459		
	Max	1.000	Unlimited	0.186	0.323	0.000	0.000	0.000	5.895	0.015	10.129	282.459		
	Mode 1	1.000	03:13:45	0.000	0.000	0.000	1.000	1.384	0.980	0.015	10.129	282.459		
Hong Kong	Mode 2	1.000	04:14:45	0.000	0.000	0.000	1.000	1.820	0.980	0.015	10.129	282.459		
	Min	1.000	01:20:28	0.000	0.000	0.000	1.000	0.575	0.980	0.015	10.129	282.459		
	Max	1.000	Unlimited	0.186	0.378	0.000	0.000	0.000	6.340	0.015	10.129	282.459		
Middle East	Mode 1	1.000	03:29:54	0.000	0.000	0.000	1.000	1.499	0.980	0.015	10.129	282.459		
	Mode 2	1.000	02:36:47	0.000	0.000	0.000	1.000	1.120	0.980	0.015	10.129	282.459		
	Min	1.000	02:11:26	0.000	0.000	0.000	1.000	0.939	0.980	0.015	10.129	282.459		
	Max	1.000	Unlimited	0.186	0.333	0.000	0.000	0.000	5.969	0.015	10.129	282.459		
	Mode 1	1.000	Unlimited	0.179	0.423	0.000	0.000	0.000	6.841	0.015	10.129	282.459		
	Mode 2	1.000	Unlimited	0.145	0.408	0.000	0.013	0.000	6.719	0.015	10.129	282.459		
	Min	1.000	01:52:57	0.000	0.000	0.000	1.000	0.807	0.980	0.015	10.129	282.459		
	Max	1.000	Unlimited	0.164	0.205	0.000	0.000	0.000	5.146	0.015	10.129	282.459		
	Mode 1	1.000	Unlimited	0.149	0.272	0.000	0.000	0.000	6.018	0.015	10.129	282.459		
	Mode 2	1.000	Unlimited	0.000	0.000	0.000	0.570	0.000	0.980	0.015	10.129	282.459		

^a Min = lowest observed combination of air and seawater temperatures; Max = highest observed combination; Mode 1 = most frequent combination; Mode 2 = second most frequent combination.

H. KPI Plots for Design 1

KPI IV (Systems Efficiency) at Minimum Temperatures

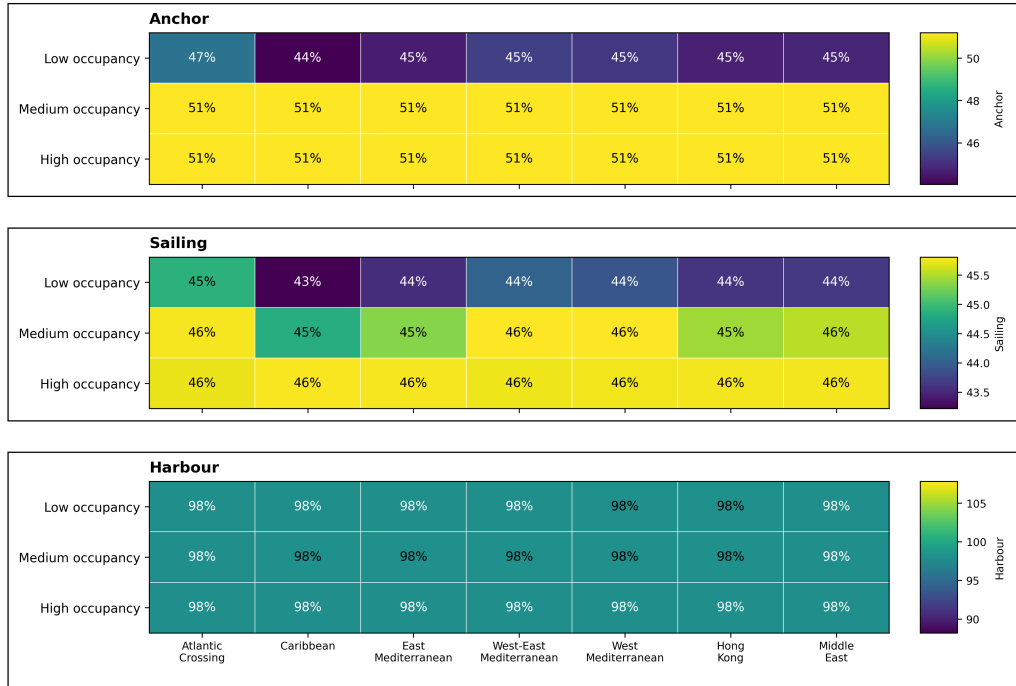


Figure H.1: KPI IV (CHPC Efficiency) at minimum temperatures.

KPI IV (Systems Efficiency) at Maximum Temperatures

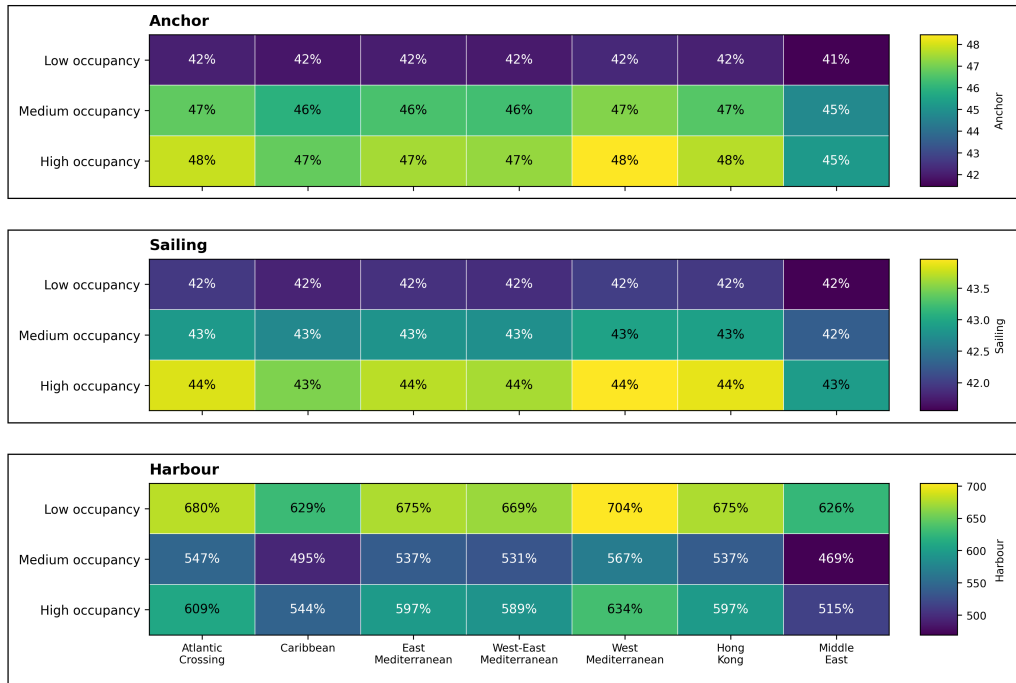


Figure H.2: KPI IV (CHPC Efficiency) at maximum temperatures.

H. KPI Plots for Design 1 (continued)

KPI IV (Systems Efficiency) at Most Frequent Temperatures

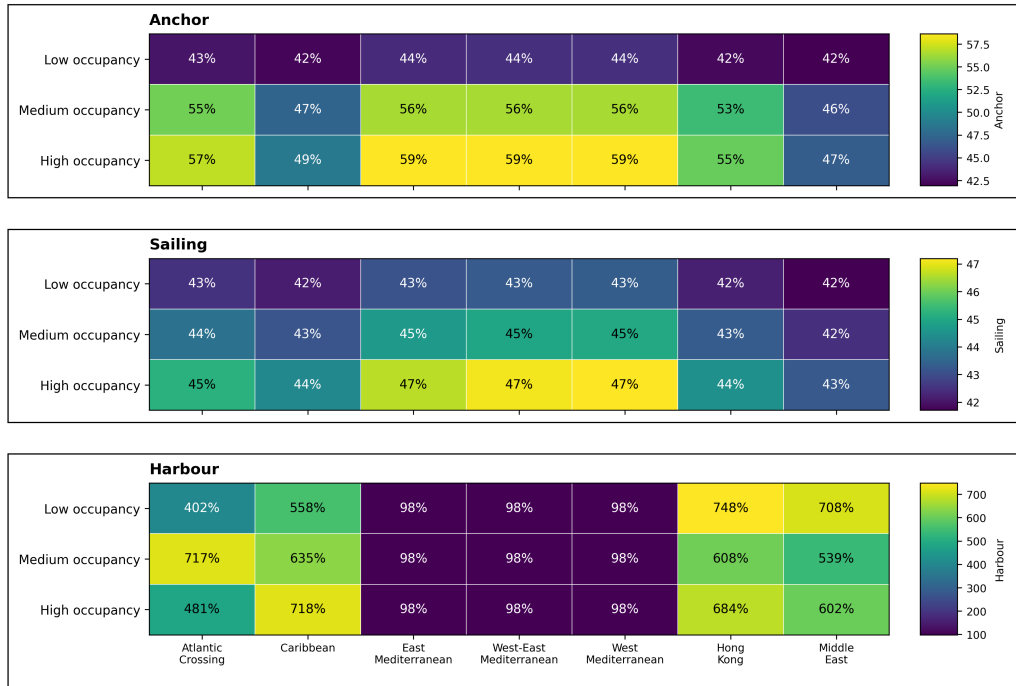


Figure H.3: KPI IV (CHPC Efficiency) at most frequent temperatures.

KPI IV (Systems Efficiency) at Second Most Frequent Temperatures

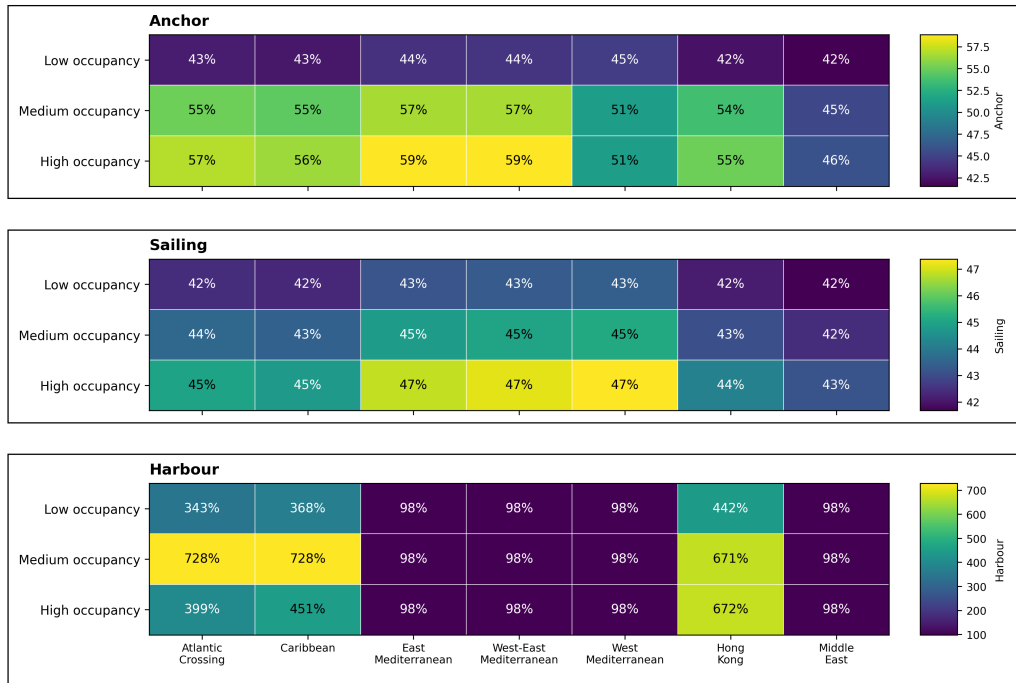


Figure H.4: KPI IV (CHPC Efficiency) at second most frequent temperatures.

H. KPI Plots for Design 1 (continued)

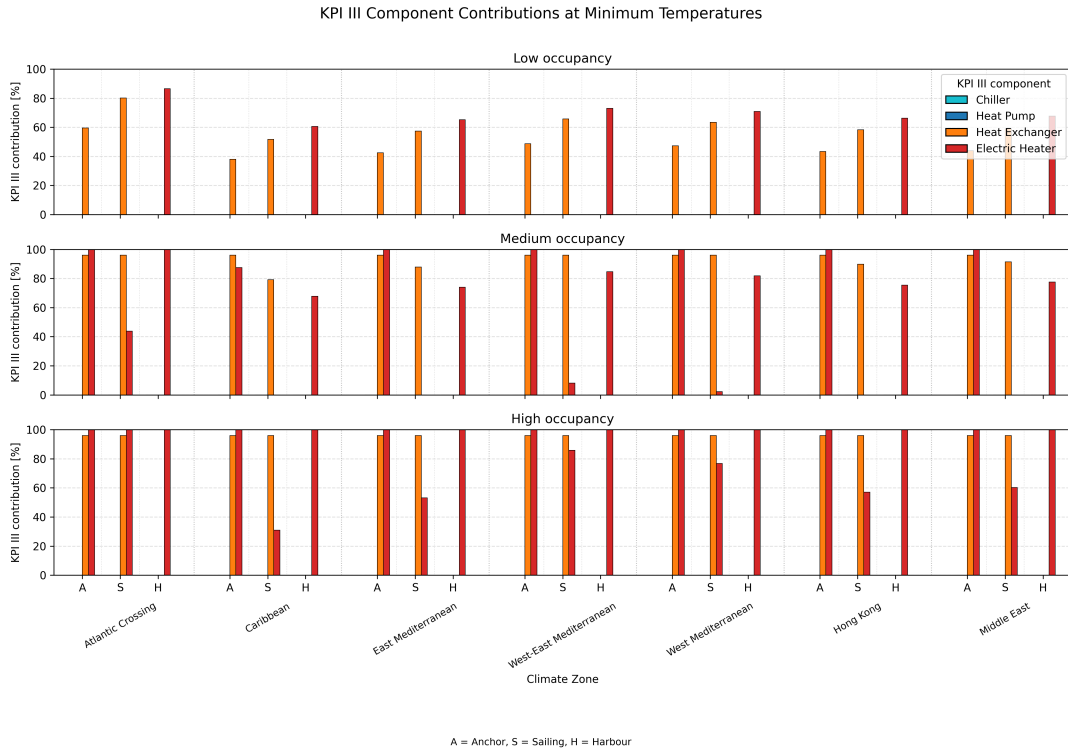


Figure H.5: KPI III component contributions at minimum temperatures.

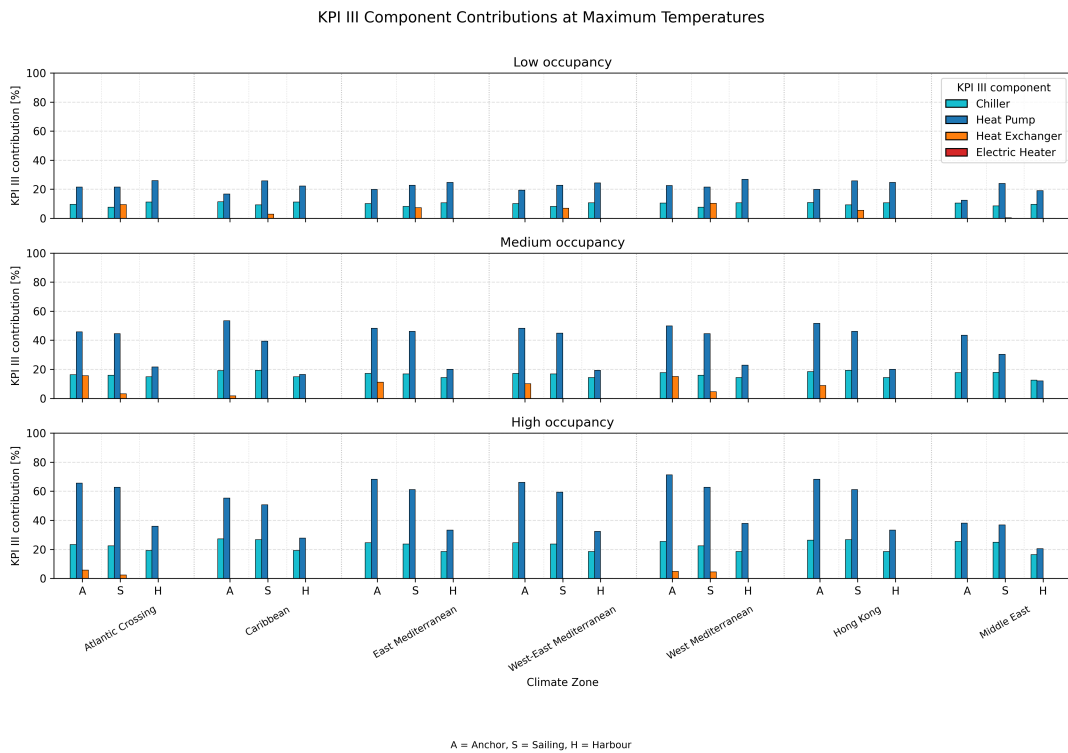


Figure H.6: KPI III component contributions at maximum temperatures.

H. KPI Plots for Design 1 (continued)

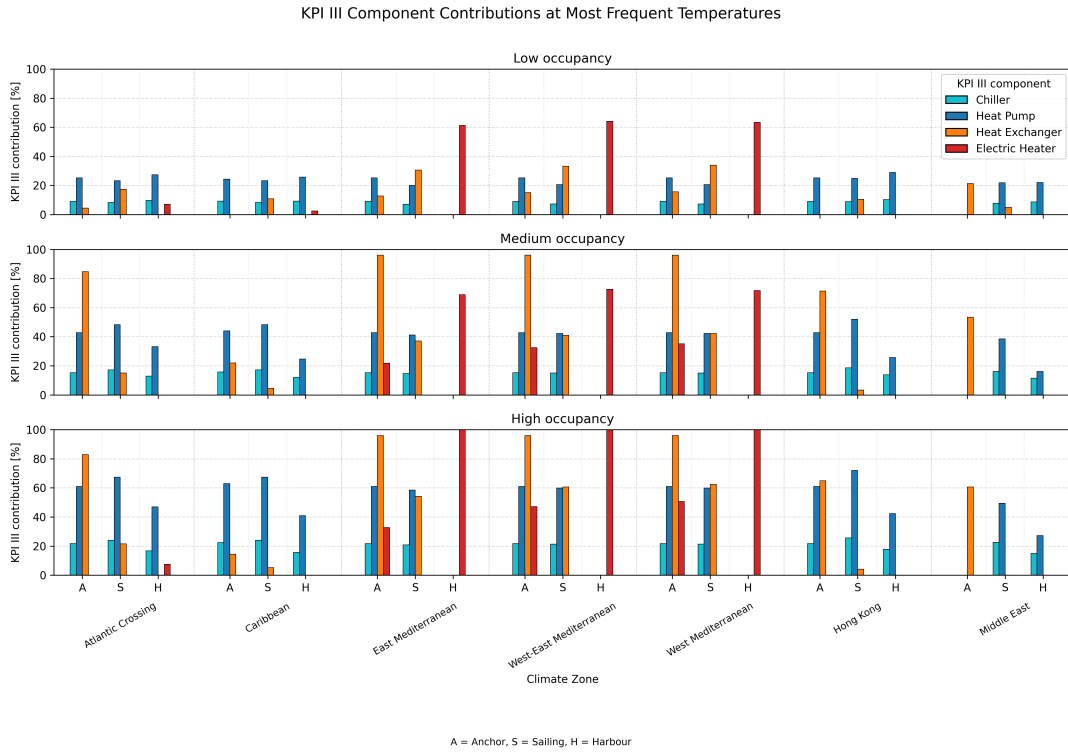


Figure H.7: KPI III component contributions at most frequent temperatures.

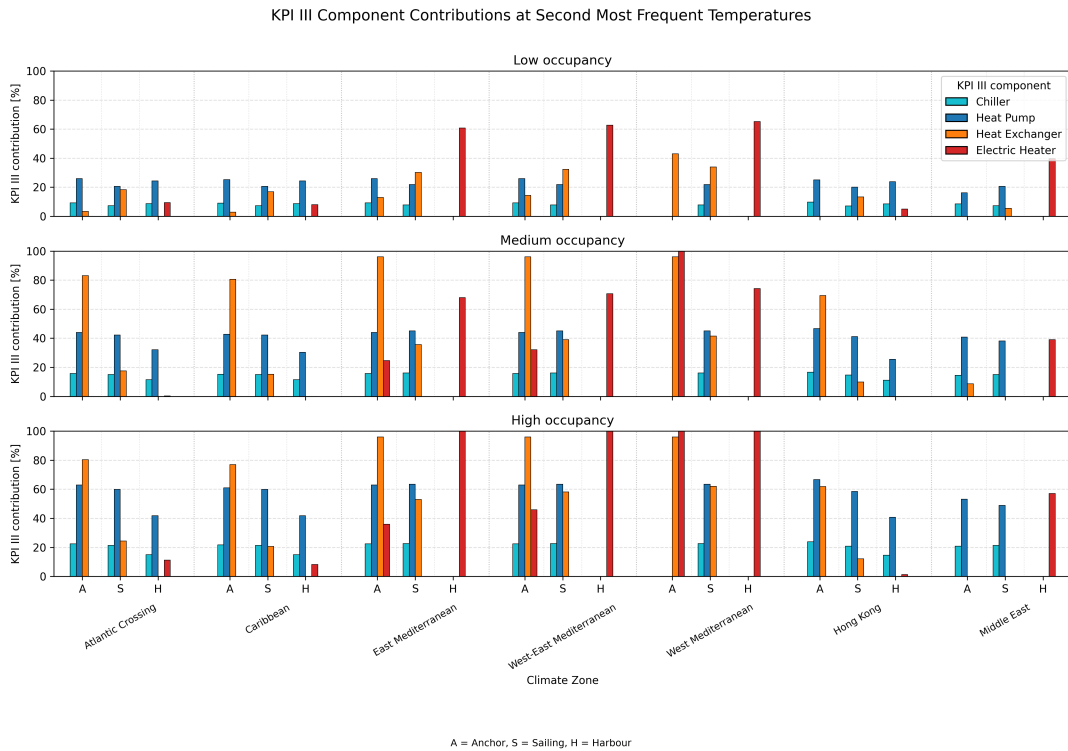


Figure H.8: KPI III component contributions at second most frequent temperatures.

H. KPI Plots for Design 1 (continued)

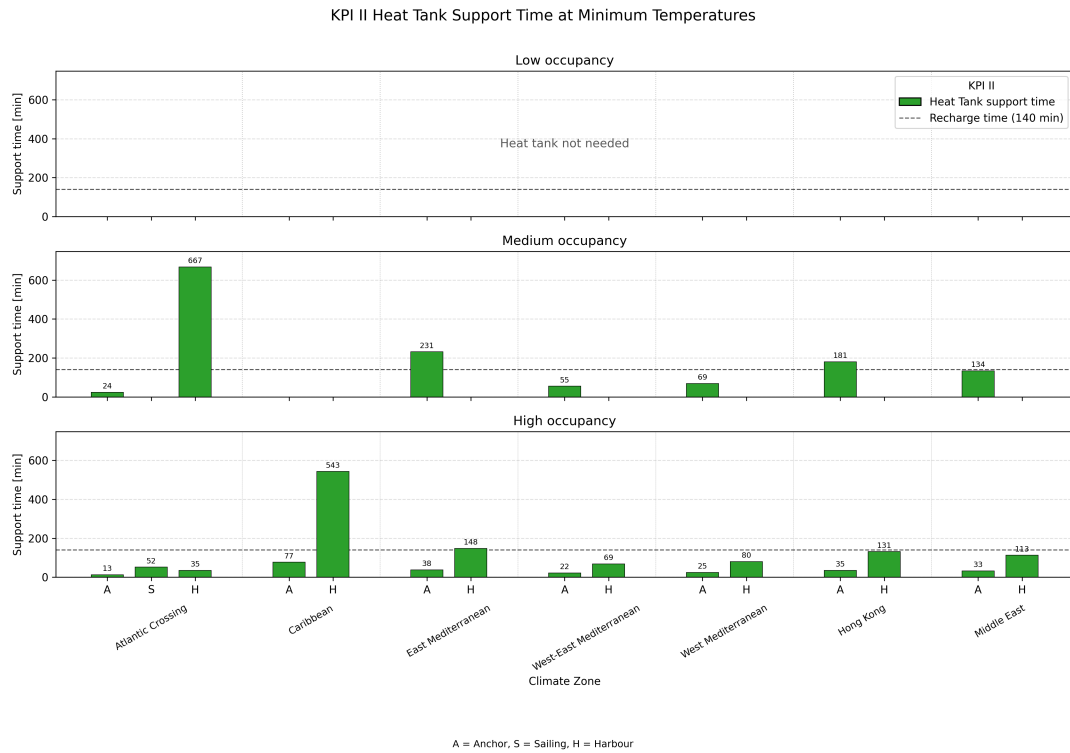


Figure H.9: KPI II heat tank support time at minimum temperatures.

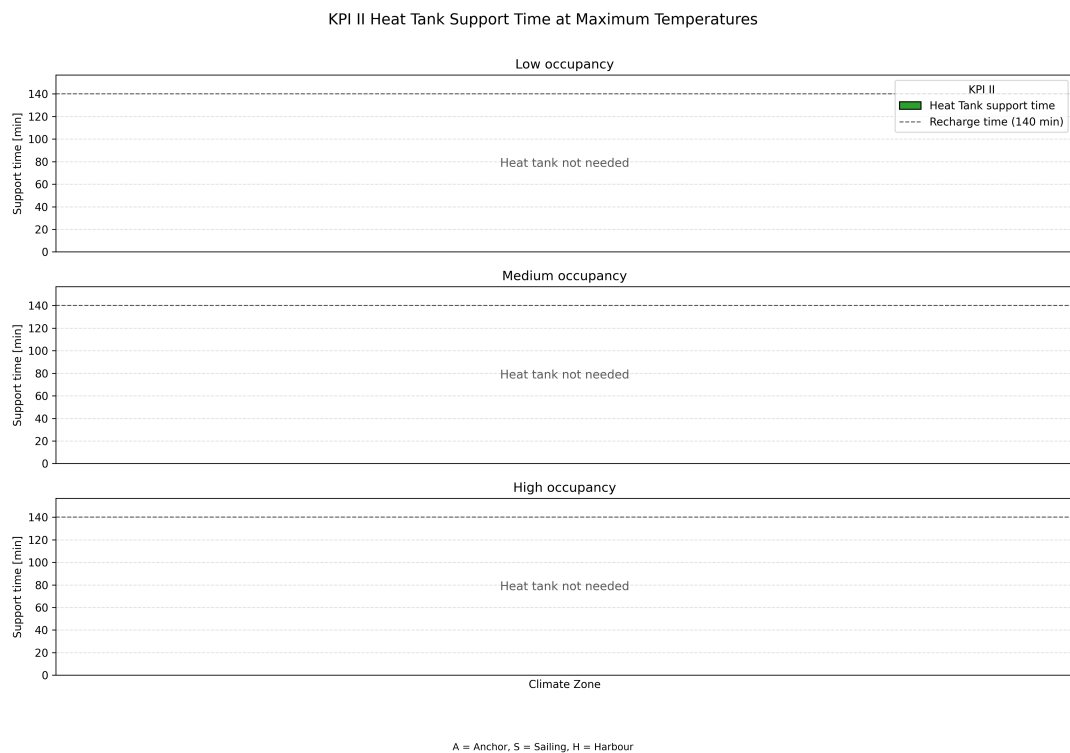


Figure H.10: KPI II heat tank support time at maximum temperatures.

H. KPI Plots for Design 1 (continued)

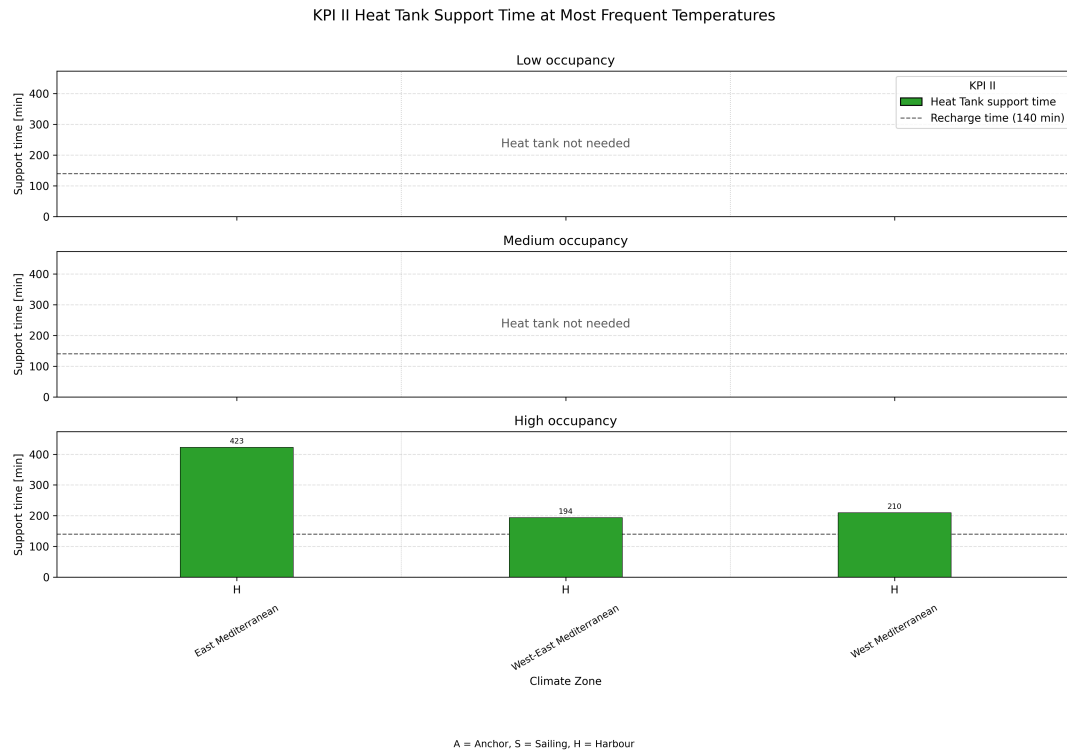


Figure H.11: KPI II heat tank support time at most frequent temperatures.

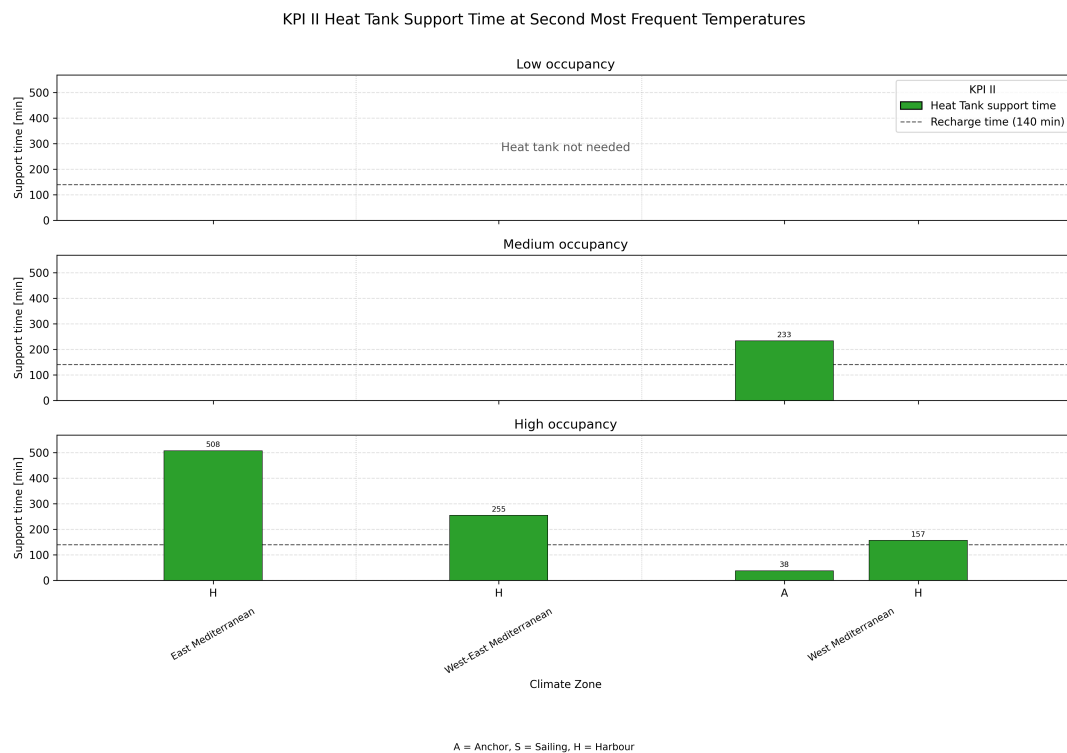


Figure H.12: KPI II heat tank support time at second most frequent temperatures.

I. Heat Generated Results for Design 2

Table I.1: Heat generation results for the anchor operational profile under low occupancy^a.

Climate Zone	Parameter	Electrical Chiller / Heat Pump					Heat Exchanger		Absorption Chiller		Electrical Heater			Heat Tank	
		Q_H [kW]	Q_C [kW]	Q_L [kW]	P_E [kW]	COP [-]	Q [kW]	Q_L [kW]	Q_H [kW]	Q_C [kW]	Q [kW]	Q_L [kW]	P_E [kW]	Q [kW]	t [min]
Atlantic Crossing	Min	0.0	0.0	0.0	0.0	0.0	333.7	13.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Max	0.0	0.0	0.0	0.0	0.0	75.2	3.1	103.6	72.5	0.0	0.0	0.0	0.0	0.0
	Mode 1	0.0	0.0	0.0	0.0	0.0	113.3	4.7	96.3	67.4	0.0	0.0	0.0	0.0	0.0
Caribbean	Mode 2	0.0	0.0	0.0	0.0	0.0	110.2	4.6	99.5	69.6	0.0	0.0	0.0	0.0	0.0
	Min	0.0	0.0	0.0	0.0	0.0	212.9	8.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Max	0.0	0.0	0.0	0.0	0.0	58.3	2.4	121.1	84.8	0.0	0.0	0.0	0.0	0.0
East Mediterranean	Mode 1	0.0	0.0	0.0	0.0	0.0	85.2	3.5	99.5	69.6	0.0	0.0	0.0	0.0	0.0
	Mode 2	0.0	0.0	0.0	0.0	0.0	103.9	4.3	96.3	67.4	0.0	0.0	0.0	0.0	0.0
	Min	0.0	0.0	0.0	0.0	0.0	238.0	9.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0
West-East Mediterranean	Max	0.0	0.0	0.0	0.0	0.0	69.5	2.9	109.0	76.3	0.0	0.0	0.0	0.0	0.0
	Mode 1	0.0	0.0	0.0	0.0	0.0	160.2	6.7	96.3	67.4	0.0	0.0	0.0	0.0	0.0
	Mode 2	0.0	0.0	0.0	0.0	0.0	163.3	6.8	99.5	69.6	0.0	0.0	0.0	0.0	0.0
West Mediterranean	Min	0.0	0.0	0.0	0.0	0.0	273.0	11.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Max	0.0	0.0	0.0	0.0	0.0	67.7	2.8	109.0	76.3	0.0	0.0	0.0	0.0	0.0
	Mode 1	0.0	0.0	0.0	0.0	0.0	172.7	7.2	96.3	67.4	0.0	0.0	0.0	0.0	0.0
Hong Kong	Mode 2	0.0	0.0	0.0	0.0	0.0	172.1	7.2	99.5	69.6	0.0	0.0	0.0	0.0	0.0
	Min	0.0	0.0	0.0	0.0	0.0	264.6	11.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Max	0.0	0.0	0.0	0.0	0.0	78.9	3.3	112.8	78.9	0.0	0.0	0.0	0.0	0.0
Middle East	Mode 1	0.0	0.0	0.0	0.0	0.0	175.8	7.3	96.3	67.4	0.0	0.0	0.0	0.0	0.0
	Max	0.0	0.0	0.0	0.0	0.0	241.1	10.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Mode 2	0.0	0.0	0.0	0.0	0.0	242.6	10.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Min	0.0	0.0	0.0	0.0	0.0	69.5	2.9	116.9	81.8	0.0	0.0	0.0	0.0	0.0
	Max	0.0	0.0	0.0	0.0	0.0	88.3	3.7	96.3	67.4	0.0	0.0	0.0	0.0	0.0
	Mode 1	0.0	0.0	0.0	0.0	0.0	87.7	3.7	105.5	73.9	0.0	0.0	0.0	0.0	0.0
	Min	0.0	0.0	0.0	0.0	0.0	246.1	10.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Max	0.0	3.0	0.0	0.0	3.0	43.3	1.8	112.8	78.9	0.0	0.0	0.0	0.0	0.0
	Mode 1	0.0	0.0	0.0	0.0	0.0	119.2	5.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Mode 2	0.0	0.0	0.0	0.0	0.0	56.4	2.4	91.9	64.3	0.0	0.0	0.0	0.0	0.0

^a Min = lowest observed combination of air and seawater temperatures; Max = highest observed combination; Mode 1 = most frequent combination; Mode 2 = second most frequent combination.

Table I.2: Heat generation results for the sailing operational profile under low occupancy^a.

Climate Zone	Parameter	Electrical Chiller / Heat Pump					Heat Exchanger		Absorption Chiller		Electrical Heater			Heat Tank	
		Q_H [kW]	Q_C [kW]	Q_L [kW]	P_E [kW]	COP [-]	Q [kW]	Q_L [kW]	Q_H [kW]	Q_C [kW]	Q [kW]	Q_L [kW]	P_E [kW]	Q [kW]	t [min]
Atlantic Crossing	Min	0.0	0.0	0.0	0.0	0.0	448.4	18.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Max	0.0	0.0	0.0	0.0	0.0	128.3	5.3	82.5	57.7	0.0	0.0	0.0	0.0	0.0
	Mode 1	0.0	0.0	0.0	0.0	0.0	179.1	7.5	88.7	62.1	0.0	0.0	0.0	0.0	0.0
Caribbean	Mode 2	0.0	0.0	0.0	0.0	0.0	174.9	7.3	78.9	55.2	0.0	0.0	0.0	0.0	0.0
	Min	0.0	0.0	0.0	0.0	0.0	289.3	12.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Max	0.0	0.0	0.0	0.0	0.0	105.8	4.4	98.4	68.9	0.0	0.0	0.0	0.0	0.0
East Mediterranean	Mode 1	0.0	0.0	0.0	0.0	0.0	141.6	5.9	88.7	62.1	0.0	0.0	0.0	0.0	0.0
	Mode 2	0.0	0.0	0.0	0.0	0.0	166.6	6.9	78.9	55.2	0.0	0.0	0.0	0.0	0.0
	Min	0.0	0.0	0.0	0.0	0.0	321.6	13.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0
West-East Mediterranean	Max	0.0	0.0	0.0	0.0	0.0	120.8	5.0	87.0	60.9	0.0	0.0	0.0	0.0	0.0
	Mode 1	0.0	0.0	0.0	0.0	0.0	241.5	10.1	77.0	53.9	0.0	0.0	0.0	0.0	0.0
	Mode 2	0.0	0.0	0.0	0.0	0.0	245.7	10.2	83.5	58.4	0.0	0.0	0.0	0.0	0.0
West Mediterranean	Min	0.0	0.0	0.0	0.0	0.0	368.3	15.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Max	0.0	0.0	0.0	0.0	0.0	118.3	4.9	87.0	60.9	0.0	0.0	0.0	0.0	0.0
	Mode 1	0.0	0.0	0.0	0.0	0.0	258.2	10.8	78.9	55.2	0.0	0.0	0.0	0.0	0.0
Hong Kong	Mode 2	0.0	0.0	0.0	0.0	0.0	257.4	10.7	83.5	58.4	0.0	0.0	0.0	0.0	0.0
	Min	0.0	0.0	0.0	0.0	0.0	355.3	14.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Max	0.0	0.0	0.0	0.0	0.0	133.3	5.6	82.5	57.7	0.0	0.0	0.0	0.0	0.0
Middle East	Mode 1	0.0	0.0	0.0	0.0	0.0	262.4	10.9	78.9	55.2	0.0	0.0	0.0	0.0	0.0
	Mode 2	0.0	0.0	0.0	0.0	0.0	266.5	11.1	83.5	58.4	0.0	0.0	0.0	0.0	0.0
	Min	0.0	0.0	0.0	0.0	0.0	326.5	13.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Max	0.0	0.0	0.0	0.0	0.0	120.8	5.0	98.4	68.9	0.0	0.0	0.0	0.0	0.0
	Mode 1	0.0	0.0	0.0	0.0	0.0	145.8	6.1	94.9	66.4	0.0	0.0	0.0	0.0	0.0
	Mode 2	0.0	0.0	0.0	0.0	0.0	144.9	6.0	77.0	53.9	0.0	0.0	0.0	0.0	0.0
	Min	0.0	0.0	0.0	0.0	0.0	330.5	13.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Max	0.0	0.0	0.0	0.0	0.0	85.8	3.6	91.6	64.1	0.0	0.0	0.0	0.0	0.0
	Mode 1	0.0	0.0	0.0	0.0	0.0	104.1	4.3	83.5	58.4	0.0	0.0	0.0	0.0	0.0
	Mode 2	0.0	0.0	0.0	0.0	0.0	103.3	4.3	78.9	55.2	0.0	0.0	0.0	0.0	0.0

^a Min = lowest observed combination of air and seawater temperatures; Max = highest observed combination; Mode 1 = most frequent combination; Mode 2 = second most frequent combination.

Table I.3: Heat generation results for the harbour operational profile under low occupancy^a.

Climate Zone	Parameter	Electrical Chiller / Heat Pump					Heat Exchanger		Absorption Chiller		Electrical Heater			Heat Tank	
		Q_H [kW]	Q_C [kW]	Q_L [kW]	P_E [kW]	COP [-]	Q [kW]	Q_L [kW]	Q_H [kW]	Q_C [kW]	Q [kW]	Q_L [kW]	P_E [kW]	Q [kW]	t [min]
Atlantic Crossing	Min	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	302.8	6.2	309.0	0.0	0.0
	Max	91.1	83.4	0.0	25.7	6.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Mode 1	95.5	73.0	0.0	22.5	7.5	0.0	0.0	0.0	0.0	25.2	0.5	25.7	0.0	0.0
Caribbean	Mode 2	85.5	65.4	0.0	20.1	7.5	0.0	0.0	0.0	0.0	32.7	0.7	33.4	0.0	0.0
	Min	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	212.0	4.3	216.3	0.0	0.0
	Max	78.0	83.4	0.0	25.7	6.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
East Mediterranean	Mode 1	90.2	69.0	0.0	21.2	7.5	0.0	0.0	0.0	0.0	212.5	4.3	216.8	0.0	0.0
	Mode 2	85.5	65.4	0.0	20.1	7.5	0.0	0.0	0.0	0.0	27.9	0.6	28.5	0.0	0.0
	Min	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	228.3	4.7	232.9	0.0	0.0
West-East Mediterranean	Max	86.7	80.6	0.0	24.8	6.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Mode 1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	214.7	4.4	219.1	0.0	0.0
	Mode 2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	212.5	4.3	216.8	0.0	0.0
West Mediterranean	Min	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	255.4	5.2	260.6	0.0	0.0
	Max	85.3	80.6	0.0	24.8	6.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Mode 1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	224.4	4.6	229.0	0.0	0.0
Hong Kong	Mode 2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	219.3	4.5	223.8	0.0	0.0
	Min	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	248.0	5.1	253.1	0.0	0.0
	Max	80.0	80.6	0.0	24.8	7.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Middle East	Mode 1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	222.2	4.5	226.7	0.0	0.0
	Mode 2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	228.5	4.7	233.1	0.0	0.0
	Min	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	231.7	4.7	236.4	0.0	0.0
	Max	86.7	80.6	0.0	24.8	6.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Mode 1	101.3	77.8	0.0	23.9	7.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Mode 2	83.6	63.9	0.0	19.7	7.5	0.0	0.0	0.0	0.0	17.2	0.4	17.6	0.0	0.0
	Min	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	236.9	4.8	241.8	0.0	0.0
	Max	66.4	71.7	0.0	22.1	6.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Mode 1	77.0	65.4	0.0	20.1	7.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Mode 2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	138.4	2.8	141.2	0.0	0.0

^a Min = lowest observed combination of air and seawater temperatures; Max = highest observed combination; Mode 1 = most frequent combination; Mode 2 = second most frequent combination.

Table I.4: Heat generation results for the anchor operational profile under medium occupancy^a.

Climate Zone	Parameter	Electrical Chiller / Heat Pump					Heat Exchanger		Absorption Chiller		Electrical Heater			Heat Tank	
		Q_H [kW]	Q_C [kW]	Q_L [kW]	P_E [kW]	COP [-]	Q [kW]	Q_L [kW]	Q_H [kW]	Q_C [kW]	Q [kW]	Q_L [kW]	P_E [kW]	Q [kW]	t [min]
Atlantic Crossing	Min	0.0	0.0	0.0	0.0	0.0	580.0	24.2	0.0	0.0	350.0	7.1	357.1	275.4	27.6
	Max	0.0	0.0	0.0	0.0	0.0	247.3	10.3	175.3	122.7	0.0	0.0	0.0	0.0	0.0
	Mode 1	43.5	34.0	0.0	10.5	7.4	580.0	24.2	114.6	80.2	0.0	0.0	0.0	0.0	0.0
Caribbean	Mode 2	39.5	31.0	0.0	9.5	7.4	580.0	24.2	124.2	86.9	0.0	0.0	0.0	0.0	0.0
	Min	0.0	0.0	0.0	0.0	0.0	580.0	24.2	0.0	0.0	264.1	5.4	269.5	0.0	0.0
	Max	0.0	0.0	0.0	0.0	0.0	197.0	8.2	204.5	143.2	0.0	0.0	0.0	0.0	0.0
East Mediterranean	Mode 1	0.0	0.0	0.0	0.0	0.0	277.1	11.5	168.4	117.9	0.0	0.0	0.0	0.0	0.0
	Mode 2	20.9	16.0	0.0	4.9	7.5	580.0	24.2	140.3	98.2	0.0	0.0	0.0	0.0	0.0
	Min	0.0	0.0	0.0	0.0	0.0	580.0	24.2	0.0	0.0	340.4	6.9	347.3	0.0	0.0
West-East Mediterranean	Max	0.0	0.0	0.0	0.0	0.0	230.6	9.6	184.2	129.0	0.0	0.0	0.0	0.0	0.0
	Mode 1	149.1	114.0	0.0	35.1	7.5	580.0	24.2	0.3	0.2	34.1	0.7	34.8	0.0	0.0
	Mode 2	153.0	117.0	0.0	36.0	7.5	580.0	24.2	1.3	0.9	44.9	0.9	45.8	0.0	0.0
West Mediterranean	Min	0.0	0.0	0.0	0.0	0.0	580.0	24.2	0.0	0.0	350.0	7.1	357.1	94.7	80.1
	Max	0.0	0.0	0.0	0.0	0.0	225.0	9.4	184.2	129.0	0.0	0.0	0.0	0.0	0.0
	Mode 1	149.1	114.0	0.0	35.1	7.5	580.0	24.2	0.3	0.2	71.4	1.5	72.9	0.0	0.0
Hong Kong	Mode 2	153.0	117.0	0.0	36.0	7.5	580.0	24.2	1.3	0.9	70.9	1.4	72.4	0.0	0.0
	Min	0.0	0.0	0.0	0.0	0.0	580.0	24.2	0.0	0.0	350.0	7.1	357.1	67.5	112.4
	Max	0.0	0.0	0.0	0.0	0.0	258.5	10.8	190.6	133.4	0.0	0.0	0.0	0.0	0.0
Middle East	Mode 1	149.1	114.0	0.0	35.1	7.5	580.0	24.2	0.3	0.2	80.7	1.6	82.4	0.0	0.0
	Mode 2	0.0	0.0	0.0	0.0	0.0	580.0	24.2	0.0	0.0	340.2	6.9	347.1	0.0	0.0
	Min	0.0	0.0	0.0	0.0	0.0	580.0	24.2	0.0	0.0	349.6	7.1	356.7	0.0	0.0
	Max	0.0	0.0	0.0	0.0	0.0	230.6	9.6	197.5	138.3	0.0	0.0	0.0	0.0	0.0
	Mode 1	0.0	0.0	0.0	0.0	0.0	549.0	22.9	163.2	114.2	0.0	0.0	0.0	0.0	0.0
	Mode 2	0.0	0.0	0.0	0.0	0.0	552.5	23.0	178.6	125.0	0.0	0.0	0.0	0.0	0.0
	Min	0.0	0.0	0.0	0.0	0.0	580.0	24.2	0.0	0.0	350.0	7.1	357.1	14.3	532.3
	Max	0.0	0.0	0.0	0.0	0.0	152.3	6.3	190.6	133.4	0.0	0.0	0.0	0.0	0.0
	Mode 1	0.0	0.0	0.0	0.0	0.0	298.7	12.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Mode 2	0.0	0.0	0.0	0.0	0.0	191.4	8.0	155.8	109.1	0.0	0.0	0.0	0.0	0.0

^a Min = lowest observed combination of air and seawater temperatures; Max = highest observed combination; Mode 1 = most frequent combination; Mode 2 = second most frequent combination.

Table I.5: Heat generation results for the sailing operational profile under medium occupancy^a.

Climate Zone	Parameter	Electrical Chiller / Heat Pump					Heat Exchanger		Absorption Chiller		Electrical Heater			Heat Tank	
		Q_H [kW]	Q_C [kW]	Q_L [kW]	P_E [kW]	COP [-]	Q [kW]	Q_L [kW]	Q_H [kW]	Q_C [kW]	Q [kW]	Q_L [kW]	P_E [kW]	Q [kW]	t [min]
Atlantic Crossing	Min	0.0	0.0	0.0	0.0	0.0	580.0	24.2	0.0	0.0	111.3	2.3	113.5	0.0	0.0
	Max	0.0	0.0	0.0	0.0	0.0	173.0	7.2	170.0	119.0	0.0	0.0	0.0	0.0	0.0
	Mode 1	0.0	0.0	0.0	0.0	0.0	252.9	10.5	184.4	129.1	0.0	0.0	0.0	0.0	0.0
Caribbean	Mode 2	0.0	0.0	0.0	0.0	0.0	246.3	10.3	161.6	113.1	0.0	0.0	0.0	0.0	0.0
	Min	0.0	0.0	0.0	0.0	0.0	443.6	18.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Max	0.0	0.0	0.0	0.0	0.0	137.6	5.7	207.2	145.0	0.0	0.0	0.0	0.0	0.0
East Mediterranean	Mode 1	0.0	0.0	0.0	0.0	0.0	193.9	8.1	184.4	129.1	0.0	0.0	0.0	0.0	0.0
	Mode 2	0.0	0.0	0.0	0.0	0.0	233.2	9.7	161.6	113.1	0.0	0.0	0.0	0.0	0.0
	Min	0.0	0.0	0.0	0.0	0.0	492.5	20.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
West-East Mediterranean	Max	0.0	0.0	0.0	0.0	0.0	161.2	6.7	180.5	126.4	0.0	0.0	0.0	0.0	0.0
	Mode 1	0.0	0.0	0.0	0.0	0.0	351.1	14.6	157.1	110.0	0.0	0.0	0.0	0.0	0.0
	Mode 2	0.0	0.0	0.0	0.0	0.0	357.6	14.9	172.3	120.6	0.0	0.0	0.0	0.0	0.0
West Mediterranean	Min	0.0	0.0	0.0	0.0	0.0	565.8	23.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Max	0.0	0.0	0.0	0.0	0.0	157.3	6.6	180.5	126.4	0.0	0.0	0.0	0.0	0.0
	Mode 1	0.0	0.0	0.0	0.0	0.0	377.3	15.7	161.6	113.1	0.0	0.0	0.0	0.0	0.0
Hong Kong	Mode 2	0.0	0.0	0.0	0.0	0.0	376.0	15.7	172.3	120.6	0.0	0.0	0.0	0.0	0.0
	Min	0.0	0.0	0.0	0.0	0.0	545.6	22.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Max	0.0	0.0	0.0	0.0	0.0	180.8	7.5	170.0	119.0	0.0	0.0	0.0	0.0	0.0
Middle East	Mode 1	0.0	0.0	0.0	0.0	0.0	383.8	16.0	161.6	113.1	0.0	0.0	0.0	0.0	0.0
	Mode 2	0.0	0.0	0.0	0.0	0.0	390.4	16.3	172.3	120.6	0.0	0.0	0.0	0.0	0.0
	Min	0.0	0.0	0.0	0.0	0.0	502.5	20.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Max	0.0	0.0	0.0	0.0	0.0	161.2	6.7	207.2	145.0	0.0	0.0	0.0	0.0	0.0
	Mode 1	0.0	0.0	0.0	0.0	0.0	200.5	8.4	198.9	139.2	0.0	0.0	0.0	0.0	0.0
	Mode 2	0.0	0.0	0.0	0.0	0.0	199.2	8.3	157.1	110.0	0.0	0.0	0.0	0.0	0.0
	Min	0.0	0.0	0.0	0.0	0.0	511.9	21.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Max	0.0	0.0	0.0	0.0	0.0	106.2	4.4	191.3	133.9	0.0	0.0	0.0	0.0	0.0
	Mode 1	0.0	0.0	0.0	0.0	0.0	135.0	5.6	172.3	120.6	0.0	0.0	0.0	0.0	0.0
	Mode 2	0.0	0.0	0.0	0.0	0.0	133.7	5.6	161.6	113.1	0.0	0.0	0.0	0.0	0.0

^a Min = lowest observed combination of air and seawater temperatures; Max = highest observed combination; Mode 1 = most frequent combination; Mode 2 = second most frequent combination.

Table I.6: Heat generation results for the harbour operational profile under medium occupancy^a.

Climate Zone	Parameter	Electrical Chiller / Heat Pump					Heat Exchanger		Absorption Chiller		Electrical Heater			Heat Tank	
		Q_H [kW]	Q_C [kW]	Q_L [kW]	P_E [kW]	COP [-]	Q [kW]	Q_L [kW]	Q_H [kW]	Q_C [kW]	Q [kW]	Q_L [kW]	P_E [kW]	Q [kW]	t [min]
Atlantic Crossing	Min	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	350.0	7.1	357.1	11.4	667.5
	Max	75.8	110.9	0.0	34.1	5.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Mode 1	116.3	96.4	0.0	29.7	7.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Caribbean	Mode 2	112.1	85.7	0.0	26.4	7.5	0.0	0.0	0.0	0.0	0.9	0.0	0.9	0.0	0.0
	Min	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	237.0	4.8	241.9	0.0	0.0
	Max	57.9	110.9	0.0	34.1	4.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
East Mediterranean	Mode 1	86.4	90.7	0.0	27.9	6.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Mode 2	106.3	85.7	0.0	26.4	7.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Min	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	259.2	5.3	264.5	0.0	0.0
West-East Mediterranean	Max	69.8	107.0	0.0	32.9	5.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Mode 1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	241.0	4.9	245.9	0.0	0.0
	Mode 2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	237.8	4.9	242.7	0.0	0.0
West Mediterranean	Min	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	296.4	6.0	302.5	0.0	0.0
	Max	67.8	107.0	0.0	32.9	5.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Mode 1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	254.2	5.2	259.4	0.0	0.0
Hong Kong	Mode 2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	247.1	5.0	252.1	0.0	0.0
	Min	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	286.3	5.8	292.2	0.0	0.0
	Max	79.8	107.0	0.0	32.9	5.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Middle East	Mode 1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	251.1	5.1	256.2	0.0	0.0
	Mode 2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	259.8	5.3	265.1	0.0	0.0
	Min	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	264.0	5.4	269.4	0.0	0.0
	Max	69.8	107.0	0.0	32.9	5.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Mode 1	89.7	103.1	0.0	31.7	6.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Mode 2	89.1	83.6	0.0	25.7	6.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Min	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	271.3	5.5	276.9	0.0	0.0
	Max	41.9	94.6	0.0	29.1	4.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Mode 1	56.5	85.7	0.0	26.4	5.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Mode 2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	136.6	2.8	139.4	0.0	0.0

^a Min = lowest observed combination of air and seawater temperatures; Max = highest observed combination; Mode 1 = most frequent combination; Mode 2 = second most frequent combination.

Table I.7: Heat generation results for the anchor operational profile under high occupancy^a.

Climate Zone	Parameter	Electrical Chiller / Heat Pump					Heat Exchanger		Absorption Chiller		Electrical Heater			Heat Tank	
		Q_H [kW]	Q_C [kW]	Q_L [kW]	P_E [kW]	COP [-]	Q [kW]	Q_L [kW]	Q_H [kW]	Q_C [kW]	Q [kW]	Q_L [kW]	P_E [kW]	Q [kW]	t [min]
Atlantic Crossing	Min	0.0	0.0	0.0	0.0	0.0	580.0	24.2	0.0	0.0	350.0	7.1	357.1	543.0	14.0
	Max	0.0	0.0	0.0	0.0	0.0	261.5	10.9	250.6	175.4	0.0	0.0	0.0	0.0	0.0
	Mode 1	97.3	75.0	0.0	23.1	7.5	580.0	24.2	126.1	88.3	0.0	0.0	0.0	0.0	0.0
Caribbean	Mode 2	90.0	69.0	0.0	21.2	7.5	580.0	24.2	142.2	99.5	0.0	0.0	0.0	0.0	0.0
	Min	0.0	0.0	0.0	0.0	0.0	580.0	24.2	0.0	0.0	350.0	7.1	357.1	56.1	135.3
	Max	0.0	0.0	0.0	0.0	0.0	193.7	8.1	292.3	204.6	0.0	0.0	0.0	0.0	0.0
East Mediterranean	Mode 1	0.0	0.0	0.0	0.0	0.0	301.7	12.6	240.7	168.5	0.0	0.0	0.0	0.0	0.0
	Mode 2	64.9	50.0	0.0	15.4	7.5	580.0	24.2	161.8	113.3	0.0	0.0	0.0	0.0	0.0
	Min	0.0	0.0	0.0	0.0	0.0	580.0	24.2	0.0	0.0	350.0	7.1	357.1	158.7	47.8
West-East Mediterranean	Max	0.0	0.0	0.0	0.0	0.0	238.9	10.0	263.3	184.3	0.0	0.0	0.0	0.0	0.0
	Mode 1	213.2	163.0	0.0	50.2	7.5	580.0	24.2	0.4	0.3	72.5	1.5	73.9	0.0	0.0
	Mode 2	219.7	168.0	0.0	51.7	7.5	580.0	24.2	0.7	0.5	83.8	1.7	85.5	0.0	0.0
West Mediterranean	Min	0.0	0.0	0.0	0.0	0.0	580.0	24.2	0.0	0.0	350.0	7.1	357.1	299.4	25.3
	Max	0.0	0.0	0.0	0.0	0.0	231.3	9.6	263.3	184.3	0.0	0.0	0.0	0.0	0.0
	Mode 1	213.2	163.0	0.0	50.2	7.5	580.0	24.2	0.4	0.3	122.7	2.5	125.2	0.0	0.0
Hong Kong	Mode 2	219.7	168.0	0.0	51.7	7.5	580.0	24.2	0.7	0.5	119.0	2.4	121.4	0.0	0.0
	Min	0.0	0.0	0.0	0.0	0.0	580.0	24.2	0.0	0.0	350.0	7.1	357.1	263.0	28.9
	Max	0.0	0.0	0.0	0.0	0.0	276.5	11.5	272.4	190.7	0.0	0.0	0.0	0.0	0.0
Middle East	Mode 1	213.2	163.0	0.0	50.2	7.5	580.0	24.2	0.4	0.3	135.2	2.8	138.0	0.0	0.0
	Mode 2	0.0	0.0	0.0	0.0	0.0	580.0	24.2	0.0	0.0	350.0	7.1	357.1	157.3	48.2
	Min	0.0	0.0	0.0	0.0	0.0	580.0	24.2	0.0	0.0	350.0	7.1	357.1	171.6	44.2
	Max	0.0	0.0	0.0	0.0	0.0	238.9	10.0	282.3	197.6	0.0	0.0	0.0	0.0	0.0
	Mode 1	0.0	0.0	0.0	0.0	0.0	576.8	24.0	233.2	163.3	0.0	0.0	0.0	0.0	0.0
	Mode 2	0.0	0.0	0.0	0.0	0.0	579.6	24.2	255.2	178.6	0.0	0.0	0.0	0.0	0.0
	Min	0.0	0.0	0.0	0.0	0.0	580.0	24.2	0.0	0.0	350.0	7.1	357.1	188.8	40.2
	Max	0.0	0.0	0.0	0.0	0.0	133.4	5.6	272.4	190.7	0.0	0.0	0.0	0.0	0.0
	Mode 1	0.0	0.0	0.0	0.0	0.0	339.3	14.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Mode 2	0.0	0.0	0.0	0.0	0.0	186.1	7.8	222.7	155.9	0.0	0.0	0.0	0.0	0.0

^a Min = lowest observed combination of air and seawater temperatures; Max = highest observed combination; Mode 1 = most frequent combination; Mode 2 = second most frequent combination.

Table I.8: Heat generation results for the sailing operational profile under high occupancy^a.

Climate Zone	Parameter	Electrical Chiller / Heat Pump					Heat Exchanger		Absorption Chiller		Electrical Heater			Heat Tank	
		Q_H [kW]	Q_C [kW]	Q_L [kW]	P_E [kW]	COP [-]	Q [kW]	Q_L [kW]	Q_H [kW]	Q_C [kW]	Q [kW]	Q_L [kW]	P_E [kW]	Q [kW]	t [min]
Atlantic Crossing	Min	0.0	0.0	0.0	0.0	0.0	580.0	24.2	0.0	0.0	350.0	7.1	357.1	103.1	73.6
	Max	0.0	0.0	0.0	0.0	0.0	232.3	9.7	239.8	167.8	0.0	0.0	0.0	0.0	0.0
	Mode 1	0.0	0.0	0.0	0.0	0.0	356.4	14.8	257.7	180.4	0.0	0.0	0.0	0.0	0.0
Caribbean	Mode 2	0.0	0.0	0.0	0.0	0.0	346.2	14.4	229.3	160.5	0.0	0.0	0.0	0.0	0.0
	Min	0.0	0.0	0.0	0.0	0.0	580.0	24.2	0.0	0.0	66.0	1.3	67.4	0.0	0.0
	Max	0.0	0.0	0.0	0.0	0.0	177.4	7.4	285.8	200.1	0.0	0.0	0.0	0.0	0.0
East Mediterranean	Mode 1	0.0	0.0	0.0	0.0	0.0	264.8	11.0	257.7	180.4	0.0	0.0	0.0	0.0	0.0
	Mode 2	0.0	0.0	0.0	0.0	0.0	325.9	13.6	229.3	160.5	0.0	0.0	0.0	0.0	0.0
	Min	0.0	0.0	0.0	0.0	0.0	580.0	24.2	0.0	0.0	143.8	2.9	146.8	0.0	0.0
West-East Mediterranean	Max	0.0	0.0	0.0	0.0	0.0	214.0	8.9	252.8	177.0	0.0	0.0	0.0	0.0	0.0
	Mode 1	0.0	0.0	0.0	0.0	0.0	508.9	21.2	223.9	156.7	0.0	0.0	0.0	0.0	0.0
	Mode 2	0.0	0.0	0.0	0.0	0.0	519.1	21.6	242.6	169.8	0.0	0.0	0.0	0.0	0.0
West Mediterranean	Min	0.0	0.0	0.0	0.0	0.0	580.0	24.2	0.0	0.0	257.7	5.3	263.0	0.0	0.0
	Max	0.0	0.0	0.0	0.0	0.0	207.9	8.7	252.8	177.0	0.0	0.0	0.0	0.0	0.0
	Mode 1	0.0	0.0	0.0	0.0	0.0	549.6	22.9	229.3	160.5	0.0	0.0	0.0	0.0	0.0
Hong Kong	Mode 2	0.0	0.0	0.0	0.0	0.0	547.5	22.8	242.6	169.8	0.0	0.0	0.0	0.0	0.0
	Min	0.0	0.0	0.0	0.0	0.0	580.0	24.2	0.0	0.0	226.2	4.6	230.8	0.0	0.0
	Max	0.0	0.0	0.0	0.0	0.0	244.5	10.2	239.8	167.8	0.0	0.0	0.0	0.0	0.0
Middle East	Mode 1	0.0	0.0	0.0	0.0	0.0	559.8	23.3	229.3	160.5	0.0	0.0	0.0	0.0	0.0
	Mode 2	0.0	0.0	0.0	0.0	0.0	569.9	23.7	242.6	169.8	0.0	0.0	0.0	0.0	0.0
	Min	0.0	0.0	0.0	0.0	0.0	580.0	24.2	0.0	0.0	157.1	3.2	160.3	0.0	0.0
	Max	0.0	0.0	0.0	0.0	0.0	214.0	8.9	285.8	200.1	0.0	0.0	0.0	0.0	0.0
	Mode 1	0.0	0.0	0.0	0.0	0.0	275.0	11.5	275.5	192.9	0.0	0.0	0.0	0.0	0.0
	Mode 2	0.0	0.0	0.0	0.0	0.0	273.0	11.4	223.9	156.7	0.0	0.0	0.0	0.0	0.0
	Min	0.0	0.0	0.0	0.0	0.0	580.0	24.2	0.0	0.0	168.8	3.4	172.2	0.0	0.0
	Max	0.0	0.0	0.0	0.0	0.0	128.6	5.4	266.1	186.3	0.0	0.0	0.0	0.0	0.0
	Mode 1	0.0	0.0	0.0	0.0	0.0	173.3	7.2	242.6	169.8	0.0	0.0	0.0	0.0	0.0
	Mode 2	0.0	0.0	0.0	0.0	0.0	171.3	7.1	229.3	160.5	0.0	0.0	0.0	0.0	0.0

^a Min = lowest observed combination of air and seawater temperatures; Max = highest observed combination; Mode 1 = most frequent combination; Mode 2 = second most frequent combination.

Table I.9: Heat generation results for the harbour operational profile under high occupancy^a.

Climate Zone	Parameter	Electrical Chiller / Heat Pump					Heat Exchanger		Absorption Chiller		Electrical Heater			Heat Tank	
		Q_H [kW]	Q_C [kW]	Q_L [kW]	P_E [kW]	COP [-]	Q [kW]	Q_L [kW]	Q_H [kW]	Q_C [kW]	Q [kW]	Q_L [kW]	P_E [kW]	Q [kW]	t [min]
Atlantic Crossing	Min	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	350.0	7.1	357.1	214.1	35.4
	Max	125.9	144.2	0.0	44.4	6.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Mode 1	164.1	125.5	0.0	38.6	7.5	0.0	0.0	0.0	0.0	26.5	0.5	27.1	0.0	0.0
Caribbean	Mode 2	146.1	111.7	0.0	34.4	7.5	0.0	0.0	0.0	0.0	39.2	0.8	40.0	0.0	0.0
	Min	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	350.0	7.1	357.1	14.0	543.3
	Max	97.3	144.2	0.0	44.4	5.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
East Mediterranean	Mode 1	142.9	118.2	0.0	36.4	7.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Mode 2	146.1	111.7	0.0	34.4	7.5	0.0	0.0	0.0	0.0	28.6	0.6	29.2	0.0	0.0
	Min	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	350.0	7.1	357.1	51.2	148.2
West-East Mediterranean	Max	116.4	139.1	0.0	42.8	6.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Mode 1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	350.0	7.1	357.1	17.9	422.7
	Mode 2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	350.0	7.1	357.1	14.9	508.0
West Mediterranean	Min	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	350.0	7.1	357.1	110.6	68.6
	Max	113.2	139.1	0.0	42.8	5.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Mode 1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	350.0	7.1	357.1	39.2	193.7
Hong Kong	Mode 2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	350.0	7.1	357.1	29.8	254.7
	Min	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	350.0	7.1	357.1	94.3	80.5
	Max	132.3	139.1	0.0	42.8	6.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Middle East	Mode 1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	350.0	7.1	357.1	36.1	209.9
	Mode 2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	350.0	7.1	357.1	48.4	156.8
	Min	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	350.0	7.1	357.1	57.7	131.4
	Max	116.4	139.1	0.0	42.8	6.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Mode 1	148.2	134.1	0.0	41.3	6.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Mode 2	142.7	109.1	0.0	33.6	7.5	0.0	0.0	0.0	0.0	4.5	0.1	4.6	0.0	0.0
	Min	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	350.0	7.1	357.1	67.2	113.0
	Max	71.8	123.1	0.0	37.9	5.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Mode 1	95.2	111.7	0.0	34.4	6.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Mode 2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	199.4	4.1	203.5	0.0	0.0

^a Min = lowest observed combination of air and seawater temperatures; Max = highest observed combination; Mode 1 = most frequent combination; Mode 2 = second most frequent combination.

J. Heat Generated Plots for Design 2

Heat Generated by System and Unmet Heat at Minimum Temperatures

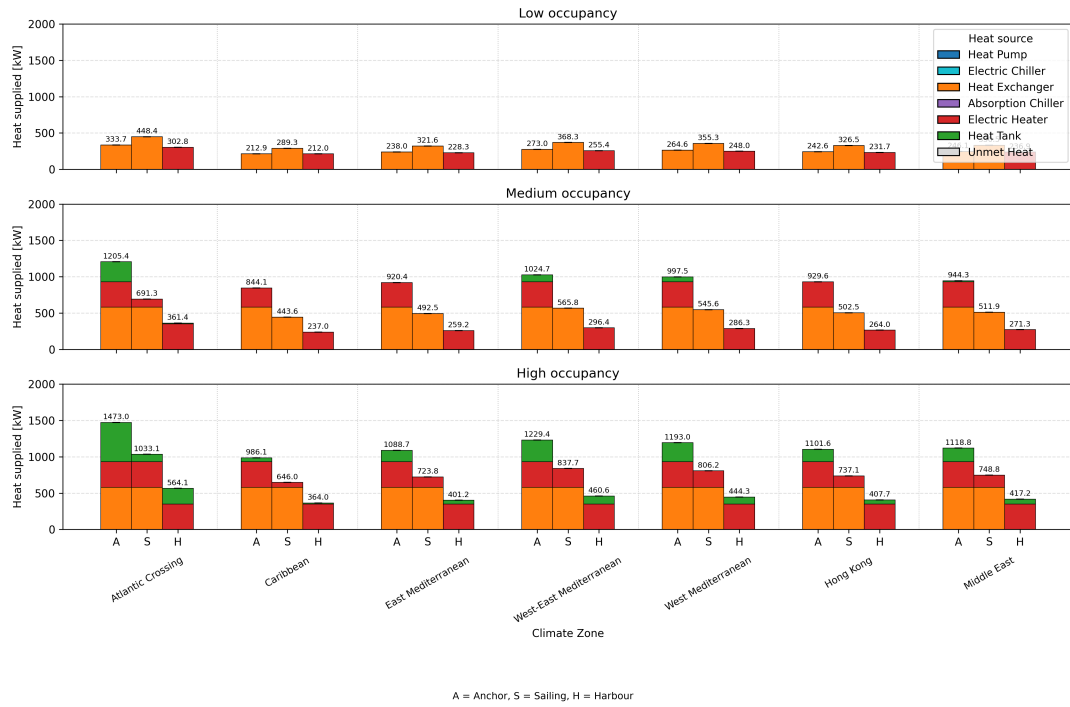


Figure J.1: Heat generated at minimum temperatures.

Heat Generated by System and Unmet Heat at Maximum Temperatures

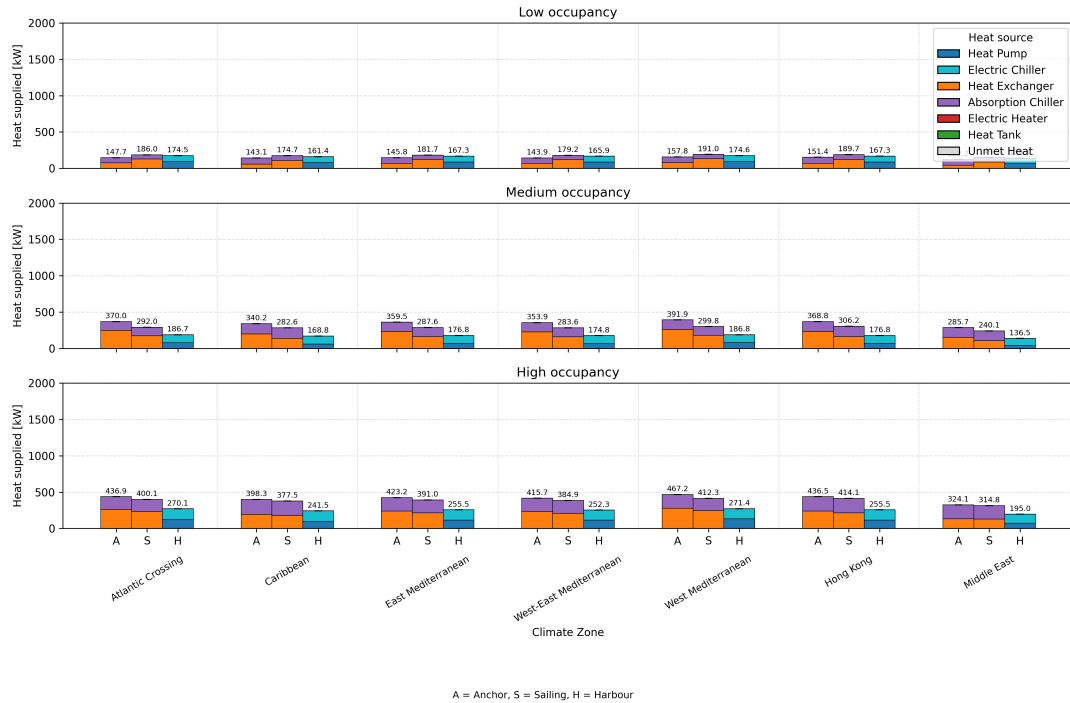


Figure J.2: Heat generated at maximum temperatures.

J. Heat Generated Plots for Design 2 (continued)

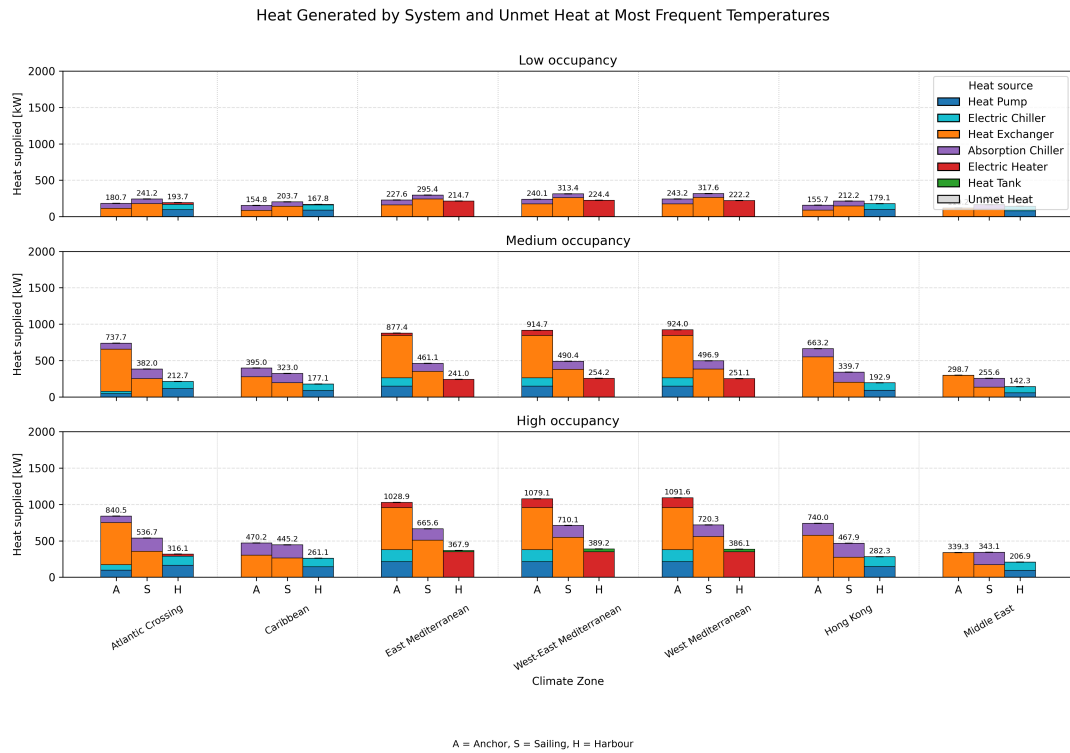


Figure J.3: Heat generated at most frequent temperatures.
Heat Generated by System and Unmet Heat at Second Most Frequent Temperatures

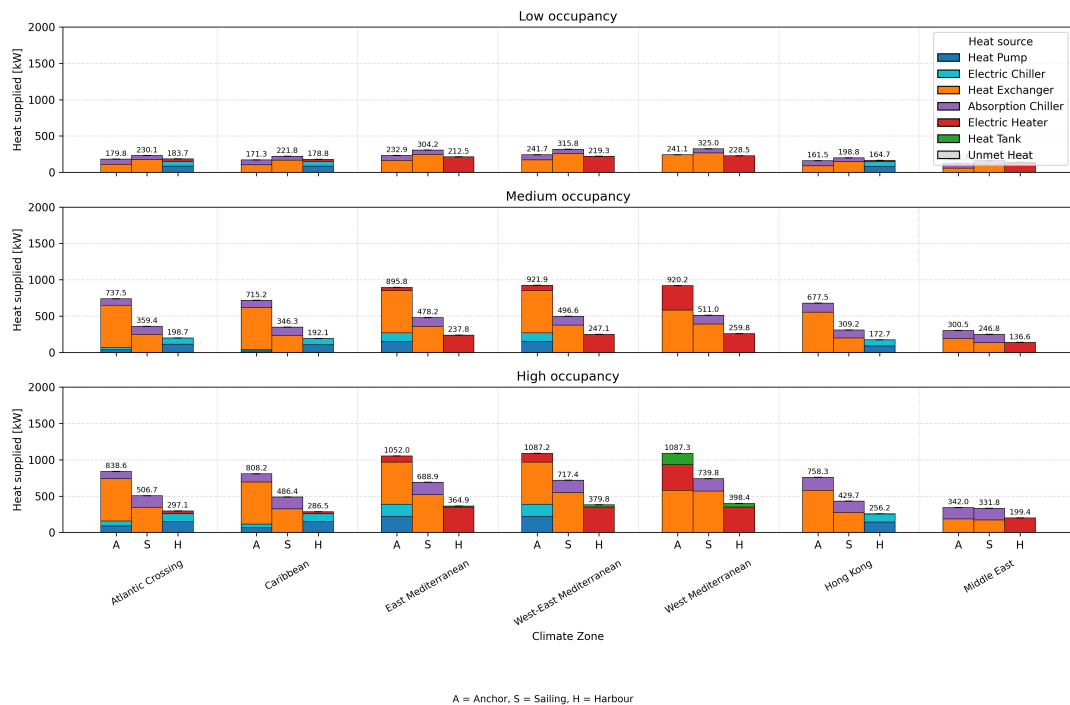


Figure J.4: Heat generated at second most frequent temperatures.

K. KPI Results for Design 2

Table K.1: KPI results for the anchor operational profile under low-occupancy scenarios^a.

Climate Zone	Parameter	KPI I	KPI II	KPI III				KPI IV KPI V KPI VI KPI VII					
		[-]	[hh:mm:ss / -]	E. Chiller / HP C	E. Chiller / HP H	Heat Exch.	Abs. Chiller	E. Heater	Heat Tank	[-]	[-]	[-]	[-]
				[-]	[-]	[-]	[-]	[-]	[-]				
Atlantic Crossing	Min	1.000	Unlimited	0.000	0.000	0.596	0.000	0.000	0.000	0.468	0.021	13.849	321.613
	Max	1.000	Unlimited	0.000	0.000	0.134	0.159	0.000	0.000	0.426	0.021	13.849	321.613
	Mode 1	1.000	Unlimited	0.000	0.000	0.202	0.148	0.000	0.000	0.433	0.021	13.849	321.613
Caribbean	Mode 2	1.000	Unlimited	0.000	0.000	0.197	0.152	0.000	0.000	0.433	0.021	13.849	321.613
	Min	1.000	Unlimited	0.000	0.000	0.380	0.000	0.000	0.000	0.440	0.021	13.849	321.613
	Max	1.000	Unlimited	0.000	0.000	0.104	0.186	0.000	0.000	0.425	0.021	13.849	321.613
East Mediterranean	Mode 1	1.000	Unlimited	0.000	0.000	0.152	0.152	0.000	0.000	0.427	0.021	13.849	321.613
	Mode 2	1.000	Unlimited	0.000	0.000	0.186	0.148	0.000	0.000	0.431	0.021	13.849	321.613
	Min	1.000	Unlimited	0.000	0.000	0.425	0.000	0.000	0.000	0.446	0.021	13.849	321.613
West-East Mediterranean	Max	1.000	Unlimited	0.000	0.000	0.124	0.167	0.000	0.000	0.425	0.021	13.849	321.613
	Mode 1	1.000	Unlimited	0.000	0.000	0.286	0.148	0.000	0.000	0.444	0.021	13.849	321.613
	Mode 2	1.000	Unlimited	0.000	0.000	0.292	0.152	0.000	0.000	0.445	0.021	13.849	321.613
West Mediterranean	Min	1.000	Unlimited	0.000	0.000	0.488	0.000	0.000	0.000	0.454	0.021	13.849	321.613
	Max	1.000	Unlimited	0.000	0.000	0.121	0.167	0.000	0.000	0.425	0.021	13.849	321.613
	Mode 1	1.000	Unlimited	0.000	0.000	0.308	0.148	0.000	0.000	0.447	0.021	13.849	321.613
Hong Kong	Mode 2	1.000	Unlimited	0.000	0.000	0.307	0.152	0.000	0.000	0.447	0.021	13.849	321.613
	Min	1.000	Unlimited	0.000	0.000	0.473	0.000	0.000	0.000	0.452	0.021	13.849	321.613
	Max	1.000	Unlimited	0.000	0.000	0.141	0.173	0.000	0.000	0.428	0.021	13.849	321.613
Middle East	Mode 1	1.000	Unlimited	0.000	0.000	0.314	0.148	0.000	0.000	0.447	0.021	13.849	321.613
	Mode 2	1.000	Unlimited	0.000	0.000	0.430	0.000	0.000	0.000	0.447	0.021	13.849	321.613
	Min	1.000	Unlimited	0.000	0.000	0.433	0.000	0.000	0.000	0.447	0.021	13.849	321.613
	Max	1.000	Unlimited	0.000	0.000	0.124	0.179	0.000	0.000	0.427	0.021	13.849	321.613
	Mode 1	1.000	Unlimited	0.000	0.000	0.158	0.148	0.000	0.000	0.428	0.021	13.849	321.613
	Mode 2	1.000	Unlimited	0.000	0.000	0.157	0.162	0.000	0.000	0.429	0.021	13.849	321.613
	Min	1.000	Unlimited	0.000	0.000	0.440	0.000	0.000	0.000	0.448	0.021	13.849	321.613
	Max	1.000	Unlimited	0.000	0.000	0.077	0.173	0.000	0.000	0.420	0.021	13.849	321.613
	Mode 1	1.000	Unlimited	0.000	0.000	0.213	0.000	0.000	0.000	0.419	0.021	13.849	321.613
	Mode 2	1.000	Unlimited	0.000	0.000	0.101	0.141	0.000	0.000	0.420	0.021	13.849	321.613

^a Min = lowest observed combination of air and seawater temperatures; Max = highest observed combination; Mode 1 = most frequent combination; Mode 2 = second most frequent combination.

Table K.2: KPI results for the sailing operational profile under low-occupancy scenarios^a.

Climate Zone	Parameter	KPI I	KPI II	KPI III						KPI IV	KPI V	KPI VI	KPI VII			
		[-]	[hh:mm:ss / -]	E. Chiller / HP C		E. Chiller / HP H		Heat Exch.	Abs.	Chiller E. Heater		Heat Tank	[-]	[-]	[-]	[-]
				[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]					
Atlantic Crossing	Min	1.000	Unlimited	0.000	0.000	0.801	0.000	0.000	0.000	0.449	0.021	13.849	321.613			
	Max	1.000	Unlimited	0.000	0.000	0.229	0.000	0.000	0.000	0.421	0.021	13.849	321.613			
	Mode 1	1.000	Unlimited	0.000	0.000	0.320	0.136	0.000	0.000	0.427	0.021	13.849	321.613			
Caribbean	Mode 2	1.000	Unlimited	0.000	0.000	0.312	0.121	0.000	0.000	0.426	0.021	13.849	321.613			
	Min	1.000	Unlimited	0.000	0.000	0.517	0.000	0.000	0.000	0.432	0.021	13.849	321.613			
	Max	1.000	Unlimited	0.000	0.000	0.189	0.151	0.000	0.000	0.420	0.021	13.849	321.613			
East Mediterranean	Mode 1	1.000	Unlimited	0.000	0.000	0.253	0.136	0.000	0.000	0.423	0.021	13.849	321.613			
	Mode 2	1.000	Unlimited	0.000	0.000	0.297	0.121	0.000	0.000	0.425	0.021	13.849	321.613			
	Min	1.000	Unlimited	0.000	0.000	0.574	0.000	0.000	0.000	0.436	0.021	13.849	321.613			
West-East Mediterranean	Max	1.000	Unlimited	0.000	0.000	0.216	0.133	0.000	0.000	0.421	0.021	13.849	321.613			
	Mode 1	1.000	Unlimited	0.000	0.000	0.431	0.118	0.000	0.000	0.433	0.021	13.849	321.613			
	Mode 2	1.000	Unlimited	0.000	0.000	0.439	0.128	0.000	0.000	0.434	0.021	13.849	321.613			
West Mediterranean	Min	1.000	Unlimited	0.000	0.000	0.658	0.000	0.000	0.000	0.440	0.021	13.849	321.613			
	Max	1.000	Unlimited	0.000	0.000	0.211	0.133	0.000	0.000	0.421	0.021	13.849	321.613			
	Mode 1	1.000	Unlimited	0.000	0.000	0.461	0.121	0.000	0.000	0.435	0.021	13.849	321.613			
Hong Kong	Mode 2	1.000	Unlimited	0.000	0.000	0.460	0.128	0.000	0.000	0.435	0.021	13.849	321.613			
	Min	1.000	Unlimited	0.000	0.000	0.634	0.000	0.000	0.000	0.439	0.021	13.849	321.613			
	Max	1.000	Unlimited	0.000	0.000	0.238	0.126	0.000	0.000	0.422	0.021	13.849	321.613			
Middle East	Mode 1	1.000	Unlimited	0.000	0.000	0.469	0.121	0.000	0.000	0.435	0.021	13.849	321.613			
	Mode 2	1.000	Unlimited	0.000	0.000	0.476	0.128	0.000	0.000	0.436	0.021	13.849	321.613			
	Min	1.000	Unlimited	0.000	0.000	0.583	0.000	0.000	0.000	0.436	0.021	13.849	321.613			
	Max	1.000	Unlimited	0.000	0.000	0.216	0.151	0.000	0.000	0.422	0.021	13.849	321.613			
	Mode 1	1.000	Unlimited	0.000	0.000	0.260	0.145	0.000	0.000	0.424	0.021	13.849	321.613			
	Mode 2	1.000	Unlimited	0.000	0.000	0.259	0.118	0.000	0.000	0.423	0.021	13.849	321.613			
	Min	1.000	Unlimited	0.000	0.000	0.590	0.000	0.000	0.000	0.436	0.021	13.849	321.613			
	Max	1.000	Unlimited	0.000	0.000	0.153	0.140	0.000	0.000	0.418	0.021	13.849	321.613			
	Mode 1	1.000	Unlimited	0.000	0.000	0.186	0.128	0.000	0.000	0.419	0.021	13.849	321.613			
	Mode 2	1.000	Unlimited	0.000	0.000	0.184	0.121	0.000	0.000	0.419	0.021	13.849	321.613			

^a Min = lowest observed combination of air and seawater temperatures; Max = highest observed combination; Mode 1 = most frequent combination; Mode 2 = second most frequent combination.

Table K.3: KPI results for the harbour operational profile under low-occupancy scenarios^a.

Climate Zone	Parameter	KPI I		KPI II		KPI III								KPI IV KPI V KPI VI KPI VII			
		[-]	[hh:mm:ss / -]	[-]	[-]	E. Chiller / HP C		E. Chiller / HP H		Heat Exch.	Abs. Chiller	E. Heater	Heat Tank	[-]	[-]	[-]	[-]
						[-]	[-]	[-]	[-]								
Atlantic Crossing	Min	1.000	Unlimited	0.000	0.000	0.000	0.000	0.000	0.000	0.865	0.000	0.000	0.000	0.980	0.021	13.849	321.613
	Max	1.000	Unlimited	0.167	0.260	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	6.800	0.021	13.849	321.613
	Mode 1	1.000	Unlimited	0.146	0.273	0.000	0.000	0.000	0.000	0.072	0.000	0.000	0.000	4.020	0.021	13.849	321.613
Caribbean	Mode 2	1.000	Unlimited	0.131	0.244	0.000	0.000	0.000	0.000	0.094	0.000	0.000	0.000	3.430	0.021	13.849	321.613
	Min	1.000	Unlimited	0.000	0.000	0.000	0.000	0.000	0.000	0.606	0.000	0.000	0.000	0.980	0.021	13.849	321.613
	Max	1.000	Unlimited	0.167	0.223	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	6.290	0.021	13.849	321.613
East Mediterranean	Mode 1	1.000	Unlimited	0.138	0.258	0.000	0.000	0.000	0.000	0.025	0.000	0.000	0.000	5.583	0.021	13.849	321.613
	Mode 2	1.000	Unlimited	0.131	0.244	0.000	0.000	0.000	0.000	0.080	0.000	0.000	0.000	3.680	0.021	13.849	321.613
	Min	1.000	Unlimited	0.000	0.000	0.000	0.000	0.000	0.000	0.652	0.000	0.000	0.000	0.980	0.021	13.849	321.613
West-East Mediterranean	Max	1.000	Unlimited	0.161	0.248	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	6.747	0.021	13.849	321.613
	Mode 1	1.000	Unlimited	0.000	0.000	0.000	0.000	0.000	0.000	0.613	0.000	0.000	0.000	0.980	0.021	13.849	321.613
	Mode 2	1.000	Unlimited	0.000	0.000	0.000	0.000	0.000	0.000	0.709	0.000	0.000	0.000	0.980	0.021	13.849	321.613
West Mediterranean	Min	1.000	Unlimited	0.000	0.000	0.000	0.000	0.000	0.000	0.730	0.000	0.000	0.000	0.980	0.021	13.849	321.613
	Max	1.000	Unlimited	0.161	0.244	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	6.689	0.021	13.849	321.613
	Mode 1	1.000	Unlimited	0.000	0.000	0.000	0.000	0.000	0.000	0.641	0.000	0.000	0.000	0.980	0.021	13.849	321.613
Hong Kong	Mode 2	1.000	Unlimited	0.000	0.000	0.000	0.000	0.000	0.000	0.627	0.000	0.000	0.000	0.980	0.021	13.849	321.613
	Min	1.000	Unlimited	0.000	0.000	0.000	0.000	0.000	0.000	0.709	0.000	0.000	0.000	0.980	0.021	13.849	321.613
	Max	1.000	Unlimited	0.161	0.248	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	6.747	0.021	13.849	321.613
Middle East	Mode 1	1.000	Unlimited	0.156	0.289	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	7.041	0.021	13.849	321.613
	Mode 2	1.000	Unlimited	0.000	0.000	0.000	0.000	0.000	0.000	0.635	0.000	0.000	0.000	0.980	0.021	13.849	321.613
	Min	1.000	Unlimited	0.000	0.000	0.000	0.000	0.000	0.000	0.653	0.000	0.000	0.000	0.980	0.021	13.849	321.613
	Max	1.000	Unlimited	0.000	0.000	0.000	0.000	0.000	0.000	0.662	0.000	0.000	0.000	0.980	0.021	13.849	321.613
	Mode 1	1.000	Unlimited	0.143	0.190	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	6.258	0.021	13.849	321.613
	Mode 2	1.000	Unlimited	0.131	0.220	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	7.079	0.021	13.849	321.613
	Min	1.000	Unlimited	0.000	0.000	0.000	0.000	0.000	0.000	0.395	0.000	0.000	0.000	0.980	0.021	13.849	321.613

^a Min = lowest observed combination of air and seawater temperatures; Max = highest observed combination; Mode 1 = most frequent combination; Mode 2 = second most frequent combination.

Table K.4: KPI results for the anchor operational profile under medium-occupancy scenarios^a.

Climate Zone	Parameter	KPI I		KPI II		KPI III								KPI IV KPI V KPI VI KPI VII			
		[-]	[hh:mm:ss / -]	[-]	[-]	E. Chiller / HP C		E. Chiller / HP H		Heat Exch.	Abs. Chiller	E. Heater	Heat Tank	[-]	[-]	[-]	[-]
						[-]	[-]	[-]	[-]								
Atlantic Crossing	Min	1.000	00:27:33	0.000	0.000	1.036	0.000	1.000	0.197	0.521	0.021	13.849	321.613	0.521	0.021	13.849	321.613
	Max	1.000	Unlimited	0.000	0.000	0.442	0.269	0.000	0.000	0.476	0.021	13.849	321.613	0.476	0.021	13.849	321.613
	Mode 1	1.000	Unlimited	0.068	0.124	1.036	0.176	0.000	0.000	0.556	0.021	13.849	321.613	0.556	0.021	13.849	321.613
Caribbean	Mode 2	1.000	Unlimited	0.062	0.113	1.036	0.190	0.000	0.000	0.556	0.021	13.849	321.613	0.556	0.021	13.849	321.613
	Min	1.000	Unlimited	0.000	0.000	1.036	0.000	0.755	0.000	0.522	0.021	13.849	321.613	0.522	0.021	13.849	321.613
	Max	1.000	Unlimited	0.000	0.000	0.352	0.313	0.000	0.000	0.469	0.021	13.849	321.613	0.469	0.021	13.849	321.613
East Mediterranean	Mode 1	1.000	Unlimited	0.000	0.000	0.495	0.258	0.000	0.000	0.481	0.021	13.849	321.613	0.481	0.021	13.849	321.613
	Mode 2	1.000	Unlimited	0.032	0.060	1.036	0.215	0.000	0.000	0.552	0.021	13.849	321.613	0.552	0.021	13.849	321.613
	Min	1.000	Unlimited	0.000	0.000	1.036	0.000	0.972	0.000	0.521	0.021	13.849	321.613	0.521	0.021	13.849	321.613
West-East Mediterranean	Max	1.000	Unlimited	0.000	0.000	0.412	0.282	0.000	0.000	0.473	0.021	13.849	321.613	0.473	0.021	13.849	321.613
	Mode 1	1.000	Unlimited	0.228	0.426	1.036	0.001	0.098	0.000	0.574	0.021	13.849	321.613	0.574	0.021	13.849	321.613
	Mode 2	1.000	Unlimited	0.234	0.437	1.036	0.002	0.128	0.000	0.576	0.021	13.849	321.613	0.576	0.021	13.849	321.613
West Mediterranean	Min	1.000	01:29:08	0.000	0.000	1.036	0.000	1.000	0.572	0.521	0.021	13.849	321.613	0.521	0.021	13.849	321.613
	Max	1.000	Unlimited	0.000	0.000	0.402	0.282	0.000	0.000	0.472	0.021	13.849	321.613	0.472	0.021	13.849	321.613
	Mode 1	1.000	Unlimited	0.228	0.426	1.036	0.001	0.204	0.000	0.574	0.021	13.849	321.613	0.574	0.021	13.849	321.613
Hong Kong	Mode 2	1.000	Unlimited	0.234	0.437	1.036	0.002	0.203	0.000	0.575	0.021	13.849	321.613	0.575	0.021	13.849	321.613
	Min	1.000	01:52:22	0.000	0.000	1.036	0.000	1.000	0.803	0.521	0.021	13.849	321.613	0.521	0.021	13.849	321.613
	Max	1.000	Unlimited	0.000	0.000	0.462	0.292	0.000	0.000	0.481	0.021	13.849	321.613	0.481	0.021	13.849	321.613
Middle East	Mode 1	1.000	Unlimited	0.228	0.426	1.036	0.001	0.231	0.000	0.574	0.021	13.849	321.613	0.574	0.021	13.849	321.613
	Mode 2	1.000	Unlimited	0.000	0.000	1.036	0.000	0.972	0.000	0.521	0.021	13.849	321.613	0.521	0.021	13.849	321.613
	Min	1.000	08:52:19	0.000	0.000	1.036	0.000	1.000	3.802	0.521	0.021	13.849	321.613	0.521	0.021	13.849	321.613
	Max	1.000	Unlimited	0.000	0.000	0.272	0.292	0.000	0.000	0.457	0.021	13.849	321.613	0.457	0.021	13.849	321.613
	Mode 1	1.000	Unlimited	0.000	0.000	0.533	0.000	0.000	0.000	0.460	0.021	13.849	321.613	0.460	0.021	13.849	321.613
	Mode 2	1.000	Unlimited	0.000	0.000	0.342	0.239	0.000	0.000	0.460	0.021	13.849	321.613	0.460	0.021	13.849	321.613

^a Min = lowest observed combination of air and seawater temperatures; Max = highest observed combination; Mode 1 = most frequent combination; Mode 2 = second most frequent combination.

Table K.5: KPI results for the sailing operational profile under medium-occupancy scenarios^a.

Climate Zone	Parameter	KPI I		KPI II		KPI III								KPI IV KPI V KPI VI KPI VII			
		[-]	[hh:mm:ss / -]	[-]	[-]	E. Chiller / HP C		E. Chiller / HP H		Heat Exch.	Abs. Chiller	E. Heater	Heat Tank	[-]	[-]	[-]	[-]
						[-]	[-]	[-]	[-]								
Atlantic Crossing	Min	1.000	Unlimited	0.000	0.000	0.000	0.000	1.036	0.000	0.318	0.000	0.000	0.462	0.021	13.849	321.613	
	Max	1.000	Unlimited	0.000	0.000	0.309	0.260	0.452	0.283	0.000	0.000	0.442	0.021	13.849	321.613		
	Mode 1	1.000	Unlimited	0.000	0.000	0.440	0.247	0.000	0.000	0.000	0.000	0.439	0.021	13.849	321.613		
Caribbean	Min	1.000	Unlimited	0.000	0.000	0.792	0.000	0.000	0.000	0.000	0.000	0.448	0.021	13.849	321.613		
	Max	1.000	Unlimited	0.000	0.000	0.246	0.317	0.000	0.000	0.000	0.000	0.431	0.021	13.849	321.613		
	Mode 1	1.000	Unlimited	0.000	0.000	0.346	0.283	0.000	0.000	0.000	0.000	0.436	0.021	13.849	321.613		
East Mediterranean	Min	1.000	Unlimited	0.000	0.000	0.416	0.247	0.000	0.000	0.000	0.000	0.438	0.021	13.849	321.613		
	Max	1.000	Unlimited	0.000	0.000	0.879	0.000	0.000	0.000	0.000	0.000	0.453	0.021	13.849	321.613		
	Mode 1	1.000	Unlimited	0.000	0.000	0.627	0.241	0.000	0.000	0.000	0.000	0.450	0.021	13.849	321.613		
West-East Mediterranean	Min	1.000	Unlimited	0.000	0.000	0.639	0.264	0.000	0.000	0.000	0.000	0.452	0.021	13.849	321.613		
	Max	1.000	Unlimited	0.000	0.000	1.010	0.000	0.000	0.000	0.000	0.000	0.461	0.021	13.849	321.613		
	Mode 1	1.000	Unlimited	0.000	0.000	0.281	0.277	0.000	0.000	0.000	0.000	0.432	0.021	13.849	321.613		
West Mediterranean	Min	1.000	Unlimited	0.000	0.000	0.674	0.247	0.000	0.000	0.000	0.000	0.453	0.021	13.849	321.613		
	Max	1.000	Unlimited	0.000	0.000	0.671	0.264	0.000	0.000	0.000	0.000	0.454	0.021	13.849	321.613		
	Mode 1	1.000	Unlimited	0.000	0.000	0.974	0.000	0.000	0.000	0.000	0.000	0.459	0.021	13.849	321.613		
Hong Kong	Min	1.000	Unlimited	0.000	0.000	0.323	0.260	0.000	0.000	0.000	0.000	0.433	0.021	13.849	321.613		
	Max	1.000	Unlimited	0.000	0.000	0.685	0.247	0.000	0.000	0.000	0.000	0.454	0.021	13.849	321.613		
	Mode 1	1.000	Unlimited	0.000	0.000	0.697	0.264	0.000	0.000	0.000	0.000	0.455	0.021	13.849	321.613		
Middle East	Min	1.000	Unlimited	0.000	0.000	0.897	0.000	0.000	0.000	0.000	0.000	0.454	0.021	13.849	321.613		
	Max	1.000	Unlimited	0.000	0.000	0.288	0.317	0.000	0.000	0.000	0.000	0.434	0.021	13.849	321.613		
	Mode 1	1.000	Unlimited	0.000	0.000	0.358	0.305	0.000	0.000	0.000	0.000	0.437	0.021	13.849	321.613		
	Min	1.000	Unlimited	0.000	0.000	0.356	0.241	0.000	0.000	0.000	0.000	0.434	0.021	13.849	321.613		
	Max	1.000	Unlimited	0.000	0.000	0.914	0.000	0.000	0.000	0.000	0.000	0.455	0.021	13.849	321.613		
	Mode 1	1.000	Unlimited	0.000	0.000	0.190	0.293	0.000	0.000	0.000	0.000	0.427	0.021	13.849	321.613		
	Mode 2	1.000	Unlimited	0.000	0.000	0.241	0.264	0.000	0.000	0.000	0.000	0.429	0.021	13.849	321.613		
	Mode 2	1.000	Unlimited	0.000	0.000	0.239	0.247	0.000	0.000	0.000	0.000	0.428	0.021	13.849	321.613		

^a Min = lowest observed combination of air and seawater temperatures; Max = highest observed combination; Mode 1 = most frequent combination; Mode 2 = second most frequent combination.

Table K.6: KPI results for the harbour operational profile under medium-occupancy scenarios^a.

Climate Zone	Parameter	KPI I		KPI II		KPI III								KPI IV KPI V KPI VI KPI VII			
		[-]	[hh:mm:ss / -]	[-]	[-]	E. Chiller / HP C		E. Chiller / HP H		Heat Exch.	Abs. Chiller	E. Heater	Heat Tank	[-]	[-]	[-]	[-]
						[-]	[-]	[-]	[-]								
Atlantic Crossing	Min	1.000	11:07:27	0.000	0.000	0.000	0.000	0.000	0.000	1.000	4.768	0.980	0.021	13.849	321.613		
	Max	1.000	Unlimited	0.222	0.217	0.000	0.000	0.000	0.000	0.000	0.000	5.471	0.021	13.849	321.613		
	Mode 1	1.000	Unlimited	0.193	0.332	0.000	0.000	0.000	0.000	0.000	0.000	7.172	0.021	13.849	321.613		
Caribbean	Min	1.000	Unlimited	0.171	0.320	0.000	0.000	0.000	0.000	0.003	0.000	7.277	0.021	13.849	321.613		
	Max	1.000	Unlimited	0.000	0.000	0.000	0.000	0.000	0.000	0.677	0.000	0.980	0.021	13.849	321.613		
	Mode 1	1.000	Unlimited	0.222	0.165	0.000	0.000	0.000	0.000	0.000	0.000	4.946	0.021	13.849	321.613		
East Mediterranean	Min	1.000	Unlimited	0.181	0.247	0.000	0.000	0.000	0.000	0.000	0.000	6.346	0.021	13.849	321.613		
	Max	1.000	Unlimited	0.171	0.304	0.000	0.000	0.000	0.000	0.000	0.000	7.283	0.021	13.849	321.613		
	Mode 1	1.000	Unlimited	0.000	0.000	0.000	0.000	0.000	0.000	0.741	0.000	0.980	0.021	13.849	321.613		
West-East Mediterranean	Min	1.000	Unlimited	0.214	0.200	0.000	0.000	0.000	0.000	0.000	0.000	5.371	0.021	13.849	321.613		
	Max	1.000	Unlimited	0.000	0.000	0.000	0.000	0.000	0.000	0.688	0.000	0.980	0.021	13.849	321.613		
	Mode 1	1.000	Unlimited	0.000	0.000	0.000	0.000	0.000	0.000	0.679	0.000	0.980	0.021	13.849	321.613		
West Mediterranean	Min	1.000	Unlimited	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.980	0.021	13.849	321.613		
	Max	1.000	Unlimited	0.214	0.194	0.000	0.000	0.000	0.000	0.000	0.000	5.310	0.021	13.849	321.613		
	Mode 1	1.000	Unlimited	0.000	0.000	0.000	0.000	0.000	0.000	0.726	0.000	0.980	0.021	13.849	321.613		
Hong Kong	Min	1.000	Unlimited	0.000	0.000	0.000	0.000	0.000	0.000	0.706	0.000	0.980	0.021	13.849	321.613		
	Max	1.000	Unlimited	0.000	0.000	0.000	0.000	0.000	0.000	0.818	0.000	0.980	0.021	13.849	321.613		
	Mode 1	1.000	Unlimited	0.214	0.228	0.000	0.000	0.000	0.000	0.000	0.000	5.673	0.021	13.849	321.613		
Middle East	Min	1.000	Unlimited	0.000	0.000	0.000	0.000	0.000	0.000	0.717	0.000	0.980	0.021	13.849	321.613		
	Max	1.000	Unlimited	0.000	0.000	0.000	0.000	0.000	0.000	0.742	0.000	0.980	0.021	13.849	321.613		
	Mode 1	1.000	Unlimited	0.000	0.000	0.000	0.000	0.000	0.000	0.754	0.000	0.980	0.021	13.849	321.613		
	Min	1.000	Unlimited	0.214	0.200	0.000	0.000	0.000	0.000	0.000	0.000	5.371	0.021	13.849	321.613		
	Max	1.000	Unlimited	0.206	0.256	0.000	0.000	0.000	0.000	0.000	0.000	6.078	0.021	13.849	321.613		
	Mode 1	1.000	Unlimited	0.167	0.255	0.000	0.000	0.000	0.000	0.000	0.000	6.711	0.021	13.849	321.613		
	Min	1.000	Unlimited	0.000	0.000	0.000	0.000	0.000	0.000	0.775	0.000	0.980	0.021	13.849	321.613		
	Max	1.000	Unlimited	0.189	0.120	0.000	0.000	0.000	0.000	0.000	0.000	4.691	0.021	13.849	321.613		
	Mode 1	1.000	Unlimited	0.171	0.162	0.000	0.000	0.000	0.000	0.000	0.000	5.394	0.021	13.849	321.613		
	Mode 2	1.000	Unlimited	0.000	0.000	0.000	0.000	0.000	0.000	0.390	0.000	0.980	0.021	13.849	321.613		

^a Min = lowest observed combination of air and seawater temperatures; Max = highest observed combination; Mode 1 = most frequent combination; Mode 2 = second most frequent combination.

Table K.7: KPI results for the anchor operational profile under high-occupancy scenarios^a.

Climate Zone	Parameter	KPI I	KPI II	KPI III								KPI IV	KPI V	KPI VI	KPI VII	
		[-]	[hh:mm:ss / -]	E. Chiller / HP C		E. Chiller / HP H		Heat Exch.	Abs.	Chiller E.	Heater	Heat Tank	[-]	[-]	[-]	[-]
				[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]				
Atlantic Crossing	Min	1.000	00:13:58	0.000	0.000	1.036	0.000	1.000	0.100	0.521	0.021	13.849	321.613			
	Max	1.000	Unlimited	0.000	0.000	0.467	0.384	0.000	0.000	0.491	0.021	13.849	321.613			
	Mode 1	1.000	Unlimited	0.150	0.278	1.036	0.193	0.000	0.000	0.576	0.021	13.849	321.613			
Caribbean	Mode 2	1.000	Unlimited	0.138	0.257	1.036	0.218	0.000	0.000	0.576	0.021	13.849	321.613			
	Min	1.000	02:15:18	0.000	0.000	1.036	0.000	1.000	0.966	0.521	0.021	13.849	321.613			
	Max	1.000	Unlimited	0.000	0.000	0.346	0.448	0.000	0.000	0.482	0.021	13.849	321.613			
East Mediterranean	Mode 1	1.000	Unlimited	0.000	0.000	0.539	0.369	0.000	0.000	0.498	0.021	13.849	321.613			
	Mode 2	1.000	Unlimited	0.100	0.185	1.036	0.248	0.000	0.000	0.571	0.021	13.849	321.613			
	Min	1.000	00:47:48	0.000	0.000	1.036	0.000	1.000	0.341	0.521	0.021	13.849	321.613			
West-East Mediterranean	Max	1.000	Unlimited	0.000	0.000	0.427	0.403	0.000	0.000	0.488	0.021	13.849	321.613			
	Mode 1	1.000	Unlimited	0.326	0.609	1.036	0.001	0.207	0.000	0.596	0.021	13.849	321.613			
	Mode 2	1.000	Unlimited	0.336	0.628	1.036	0.001	0.239	0.000	0.598	0.021	13.849	321.613			
West Mediterranean	Min	1.000	00:25:21	0.000	0.000	1.036	0.000	1.000	0.181	0.521	0.021	13.849	321.613			
	Max	1.000	Unlimited	0.000	0.000	0.413	0.403	0.000	0.000	0.486	0.021	13.849	321.613			
	Mode 1	1.000	Unlimited	0.326	0.609	1.036	0.001	0.351	0.000	0.596	0.021	13.849	321.613			
Hong Kong	Mode 2	1.000	Unlimited	0.336	0.628	1.036	0.001	0.340	0.000	0.598	0.021	13.849	321.613			
	Min	1.000	00:28:51	0.000	0.000	1.036	0.000	1.000	0.206	0.521	0.021	13.849	321.613			
	Max	1.000	Unlimited	0.000	0.000	0.494	0.417	0.000	0.000	0.498	0.021	13.849	321.613			
Middle East	Mode 1	1.000	Unlimited	0.326	0.609	1.036	0.001	0.386	0.000	0.596	0.021	13.849	321.613			
	Mode 2	1.000	00:48:14	0.000	0.000	1.036	0.000	1.000	0.345	0.521	0.021	13.849	321.613			
	Min	1.000	00:44:12	0.000	0.000	1.036	0.000	1.000	0.316	0.521	0.021	13.849	321.613			
	Max	1.000	Unlimited	0.000	0.000	0.427	0.432	0.000	0.000	0.491	0.021	13.849	321.613			
	Mode 1	1.000	Unlimited	0.000	0.000	1.030	0.357	0.000	0.000	0.559	0.021	13.849	321.613			
	Mode 2	1.000	Unlimited	0.000	0.000	1.035	0.391	0.000	0.000	0.563	0.021	13.849	321.613			
	Min	1.000	00:40:11	0.000	0.000	1.036	0.000	1.000	0.287	0.521	0.021	13.849	321.613			
	Max	1.000	Unlimited	0.000	0.000	0.238	0.417	0.000	0.000	0.465	0.021	13.849	321.613			
	Mode 1	1.000	Unlimited	0.000	0.000	0.606	0.000	0.000	0.000	0.469	0.021	13.849	321.613			
	Mode 2	1.000	Unlimited	0.000	0.000	0.332	0.341	0.000	0.000	0.469	0.021	13.849	321.613			

^a Min = lowest observed combination of air and seawater temperatures; Max = highest observed combination; Mode 1 = most frequent combination; Mode 2 = second most frequent combination.

Table K.8: KPI results for the sailing operational profile under high-occupancy scenarios^a.

Climate Zone	Parameter	KPI I	KPI II	KPI III								KPI IV	KPI V	KPI VI	KPI VII
				E. Chiller / HP C	E. Chiller / HP H	Heat Exch.	Abs.	Chiller E.	Heater	Heat Tank					
		[-]	[hh:mm:ss / -]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	
Atlantic Crossing	Min	1.000	01:13:37	0.000	0.000	1.036	0.000	1.000	0.526	0.462	0.021	13.849	321.613		
	Max	1.000	Unlimited	0.000	0.000	0.415	0.367	0.000	0.000	0.444	0.021	13.849	321.613		
	Mode 1	1.000	Unlimited	0.000	0.000	0.636	0.395	0.000	0.000	0.458	0.021	13.849	321.613		
Caribbean	Mode 2	1.000	Unlimited	0.000	0.000	0.618	0.351	0.000	0.000	0.455	0.021	13.849	321.613		
	Min	1.000	Unlimited	0.000	0.000	1.036	0.000	0.189	0.000	0.462	0.021	13.849	321.613		
	Max	1.000	Unlimited	0.000	0.000	0.317	0.438	0.000	0.000	0.441	0.021	13.849	321.613		
East Mediterranean	Mode 1	1.000	Unlimited	0.000	0.000	0.473	0.395	0.000	0.000	0.448	0.021	13.849	321.613		
	Mode 2	1.000	Unlimited	0.000	0.000	0.582	0.351	0.000	0.000	0.453	0.021	13.849	321.613		
	Min	1.000	Unlimited	0.000	0.000	1.036	0.000	0.411	0.000	0.462	0.021	13.849	321.613		
West-East Mediterranean	Max	1.000	Unlimited	0.000	0.000	0.382	0.387	0.000	0.000	0.443	0.021	13.849	321.613		
	Mode 1	1.000	Unlimited	0.000	0.000	0.909	0.343	0.000	0.000	0.471	0.021	13.849	321.613		
	Mode 2	1.000	Unlimited	0.000	0.000	0.927	0.372	0.000	0.000	0.474	0.021	13.849	321.613		
West Mediterranean	Min	1.000	Unlimited	0.000	0.000	1.036	0.000	0.736	0.000	0.462	0.021	13.849	321.613		
	Max	1.000	Unlimited	0.000	0.000	0.371	0.387	0.000	0.000	0.442	0.021	13.849	321.613		
	Mode 1	1.000	Unlimited	0.000	0.000	0.981	0.351	0.000	0.000	0.476	0.021	13.849	321.613		
Hong Kong	Mode 2	1.000	Unlimited	0.000	0.000	0.978	0.372	0.000	0.000	0.477	0.021	13.849	321.613		
	Min	1.000	Unlimited	0.000	0.000	1.000	0.351	0.000	0.000	0.477	0.021	13.849	321.613		
	Max	1.000	Unlimited	0.000	0.000	1.018	0.372	0.000	0.000	0.479	0.021	13.849	321.613		
Middle East	Mode 1	1.000	Unlimited	0.000	0.000	1.036	0.000	0.449	0.000	0.462	0.021	13.849	321.613		
	Mode 2	1.000	Unlimited	0.000	0.000	0.382	0.438	0.000	0.000	0.445	0.021	13.849	321.613		
	Min	1.000	Unlimited	0.000	0.000	0.491	0.422	0.000	0.000	0.451	0.021	13.849	321.613		
	Mode 1	1.000	Unlimited	0.000	0.000	0.487	0.343	0.000	0.000	0.447	0.021	13.849	321.613		
	Mode 2	1.000	Unlimited	0.000	0.000	0.230	0.408	0.000	0.000	0.435	0.021	13.849	321.613		
	Min	1.000	Unlimited	0.000	0.000	0.309	0.372	0.000	0.000	0.438	0.021	13.849	321.613		
	Mode 2	1.000	Unlimited	0.000	0.000	0.306	0.351	0.000	0.000	0.437	0.021	13.849	321.613		

^a Min = lowest observed combination of air and seawater temperatures; Max = highest observed combination; Mode 1 = most frequent combination; Mode 2 = second most frequent combination.

Table K.9: KPI results for the harbour operational profile under high-occupancy scenarios^a.

Climate Zone	Parameter	KPI I	KPI II	KPI III								KPI IV	KPI V	KPI VI	KPI VII
				E. Chiller / HP C		E. Chiller / HP H		Heat Exch.	Abs. Chiller	E. Heater	Heat Tank				
		[-]	[hh:mm:ss / -]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]
Atlantic Crossing	Min	1.000	00:35:26	0.000	0.000	0.000	0.000	0.000	0.000	1.000	0.253	0.980	0.021	13.849	321.613
	Max	1.000	Unlimited	0.288	0.360	0.000	0.000	0.000	0.000	0.000	0.000	6.089	0.021	13.849	321.613
	Mode 1	1.000	Unlimited	0.251	0.469	0.000	0.000	0.000	0.000	0.076	0.000	4.812	0.021	13.849	321.613
	Mode 2	1.000	Unlimited	0.223	0.418	0.000	0.000	0.000	0.000	0.112	0.000	3.994	0.021	13.849	321.613
Caribbean	Min	1.000	09:03:19	0.000	0.000	0.000	0.000	0.000	0.000	1.000	3.881	0.980	0.021	13.849	321.613
	Max	1.000	Unlimited	0.288	0.278	0.000	0.000	0.000	0.000	0.000	0.000	5.444	0.021	13.849	321.613
	Mode 1	1.000	Unlimited	0.236	0.408	0.000	0.000	0.000	0.000	0.000	0.000	7.179	0.021	13.849	321.613
	Mode 2	1.000	Unlimited	0.223	0.418	0.000	0.000	0.000	0.000	0.082	0.000	4.507	0.021	13.849	321.613
East Mediterranean	Min	1.000	02:28:12	0.000	0.000	0.000	0.000	0.000	0.000	1.000	1.059	0.980	0.021	13.849	321.613
	Max	1.000	Unlimited	0.278	0.333	0.000	0.000	0.000	0.000	0.000	0.000	5.969	0.021	13.849	321.613
	Mode 1	1.000	07:02:42	0.000	0.000	0.000	0.000	0.000	0.000	1.000	3.019	0.980	0.021	13.849	321.613
	Mode 2	1.000	08:28:00	0.000	0.000	0.000	0.000	0.000	0.000	1.000	3.629	0.980	0.021	13.849	321.613
West-East Mediterranean	Min	1.000	01:08:36	0.000	0.000	0.000	0.000	0.000	0.000	1.000	0.490	0.980	0.021	13.849	321.613
	Max	1.000	Unlimited	0.278	0.323	0.000	0.000	0.000	0.000	0.000	0.000	5.895	0.021	13.849	321.613
	Mode 1	1.000	03:13:45	0.000	0.000	0.000	0.000	0.000	0.000	1.000	1.384	0.980	0.021	13.849	321.613
	Mode 2	1.000	04:14:45	0.000	0.000	0.000	0.000	0.000	0.000	1.000	1.820	0.980	0.021	13.849	321.613
West Mediterranean	Min	1.000	01:20:28	0.000	0.000	0.000	0.000	0.000	0.000	1.000	0.575	0.980	0.021	13.849	321.613
	Max	1.000	Unlimited	0.278	0.378	0.000	0.000	0.000	0.000	0.000	0.000	6.340	0.021	13.849	321.613
	Mode 1	1.000	03:29:54	0.000	0.000	0.000	0.000	0.000	0.000	1.000	1.499	0.980	0.021	13.849	321.613
	Mode 2	1.000	02:36:47	0.000	0.000	0.000	0.000	0.000	0.000	1.000	1.120	0.980	0.021	13.849	321.613
Hong Kong	Min	1.000	02:11:26	0.000	0.000	0.000	0.000	0.000	0.000	1.000	0.939	0.980	0.021	13.849	321.613
	Max	1.000	Unlimited	0.278	0.333	0.000	0.000	0.000	0.000	0.000	0.000	5.969	0.021	13.849	321.613
	Mode 1	1.000	Unlimited	0.268	0.423	0.000	0.000	0.000	0.000	0.000	0.000	6.841	0.021	13.849	321.613
	Mode 2	1.000	Unlimited	0.218	0.408	0.000	0.000	0.000	0.000	0.013	0.000	6.719	0.021	13.849	321.613
Middle East	Min	1.000	01:52:57	0.000	0.000	0.000	0.000	0.000	0.000	1.000	0.807	0.980	0.021	13.849	321.613
	Max	1.000	Unlimited	0.246	0.205	0.000	0.000	0.000	0.000	0.000	0.000	5.146	0.021	13.849	321.613
	Mode 1	1.000	Unlimited	0.223	0.272	0.000	0.000	0.000	0.000	0.000	0.000	6.018	0.021	13.849	321.613
	Mode 2	1.000	Unlimited	0.000	0.000	0.000	0.000	0.000	0.000	0.570	0.000	0.980	0.021	13.849	321.613

^a Min = lowest observed combination of air and seawater temperatures; Max = highest observed combination; Mode 1 = most frequent combination; Mode 2 = second most frequent combination.

L. KPI Plots for Design 2

KPI IV (Systems Efficiency) at Minimum Temperatures

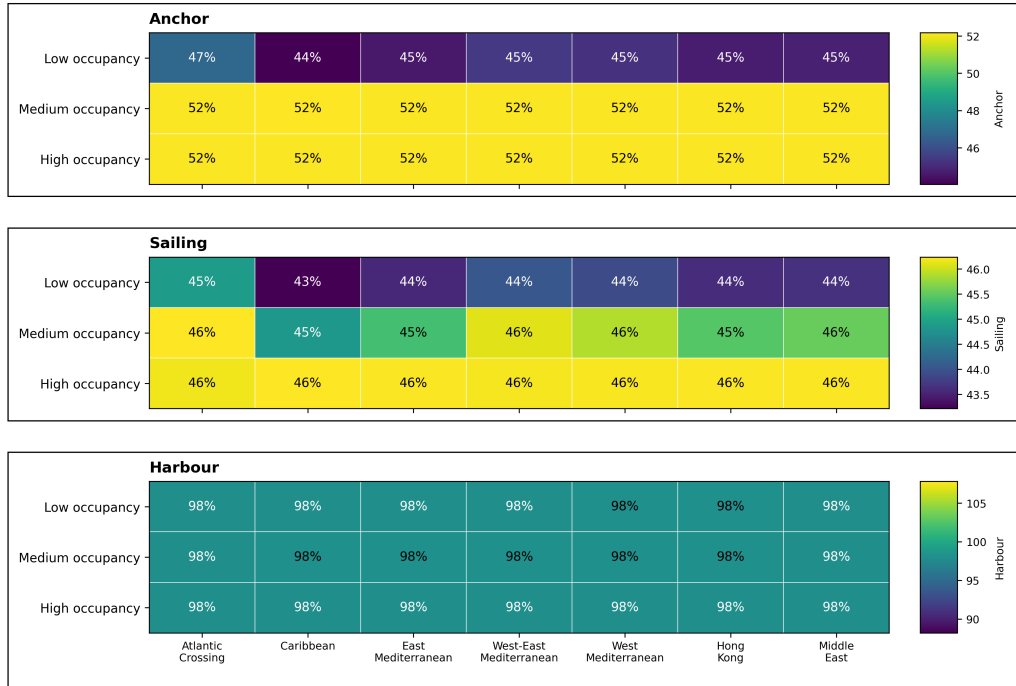


Figure L.1: KPI IV (CHPC Efficiency) at minimum temperatures.

KPI IV (Systems Efficiency) at Maximum Temperatures

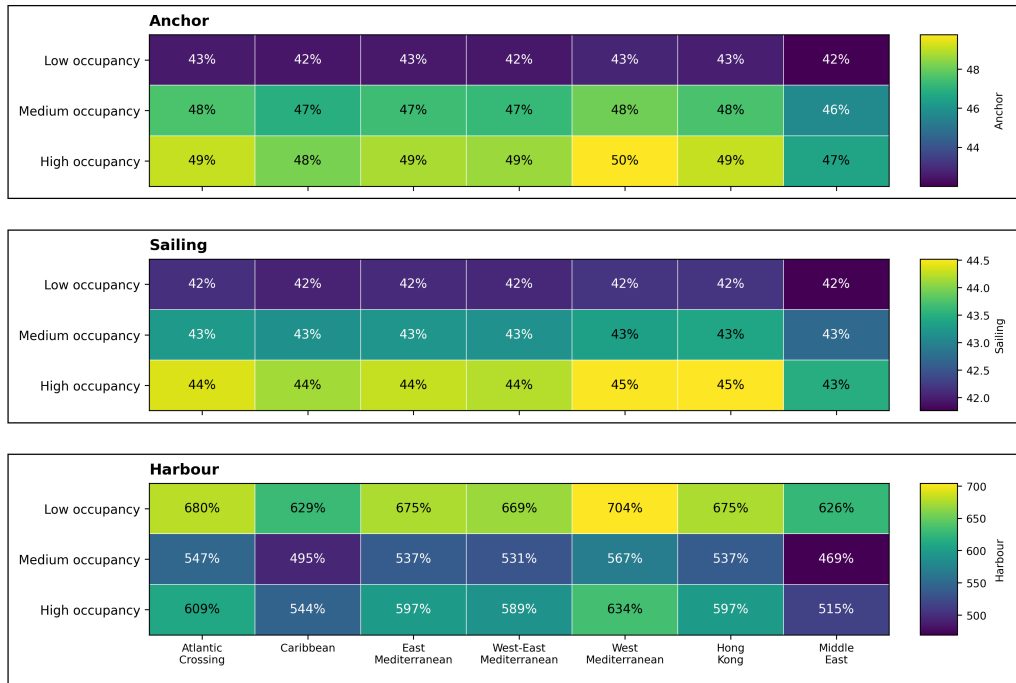


Figure L.2: KPI IV (CHPC Efficiency) at maximum temperatures.

L. KPI Plots for Design 2 (continued)

KPI IV (Systems Efficiency) at Most Frequent Temperatures



Figure L.3: KPI IV (CHPC Efficiency) at most frequent temperatures.

KPI IV (Systems Efficiency) at Second Most Frequent Temperatures



Figure L.4: KPI IV (CHPC Efficiency) at second most frequent temperatures.

L. KPI Plots for Design 2 (continued)

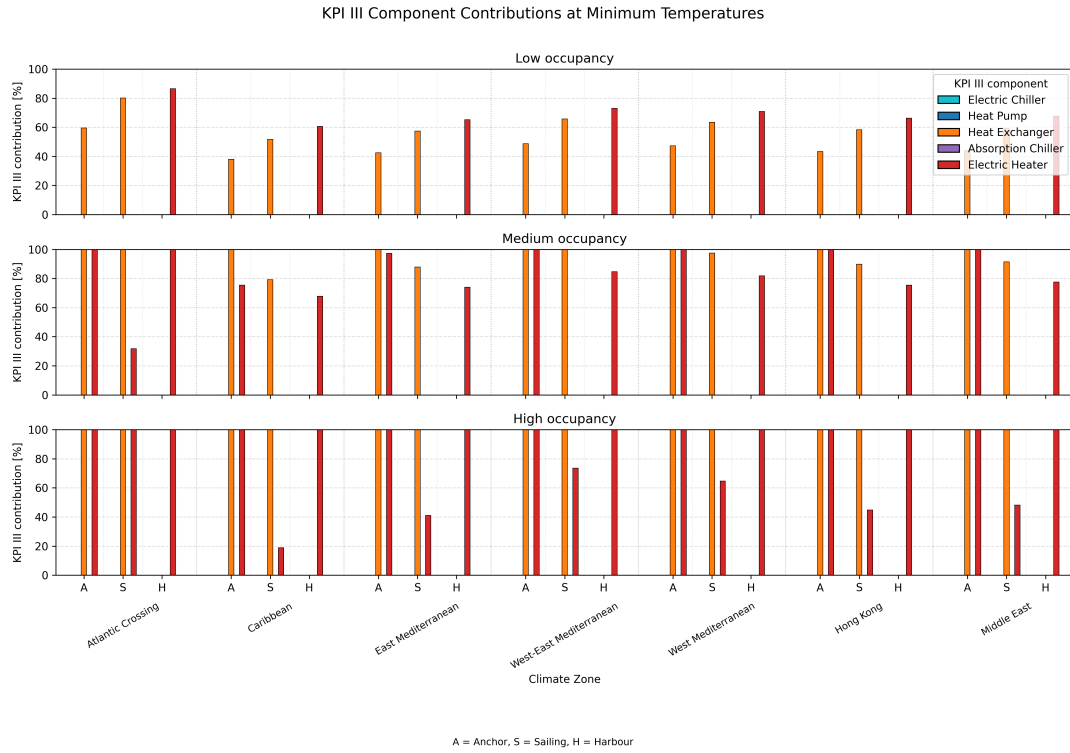


Figure L.5: KPI III component contributions at minimum temperatures.

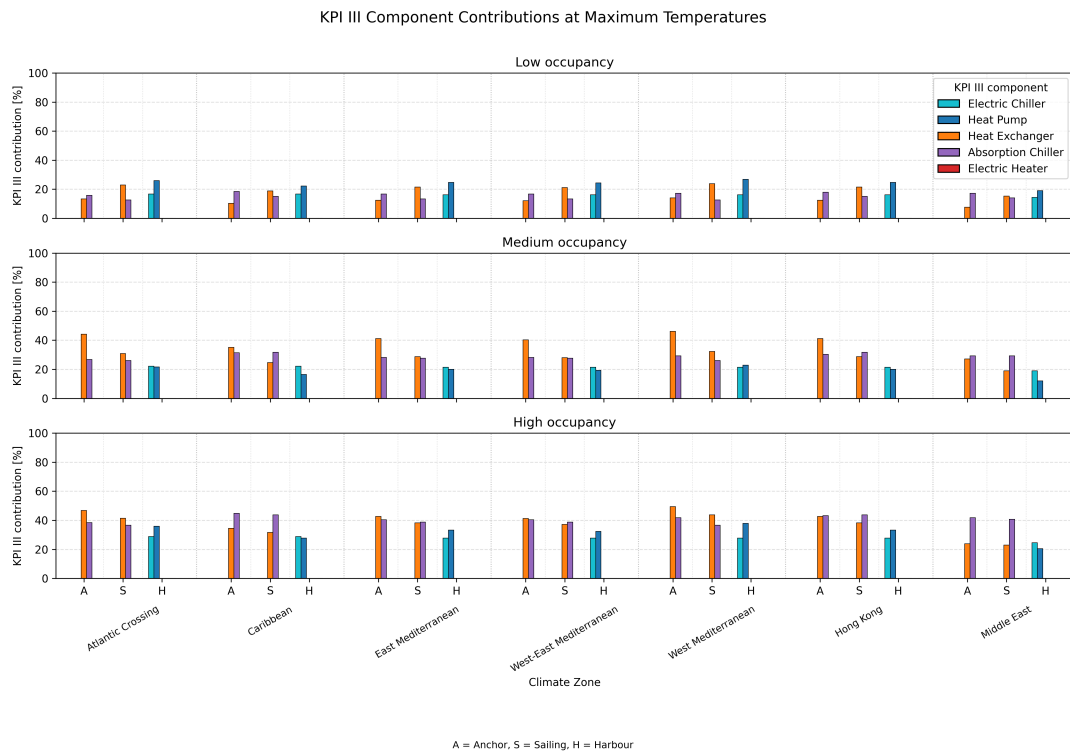


Figure L.6: KPI III component contributions at maximum temperatures.

L. KPI Plots for Design 2 (continued)

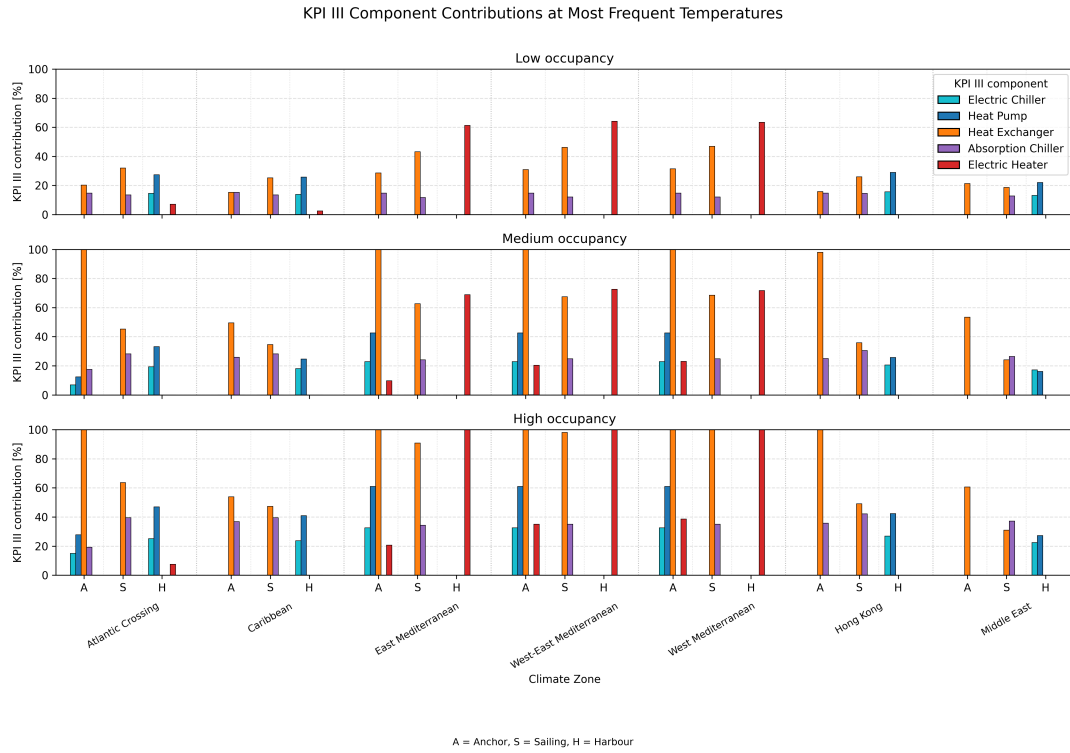


Figure L.7: KPI III component contributions at most frequent temperatures.

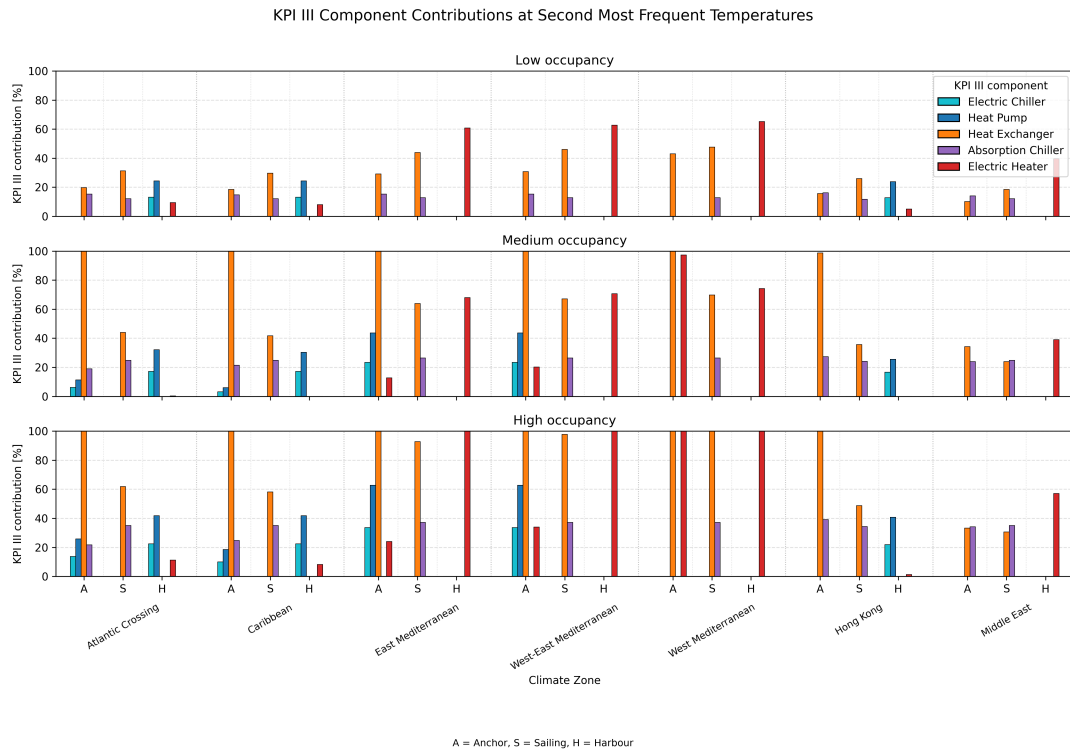


Figure L.8: KPI III component contributions at second most frequent temperatures.

L. KPI Plots for Design 2 (continued)

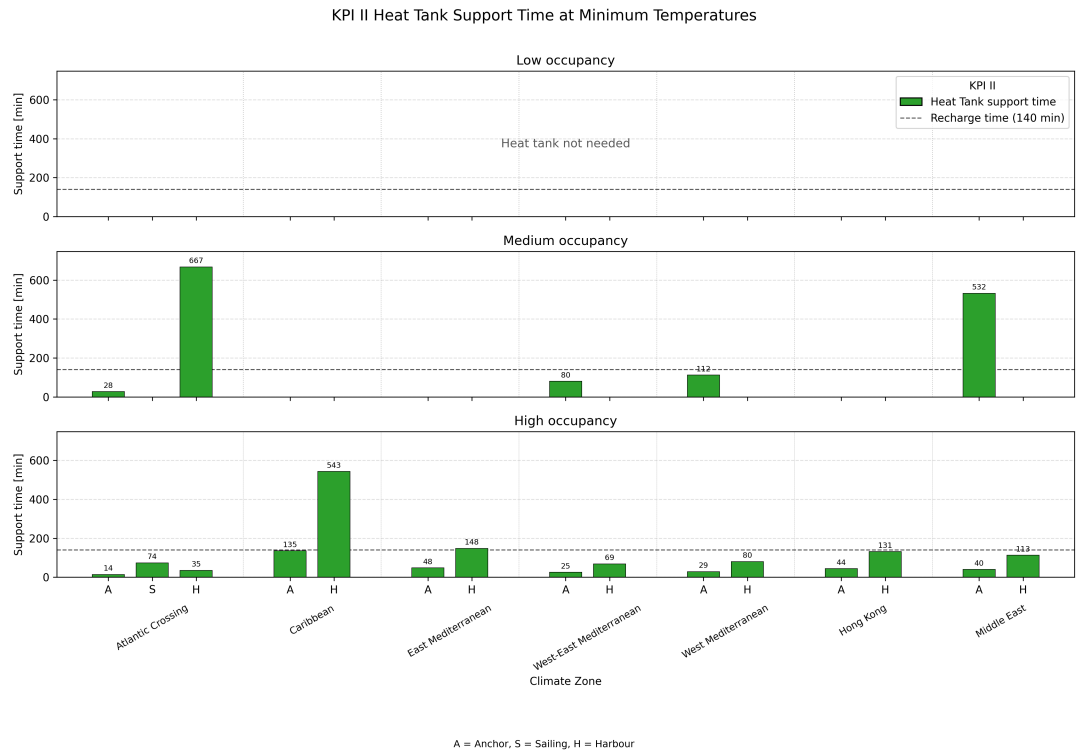


Figure L.9: KPI II heat tank support time at minimum temperatures.

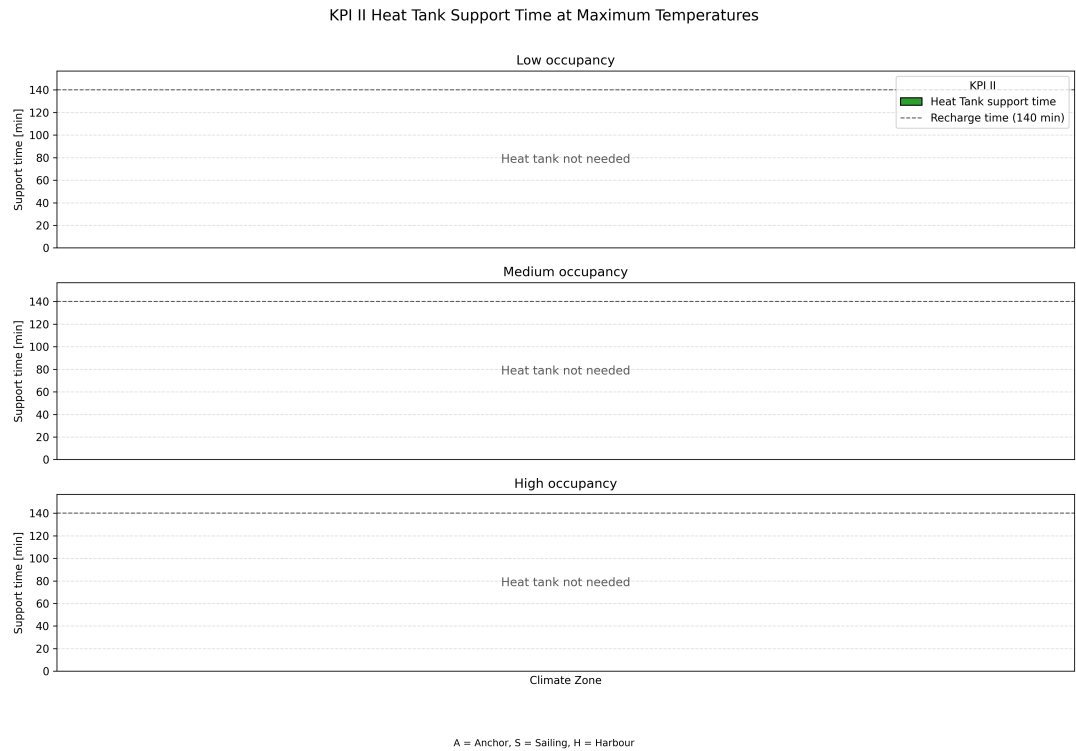


Figure L.10: KPI II heat tank support time at maximum temperatures.

L. KPI Plots for Design 2 (continued)

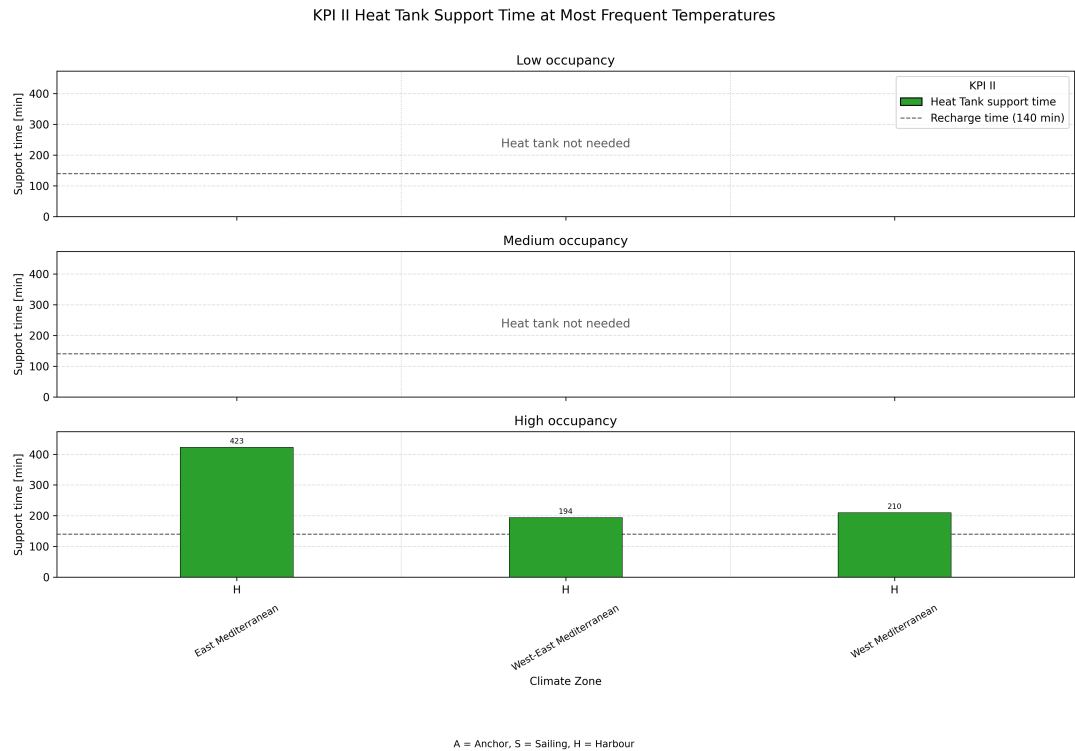


Figure L.11: KPI II heat tank support time at most frequent temperatures.

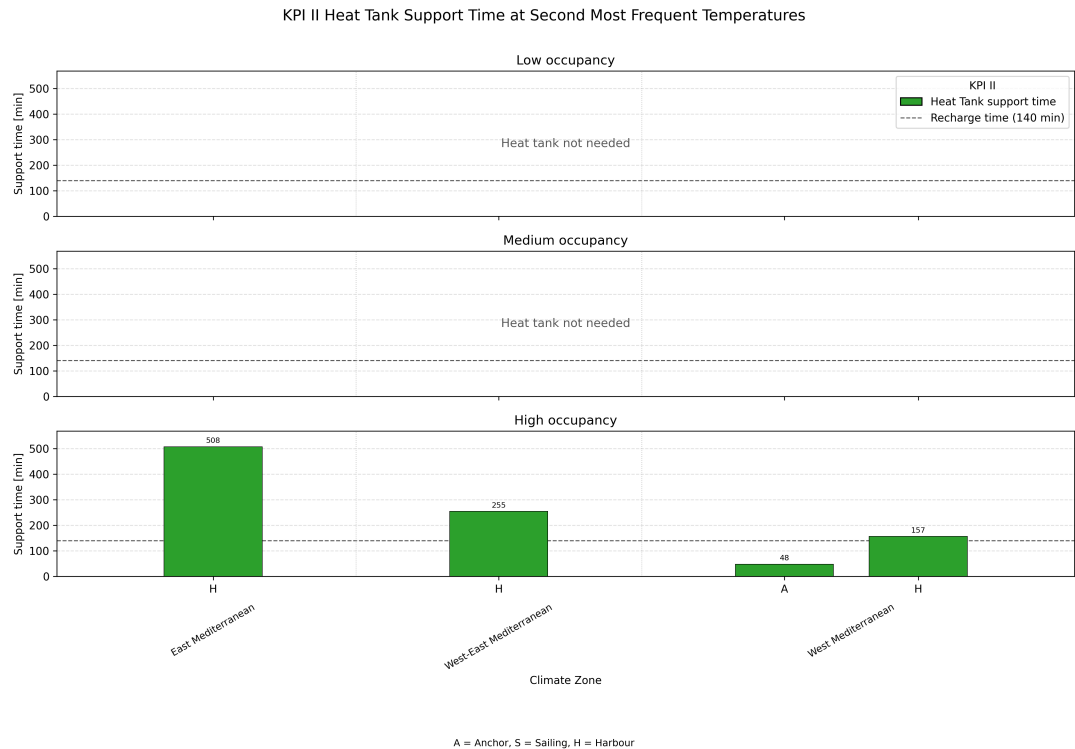


Figure L.12: KPI II heat tank support time at second most frequent temperatures.