ODes aCCSES Report:

Optimal design and control of cruise ship energy systems

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Abstract

Reducing global emissions of greenhouse gases while promoting social and economic development is one of the toughest challenges ever faced in the history of human kind.

This challenge is affecting all sectors of human activities: process plants, land-based transportation, residential buildings. In this framework, the maritime industry faces no smaller challenge. Sea trade and the cruise industry keep growing despite economic crises, while CO_2 emissions from shipping need to fall, as for any other sectors, need to fall.

This report, main deliverable of the *ODes aCCES* project (Optimal Design and Control of Cruise ship Energy Syestems) is meant to provide the interested reader with relevant information to be used in the process of optimizing the design of ship energy systems, and particularly those of cruise ships. The report presents a broad review of different optimization strategies and methods; of methods specifically developed for the optimization of energy systems; and of the application of such methods to the optimization of ship energy systems.

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1 Introduction

1.1 Background

As humanity faces the global threat of climate change, society needs to drastically reduce greenhouse gas (GHG) emissions to the atmosphere. The transport sector is a significant contributor to the global CO2 emissions [31] and, within this category, the maritime sector contributes to approximately 2.7% of the global anthropogenic CO2 emissions [47].

While this contribution appears relatively low, the maritime sector will face difficult challenges. The demand for global trade, that mostly travels by sea, is expected to grow in the future [47]. At the same time, ships are still almost entirely powered by fossil fuels. While shipping will face the fierce competition against aviation and road transport for renewable fuels [50], ship energy systems need to become more energy efficient during the transition [45].

More generally, making shipping sustainable is a challenge that will demand growing attention by the shipping industry [**?**]. Recently, the International Maritime Organization (IMO) has officially adopted an initial strategy aiming at reducing GHG emissions from shipping by 50%, compared to 2008 levels, by 2050, and to work towards phasing out them entirely by the end of the century [39].

In this context, the cruise industry is facing an even greater challenge as it is growing at a greater pace. Cruise ship passengers have increased from 17.8 million in 2009 to 25.8 million in 2017 [5], and this growth is expected to continue in the coming years [5]. Cruise travels, with an estimated average of 160 kg CO_2 per passenger and per day [23], are among the most carbon intensive in the whole tourism industry. The contribution of the cruise industry to global CO2 emissions was estimated to 19.3 Mtons annually in 2010 [23].

Altogether, these conditions present a challenge to the shipping companies who attempt to reduce their fuel consumption, environmental impact, and operative costs. A wide range of fuel saving solutions for shipping are available and partially implemented in the existing fleet, both from the design and operational perspective [14]. However, the existence of many different solutions presents a challenge in itself in the identification of the most optimal one, or of the most optimal combination of technologies, that will lead to the highest possible degree of reduction of GHG emissions, while minimizing the expected cost of the system.

1.2 Aim

The objective of this study is to develop methods to improve the energy efficiency of cruise ships. The project aims at providing:

- Detailed information on the main challenges and requirements for the application of the concept of simultaneous optimization of design and control to ship energy systems design.
- An estimation of the energy savings potential related to the application of the aforementioned optimization concept to cruise ships resulting to a case study.

The project's aim should be seen as part of broader efforts in reducing anthropogenic CO_2 emissions and in reinforcing the competitive strength of the European shipbuilding industry.

1.3 Overview

The project was divided in three main parts:

Part 1 - Optimal design : In the first phase of the project, methods based on energy systems optimization (mostly based on pinch analysis and on the concept of mixed integer-linear programming) were applied to cruise ship energy systems in order to provide a screening of the available technologies and power plant setups that should be further integrated to constitute the ship energy system. This included, for instance, the investigation of the potential of fuel cells as prime movers in shipping.

Part 2 - Optimal control : In the second phase of the project, the influence of control and of its main challenges on the optimal operations of cruise ship energy systems were addressed. This part of the work included the identification of critical control-related issues, such as in the case of the limitations in dynamic operations of high-temperature fuel cells, and a discussion on how to address them in the design optimization problem. In addition, a control system based on unsupervised machine learning algorithms was proposed, and evaluated when compared to an ideal counterpart.

Part 3 - Optimal design with control : In the third phase of the project, the results of the previous two parts were combined into a methodology able to optimize the design of the energy system of a cruise ship while efficiently including control-related requirements and constraints. Multi-objective optimization strategies were also employed in order to systematically generate a list of competing ship energy system design options.

2 State of the art: Ship technology for energy efficiency

This project is meant to employ a systems perspective towards the improvement of ship energy systems. However, while this approach can also be used in combination with existing technologies, its role can be crucial in understanding the potential of new technologies that can have an important impact in ship design. This section hence includes a short overview of those technologies that are not widely used in shipping today and that were considered in this project as potential alternatives to improve ship energy systems performance.

2.1 Fuel cells

Fuel cells are a technology for the conversion of the chemical energy stored in fuels directly to electric energy. Compared to internal combustion engines (such as Diesel engines and gas turbines), the working principle of fuel cells does not involve the intermediate conversion of chemical energy to heat. As a consequence, the efficiency of fuel cells is not theoretically bound by the Carnot principle.

The main features of fuel cells, when compared to Diesel engines, are the following:

- Fuel cells are more efficient than ICEs for small sizes. Fuel cells are generally built according to a modular principle, and the base unit (a stack of cells) is generally of the order of a few kW of design power. Depending on fuel and type, fuel cells can reach today an electric efficiency of 50-60% stand-alone [54] (more realistic operational values, however, are around 40%). When optimized in combination of a gas turbine, fuel cell systems have been proven to have the potential to reach 75% electric efficiency [15].

- Fuel cells maintain a high conversion efficiency over a wide range of operational loads [54]. This makes fuel cells particularly flexible and efficient for operations at variable load.

- Fuel cells directly generate electricity, and hence do not require additional components (and, hence, losses) for the conversion of mechanical to electric energy.

- The core of a fuel cell system, the stack, is relatively fragile and wears over time. While this depends largely on the type of fuel cell, on its quality, and on the way it is used, it is often assumed that the fuel cell stack needs to be substituted at regular intervals, in the range of 3 to 10 years depending on the use.

- Fuel cells are, as of today, much more expensive when compared to ICEs. This is mostly due to the lower production volume, and more marginally to the complexity of the system and to the cost of the raw materials. Several reports forecast a significant drop in the cost of fuel cells with increasing production volumes in the future [13], and this is considered to be a crucial requirement for the future uptake of this systems. Today, a fuel cell is around 10 times more expensive (per kW of rated power) when compared to a Diesel engine of similar size.

- Fuel cells are generally heavier and especially of larger size when compared to Diesel engines. This is particularly true when also considering the requirements in terms of fuel storage, and fuel processing units.

Fuel cell systems, while sharing the same main working principle, are designed and built according to different types, mostly depending on the operating temperature.

2.1.1 Low temperature fuel cells

As the name suggests, low temperature fuel cells operate at relatively low temperatures. Proton exchange membrane fuel cells (PEMFC) generally operate at around 80^oC, while high-temperature PEMFCs operating at around 150^oC have been designed to improve the potential for generating useful waste heat on board and to take advantage of the less stringent requirements in term of fuel purity when operating at a higher temperature [44, 52].

PEMFCs are today the leading fuel cell technology worldwide, and have been widely used as main traction unit for cars, buses and tracks. Operating at low temperature, they are responsive in load-following and have good dynamic behavior. Their main limitation lies in the fuel flexibility: PEMFCs need to be operated on high-purity hydrogen, and most other fuels and residuals (such as ammonia and carbon monoxide) are poisons for the PEMFC catalysts and need to be thoroughly removed from the feed-in gas [52]. As a consequence, the use of PEMFCs needs to be associated either to on board hydrogen storage, or to relatively complex units for fuel reforming and purification.

2.1.2 High temperature fuel cells

High temperature fuel cells operate in the range of 600-900^oC. Two main types of high-temperature fuel cells are generally referred to in literature: molten carbonate fuel cells (MCFC) and solid oxide fuel cells (SOFC). The latter have recently demonstrated a higher potential under several aspects, and will be the focus of this part of the report.

By operating at higher temperature, SOFCs can work with different, more flexible, cheaper catalysts when compared to PEFMCs. As a result, SOFCs can theoretically be run directly on a number of different fuels, including methane [53], methanol [43], and ammonia [17]. The use of more conventional fuels, such as Diesel-type fuels, is possible if associated with an external reformer, in order to avoid the deposition of carbon inside the cell [41]. While the need of a reformer increases the complexity of the system, it should be noticed that in SOFCs there is no need of the same level of purity required by PEMFCs and, hence, the system is much simpler.

SOFCs are still less mature compared to PEMFCs, and this has consequences on a number of performance indicators that are expected to improve in the future, such as power density (i.e. power per unit of weight and volume), investment cost, and dynamic properties.

2.1.3 Research and development of fuel cells in shipping

While fuel cells are still rare in shipping, there are a number of example applications that are relevant to show the viability of these systems. A thorough review of past experience in the use of fuel cells systems systems on board ships is available in [52].

Most examples of the application of fuel cells to shipping are related to the use of PEMFCs, given the higher level of technological readiness. PEMFCs have been used on submarines [46] and extensively teste on a passenger ferry [55].

Fuel cells have often been selected because of their tactical advantage of low noise operations. As a representative example, the US Navy successfully tested the use of SOFCs for the propulsion of torpedoes in slow-cruising mode [28]. Despite its low relevance for merchant shipping, this application constitutes proof that SOFCs can withstand the challenges of the maritime environment [27, 26], and that they can achieve good mass and volumetric densities.

SOFCs have also been proposed as auxiliary power units (APU) [21] because of their high efficiency in low power ranges, and because they directly generate electricity. In this application, most examples are of SOFCs powered by Diesel fuel in connection to an external reformer, showing efficiencies of up to to 55% [**?** 24]. The additional improved potential for high-temperature

waste heat resulted in a net fuel consumption reduction of about 50%. These systems showed promising results also when tested in experimental conditions [41]. Other proposed applications of SOFCs as APUs include the case of methanol-powered SOFCs [43], and the case of a combined system with solar panels and electrolyzers, a setup where the SOFC is only used in port to reduce emissions [42].

Using SOFCs for propulsion has less clear advantages, due to the high efficiency of large marine engines and of energy being needed in mechanical form. [22] proposed a system where SOFCs are used for slow-steaming propulsion, with the advantage of lower installed power (SOFCs are more expensive than Diesel engines) and higher efficiency at low loads.

For even higher efficiency, hybrid GT-SOFC systems are often proposed (as for instance in [2, 32]) but are still not considered mature from a technological perspective.

2.2 Organic Rankine cycles

Waste heat recovery (WHR) systems refer to technical devices designed to make use of the thermal energy that would otherwise be wasted to the environment, a solution which is widely used in various industrial sectors. A Diesel engine presents four main sources of waste heat. The exhaust gas are simply released to the atmosphere through the funnel, while waste heat from the lubricating oil, charge air and engine walls needs to be cooled on board.

The recovery of waste heat from the main engines for fulfilling on board heat demand is today common practice. This is generally done by making use of the thermal energy content of the exhaust gas from the main engines, using an heat recovery steam generator (HRSG) to generate steam which is then distributed to different users on board, such as HVAC and fuel heating. Other proposed uses in heat-to-heat applications include ballast water treatment and freshwater generation.

The amount of waste heat available from the prime movers often exceeds the on board demand for heat, thereby driving engineers and researchers to investigate further opportunities for WHR. One of the most interesting solutions concerns the conversion of waste heat to mechanical power.

In these regards, steam-based Rankine cycles have been proposed for the application to many ship types: containerships [19], ferries [38] and bulk carriers [51], referring to the use of both simple and dual-pressure cycles. Single-pressure steam-based Rankine cycles are installed, for instance, on E-class and on Triple-E class Maersk vessels, and ready technical solutions are offered by several engine manufacturers. The estimated fuel savings vary between different ship types and WHR technologies, ranging between 1% [51] and 10% [19].

In some cases the use of steam as a working medium for Rankine cycles is not the most convenient choice. This is mainly due to the fact that:

- At low temperatures of the heat source it is not possible to maintain a sufficiently high evaporating pressure while ensuring the required minimum level of superheating [30].
- The expansion turbine for a steam cycle is normally too expensive for low-power applications. This is due to the high enthalpy drop and low volumetric flow, which makes the design of the turbine particularly challenging [30].

Organic Rankine cycles (ORC) are often used when only low-temperature waste heat (i.e. approximately below 250°C) is available [30], which makes the more suitable in the case of two-stroke engines; their working process is analogous to that of a steam-driven Rankine cycle, but they make use of different working fluids with more suitable thermodynamic properties.

The need of choosing the working fluid among many potential candidates implies an additional degree of freedom and, therefore, higher expected performance but also a more challenging

optimisation process. This made ORCs to become the subject of many studies in scientific literature, with applications to containerships [36], LNG carriers [48], handy-size tankers [16, 9] and passenger vessels [1]. [29] also proposed the application to oil tankers by attempting to integrate the ORC system with on board heat requirements.

The fuel savings related to the installation of ORCs are slightly higher then what estimated for steam-based WHR cycles, especially in the case of two-stroke engines where the temperatures of the available heat sources are lower. It was shown that 10% fuel savings can be achieved on a marine two-stroke engine if an ORC is installed, at design load [20, 36]. Rankine cycles are not the only way proposed for recovering waste heat on board. Power turbines, driven by the exhaust gas at high engine load, are efficient and have low capital investment, although they are generally connected to lower fuel savings.

2.3 Heat pumps

A heat pump is a thermal system that can absorb heat from a cold source and release it to a warmer one, at the cost of an input of mechanical work. Heat pumps are particularly useful when the temperature difference between the hot and the cold spaces is limited, since the efficiency of the cycle strongly depends on this difference [35]. This is often the case in HVAC applications, where heat pumps are often more efficient not only than electric heaters, but also when compared to boilers. The heat source at low temperature of the heat pump can vary depending on the application. In many cases the heat comes from the environment; however, the use of low-temperature waste heat can be particularly beneficial, as this can help reducing both the heating and the cooling demand of the system.

Heat pumps are very rarely used today in shipping, while oil-fired and exhaust gas boilers are largely preferred. It should be noticed, however, that cruise ships are characterized by a large demand of relatively low-temperature heat, such as the one needed for cabin heating, or for hot water heating. On the other hand, most ships also have a large availability of low-grade heat, resulting from the low-temperature cooling systems, normally ranging between 35 and 50°C. By making use of low-grade heat, in addition, the use of heat pumps for space heating would free up part of the high-temperature waste heat, today partly used for this purpose, to generate electricity using (organic) Rankine cycles.

Given their characteristics and the boundary conditions defining the ship energy system optimization problem, the possibility of introducing heat pumps on board of cruise ship was introduced in this work for evaluation when compared to conventional alternatives.

2.4 Alternative fuels for shipping

As environmental regulations become stricter in many regards (from "conventional" pollutant emissions such as sulphur and nitrogen oxides, to greenhouse gas emissions), there are wide discussions on whether part of the solution should be achieved by not only improving the efficiency of the ship's energy system, but also changing the fuel that is used on board.

The discussion about different fuels is already a hot topic today. The use of liquefied natural gas as ship fuel is spreading around the world, mostly as a consequence of ECAs stricter environmental regulations, but also as a way to reduce GHG emissions, based on the lower carbon-to-hydrogen ration of methane when compared to conventional fuels (it should be noted, however, that the phenomenon of methane slip is raising concerns, see [12]). Methanol, today mostly used as a chemical but with a significant potential as a fuel, has also been successfully tested as ship fuel (the conversion of one of the engines of Stena Germanica to run on methanol represents one relevant example).

The work done in the ODes aCCSES project also took into account the possibility of reducing the environmental impact of cruise ship energy systems through the use of alternative fuels.

2.5 Batteries

On similar lines, similarly to the automotive market, the electrification trend is also hitting the shipping sector. More and more applications of batteries on ships can be found, a consequence of the lower cost and higher performance of electrical energy storage technology. Despite being today only relegated to few examples, and only rarely to pure-battery powered applications, there is a clear upward trend in the process of electrification of shipping, especially for short routes.

A full review of the existing and planned applications is out of the scope of this report. The list of applications presented by Corvus Energy, one of the main suppliers of marine batteries, can be taken as an example of this process. The list presents dozens of ships built or retrofitted with battery packs ranging from 100 kWh to few MWh. The case of Stena Jutlandica, that was announced early in 2018 to be converted to fully battery powered within a few years (total installed capacity: 50 MWh) shows that batteries in short-sea shipping are here to stay, and are enlarging the range of operations from river/fjord crossing, to open sea operations (in the Stena Jutlandica Case, sailing the 50 nautical miles separating Gothenburg in Sweden and Fredrikshavn in Denmark).

The case for the use of batteries in shipping lies in the complete elimination of all direct emissions to air. While the net results over the whole cycle depends on how the electric energy that was used to charged the battery was generated, these developments are considered to be particularly promising especially with the expectations of an increasingly predominant share of renewable energy generation in the national power grid, particularly in Europe.

Apart from the so far unique case of Stena Jutlandica, batteries are currently used in shipping for the following purposes:

- Emission avoidance in sensitive areas: when the capacity is not sufficient to run on battery power for the whole route, batteries are used when the ship is in, or approaching, port or coastal areas. This approach is used primarily to avoid pollutant emissions close to shore, where they generate the most harm.

- Peak shaving: batteries can be used to make sure that the engines are operated as close as possible to their ideal (and, hence, most efficient) conditions. This only true, however, when it allows avoiding very low engine loads (i.e. 10-20% load)

- Reliability: In many cases, ships maintain one extra engine running (particularly in the case of auxiliary engines) for reliability purposes: in the case of a breakdown of one of the running engines, the one kept in stand-by can immediately step up and maintain the whole system functioning. A battery can be used as a substitute stand-by unit, thus avoiding the fuel consumption of an engine running at 0% load.

3 Design optimization of ship energy systems

3.1 Optimization

Optimization refers to the act of selecting the combination of a set of controllable variables that makes the system of interest to perform best according to one or more indicators of performance.

While a complete survey of the field of mathematical optimization would be out of context, this report includes a small introduction about the main concepts of importance for the optimization of energy systems.

3.2 Tools for energy systems optimization

3.2.1 Process integration

Process integration is a name used to define a set of tools and methods used to improve the efficiency of energy systems. It includes a set of techniques devised for the minimization of the use of external energy utilities for a given process by maximizing the amount of heat recovered within the system's streams. Pinch analysis, originally developed by Linnhoff in the 80's for designing heat exchanger networks in chemical processes [37], is the first and most known of the methods used in process integration. From its first usage as a tool to estimate the maximum potential for internal energy recovery, process integration techniques have subsequently evolved towards including different types of energy, energy storage, mass flows and more [33]. Process integration, although widely applied in many other sectors such as the process industry, urban energy systems and refineries, has only seen limited application to the maritime industry.

One of the main advantages of process integration techniques is that they can be easily expressed in mathematical forms, making them particularly suitable for being combined with optimization techniques. In particular, the linear nature of the defining equations of the heat cascade (i.e. the set of equations that ensures that both the first and second law of thermodynamics are respected) makes them suitable for applications in linear programming problems. As stated by Klemes et al., *Process integration thus converged into two complementary schools of concepts, where the main contribution of thermodynamics is in generating ideas based on engineering creativity whist the main role of mathematical programming is to upgrade those ideas (and also generate new ones) by formulating them in mathematical forms in order to obtain optimal and feasible solutions of complex problems* [34].

3.2.2 Multi-period optimization

In practice, few energy systems are used in only one, main operational condition. However, certain methods typical of this field, such as pinch analysis, poorly adapt to the case of systems operating in several different load conditions, as they are based on the visual analysis of graphical results. While this is possible for few operational conditions, when the objective is to optimize such system it is necessary to find methods that are alternative and complementary. The need for defining methods capable of extending process integration to more diverse applications required a change in this paradigm led to the introduction of the concept of multi-period optimization.

The objective function (f_{obj}) of a general optimization problem is defined in Equation 1.

$$\boldsymbol{f_{\text{obj}}} = \boldsymbol{C_{\text{op}}} + \boldsymbol{C_{\text{inv,act}}} \tag{1}$$

Where the annualized investment cost ($C_{\text{inv,act}}$) is defined as:

$$C_{\text{inv,act}} = \sum_{u \epsilon \mathbb{U}} \frac{C_{\text{u}}^{\text{inv,fix}} \boldsymbol{y_{\text{u}}} + \boldsymbol{f_{\text{u}}} C_{\text{u}}^{\text{inv,var}} \dot{E}_{\text{size,u}}^{\text{max}}}{\frac{(i+1)^{N_{\text{u}}^{\text{y}}}-1}{i(1+i)^{N_{\text{u}}^{\text{y}}}}} \tag{2}$$

In a single-period optimization problem, the operational costs are defined as:

$$C_{\text{op}} = \sum_{u \epsilon \mathbb{U}} \boldsymbol{f'_{\text{u}}} C_{\text{fuel}} \dot{E}_{\text{fuel,u}}^{\text{max}} \Delta t \tag{3}$$

In a multi-period optimization problem instead the operational costs are defined as:

$$C_{\mathrm{op}} = \sum_{u \epsilon \mathbb{U}} \sum_{t \epsilon \mathbb{T}} \boldsymbol{f'_{\mathbf{u,t}}} C_{\mathrm{fuel}} \dot{E}^{\mathrm{max}}_{\mathrm{fuel,u}} \Delta t_{\mathrm{t}} \xi_{\mathrm{t}} \tag{4}$$

where the problem parameters in the equations above are: the fuel cost (C_{fuel}), the maximum fuel consumption of each utility u ($\dot{E}^{\mathrm{max}}_{\mathrm{fuel,u}}$), the duration of each time step (Δt_{t}), the number of occurrences of each time step during the year of reference (ξ_{t}) and variable (i.e. size-dependent) investment cost of each utility ($C^{\mathrm{inv,fix}}_{\mathrm{u}}$ and $C^{\mathrm{inv,var}}_{\mathrm{u}}$), the maximum energy/material flow used for sizing purposes of each utility u ($\dot{E}^{\mathrm{max}}_{\mathrm{size,u}}$), the lifetime of each utility ($N^{\mathrm{y}}_{\mathrm{u}}$), and the interest rate (i). $\mathbb{U}$ and $\mathbb{T}$ represent the set of utilities and of time steps included in the problem, respectively.

It is also clear that all operational-related equations (mass balance, energy balance, etc.) are also multiplied by the number of time steps in a multi-period optimization problem.

A multi-period problem can be expressed as a two-level optimization problem:

1. A **design**, master problem, including all variables related to the design of the system, such as the number and size of different components.

2. An **operational**, slave problem, including all variables related to the system's operations, such as the instantaneous load factor of each utility.

In absence of additional considerations, the slave problem can be separated in N independent sub-problems, and each sub-problem can be solved individually. This is because, once the design variables are set in the outer problem layer, each time step is only connected to the others by the objective function. Because of the linearity of the objective function, the minimization of the total operational cost, in this case, can be achieved by the minimization of the cost of each time step.

As the time needed to solve an optimization problem increases more than linearly with the number of variables and constraints, and particularly with the number of integer variables, this would lead to clear advantages in the decomposition of the problem. This is particularly true if the problem is represented using a nonlinear optimization approach, while linear approaches generally solve the problem as one.

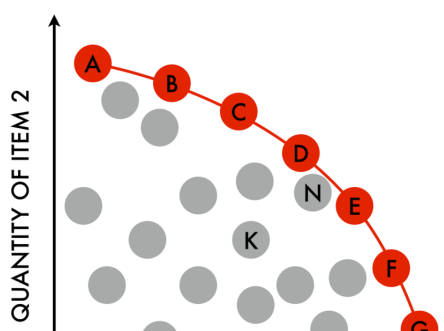
3.2.3 Multi-objective optimization

In the sections above, all problems were defined with one objective in mind: minimizing the total annualized cost of the system, calculated as the sum of the yearly operational costs, and the annualized investment cost.

This choice, while reasonable, is not necessarily the only possible one. Firstly, there could be different ways to weigh investment and operational costs, by changing the horizon of the investment. There are also a number of other objectives of interest, such as emissions of carbon dioxide, of other pollutants, the demand of primary energy, and many more.

There are many different alternative methods to take this aspect into account. The concept of Pareto optimum (and, consequently, of Pareto front) is one of the most commonly used, as it does not imply any choice or prioritization among the different objectives. A solution that is Pareto-optimal is defined as a solution that is not inferior in both objectives compared to any other solution. The concept of Pareto optimality and Pareto front is shown in Figure 1.

In addition to the application of the Pareto concept, in this work the concept of parametric optimization was applied. According to this principle, the multi-objective optimization problem is



converted to a single-objective optimization problem by transforming one of the objectives into a constraint, and by solving the optimization problem several times for different values of the constrained objective.

3.3 Control-based design constraints

The inclusion of control-based constraints involves a coupling between the different time steps, and hence makes it impossible to decompose the problem. This increases the complexity of the problem and, at the same time, generally increases computational time.

In this work, three main control-based constraints were included, based on what was deemed to be the most relevant for the problem of interest. This refers to, in particular, the use of energy storage and to the constraints related to limitations of load-following of certain components, particularly solid oxide fuel cells

3.3.1 Load limitations of SOFCs

As a result of the design optimization part of this project, fuel cells, and particularly solid oxide fuel cells, were identified as one of the most promising technologies for the future of cruise ships. This comes as a result of the high efficiency and of the flexibility in the type of fuel used in the cells, from natural gas and Diesel fuel (in presence of an appropriate reforming unit) to carbon-free fuels such as hydrogen and ammonia.

Solid oxide fuel cells operate at high temperatures (600-1000°C). This allows for the use of catalysts that are not easily poisoned as in the case of PEMFCs (for example in the case of carbon monoxide), and hence a larger fuel flexibility. However, the high temperatures, and particularly temperature gradients, put the materials under high levels of stress.

From an operational perspective, this poses two potential limitations that should be taken into account:

- SOFCs should not be subject to fast load changes. During these phases the conditions within the cell change, including the temperature of the cell. While an appropriate control of the air and fuel flows, in correspondence to changes of current density, can be used as a way to maintain temperature changes within acceptable boundaries, this is widely acknowledged to be a limitation for SOFC operations. This leads, in practice, to the need of limiting the magnitude of load changes during operations.

- Advanced control practices can be implemented in order to limit temperature gradients in SOFCs. However, if the cell is turned off, no more energy is injected in the cell and, hence, the fuel cells gradually cools down over time. This implies that, once the fuel cell is in thermal equilibrium with the environment, the rump-up time to fully operational conditions require a slow heat-up of the cell. This is a process that largely depends on the type and characteristics of the fuel cell, but that can take from several hours up to days [**?**]. While future technical developments will certainly provide improvements in these regards, these limitations should be taken into account.

In the current problem, these two aspects were implemented as inequality constraints to the optimization problem:

$$\mathbf{f}'_{SOFC,t+1} - \mathbf{f}'_{SOFC,t} <= \Delta f^{max}_{SOFC} \tag{5}$$

$$\mathbf{f}'_{SOFC,t+1} - \mathbf{f}'_{SOFC,t} >= -\Delta f^{max}_{SOFC} \tag{6}$$

$$\mathbf{y}'_{SOFC,t} = \mathbf{y}_{SOFC} \qquad \forall \ t \epsilon T \tag{7}$$

Where equations 5 and 6 are used to implement limitations on load changes between two consecutive time steps, while Equation 7 serves the purpose of forcing the SOFC unit to be either always on, or always off. As can be seen clearly the first two equations have the effect of coupling the optimization problems related to different time steps.

3.3.2 Energy storage

Energy storage can be an important element in ship energy systems. While fuel storage in conventional systems (i.e. Diesel fuel or residual oil) do not pose any challenge in terms of storage, this is not the case for many alternative fuels. Cost, weight and volume issues can become very relevant when fuels such as hydrogen and natural gas, or batteries, are taken into account.

In a linear optimization problem the concept of energy storage can be easily implemented as follows:

$$\left(\mathbf{f}'_{ES,t+1} - \mathbf{f}'_{ES,t}\right) E^{max}_{Batt} = \left(\mathbf{f}'_{ES_{in}} P^{max}_{ES_{in}} \eta^{ch}_{ES_{in}} - \frac{\mathbf{f}'_{ES_{out}} P^{max}_{ES_{out}}}{\eta^{ch}_{ES_{in}}}\right) \Delta t_t \tag{8}$$

Equation 8, similarly to equations 5 and 5, generates a connection between the optimization variables related to different time steps.

3.4 Optimal design of ship energy systems: a review

This project represent one of the first cases where the concept and methods of energy system optimization are applied specifically to cruise ship. This is not true, however, for the more general case of the application of energy system optimization to ship energy systems.

Some of the most representative work done in this case relates to the design of the whole power plant, including the number and types of prime movers (e.g. turbines, Diesel engines) and the units for heat recovery. Different approaches have been selected for these studies: Dimopoulos et al. [18] preferred a more detailed modelling of the components and hence selected a nonlinear modelling approach, associated with an evolutionary algorithm for the solution of the problem. This approach was also chosen by Armellini et al. [4], who considered the case of using gas turbines instead of Diesel engines as prime mover in the presence of a WHR system. On the other hand, [49] approached the problem as a MILP. It should be noted, however, that while Dimopolous et al. and Armellini et al. included the thermal part of the system in the optimization (a part that presents a number of inherently nonlinear relations), Solem et al. focused on the choice of the machinery, where very accurate modelling can be achieved by a simple piece-wise linearization.

Most of the work, however, focuses on the concept of retrofitting existing ships. In the work of Ancona et al. [3], the choice of the engines is fixed (as they are assumed to be already installed), but various other choices, such as the type of configuration of the propulsion system (mechanical or Diesel-electric), and the possibility of energy saving through thermal energy

storage and absorption chillers were investigated. The same case study was used by Baldi et al. [7], where a classic nonlinear approach (based on the SQP algorithm) was proposed to optimally allocate the engine load of the system, taking into account both mechanical, electrical, and heating demand, suggesting the use of a shaft generator as a potential alternative for improving the efficiency of the system, and by Ahlgren et al. [1], who proposed the installation of a WHR system.

More generally, in terms of retrofit solutions, ORC systems have been largely favored by the academic community, despite the absence of practical applications as a consequence of technological issues. While a review of these efforts is out of the scope of this work (see [40]) many of the works presented in academic literature are based on optimization, mostly in the selection of the design and operating properties of the ORC system (see, for instance, [36, 9, 19]).

In this situation, it should be noted that a number of aspects have not yet been explored, or taken into account:

- The inclusion of the thermal energy demand is rarely taken into account. This is mostly due to the fact that this contribution is often only a minor fraction of the total energy demand, thus justifying neglecting it. This is however not the case for cruise ships, that are the focus of this project.

- There is often the tendency of only considering one solution in the optimization process (e.g. in the case of the ORC systems), thus neglecting the impact that this solution might have on other parts of the system, or what other solutions might have on the operations of the ORC system. This generates a high risk of sub-optimization, and of missing potential synergies.

4 Case study: description and analysis

4.1 Ship description

The energy and exergy analysis are applied to a cruise ship operating daily cruises in the Baltic Sea between Stockholm and the island of Åland. The ship is 176.9 m long, has a beam of 28.6 m, and has a design speed of 21 knots. The ship was built in Aker Finnyards, Raumo Finland in 2004. The ship has a capacity of 1800 passengers and has several restaurants, night clubs and bars, as well as saunas and pools. This means that the heat and electricity demands are expected to be higher compared to a cargo vessel of the same size. Typical ship's operations, although they can vary slightly between different days, are represented in Figure XX. It should be noted that the ship stops and drifts in open sea during night hours before mooring at its destination in the morning, if allowed by weather conditions.

The ship systems are summarized in Figure 2, while a list of the main system components is provided in Table 1. The propulsion system is made of two propulsion lines, each composed of two engines, a gearbox, and a propeller. The main engines are four Wärtsilä 4-stroke Diesel engines (ME) rated 5850 kW each. All engines are equipped with selective catalytic reactors (SCR) for NOX emissions abatement. Propulsion power is needed whenever the ship is sailing; however, it should be noted that the ship rarely sails at full speed, and most of the time it only needs one or two engines operated simultaneously.

4.2 Energy and exergy analysis

The results of the analysis of the ship's operations are represented in Figures 3 to 5. The Sankey and Grassmann diagrams (Figures 3 and 4) represent a summary of the energy and exergy flows

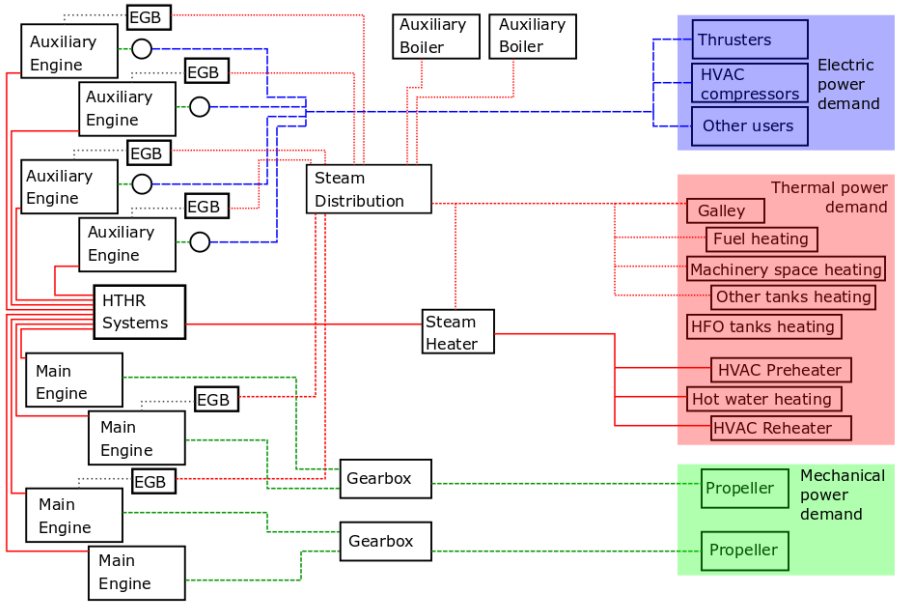


Figure 2: Schematic representation of the energy system of the case study ship. From [8]

Unit name	N	Rated Power ($\dot{W}_{des}/\dot{Q}_{des}$)	Other info
Main engine	4	5850	4-stroke, Nominal speed: 500 rpm, 6 cyl, Bore: 460 mm, Stroke: 580 mm, bsfc at rated power: 175 g/kWh
Auxiliary engine	4	2760	4-stroke, Nominal speed: 750 rpm, 6 cyl, Bore: 320 mm, Stroke: 400 mm, bsfc at rated power: 184 g/kWh
HRSG (ME)	2	800	Based on 1000 kg/h steam at 7 bar. Only installed on ME2 and ME3
HRSG (AE)	4	640	Based on 800 kg/h steam at 7 bar
Sea water cooler	2	5400	Based on a max water flow of 725 m^3/h
Electric generator	4	3312 (kVA)	8 poles, 50 Hz
Auxiliary boiler	2	4500	
HVAC - Preheater	1	3500	
HVAC - Reheater	1	1780	
HVAC - Compressors	2	2015	

Table 1: List of the main components of the ship energy systems

of the ship over one year of operations. The Sankey diagram shows how a large part of the waste heat is already recovered today on board, and shows a relatively high degree of heat integration on board. In the case of the exhuast gas, most of the heat that is not recovered today is simply

a consequence of the sulphur content in the fuel, that prevents cooling the exhaust gas below the condensation temperature of sulphuric acid. On the other hand, the fact that only two of the four main engines is equipped with a HRSG shows potential for improvement. A closer look at Figure 4 suggests that further improvements are possible by:

- Enabling the recovery of low-grade waste heat from the low temperature cooling systems.
- Improving the integration between the processes and utilities. Particularly, the steam heater in the hot water heat recovery system, while necessary to preserve the energy balance in all operational conditions using the steam coming from auxiliary boilers, generates a large exergy destruction (and, hence, is a potential source for system improvement) because of the large temperature difference between demand and availability.
- Minimizing the use of boilers, given their low exergy efficiency.

For the purpose of analysis and optimization, the ship operations were clustered in a limited number of "typical operational days". This is particularly relevant for the case study since the operational cycles and the daily ones coincide. The results of the clustering into typical days and the subsequent segmentation of the day in variable-length time steps to optimize the accuracy of the simulation (see [8] for additional details) allows the full yearly operations to be represented using only 60 time steps, when compared to the initial 32000 (resulting from 8000 hours of operations with a sampling frequency of 15 minutes).

The demand profiles resulting from this operation are represented in Figure 5

5 Project results

In this project, the main concepts and methods of energy system optimization were applied to a case study: a small cruise ship operated in the Baltic Sea. This report presents a summary of the results, that can be found more extensively in the following publications:

- Baldi et al. (2017), "Process integration as a tool for the improvement of cruise ship energy efficiency" [6]
- Baldi et al. (2018), "Energy and Exergy analysis of a cruise ship" [8]
- Baldi et al. (2018), "Integration of solid oxide fuel cells in cruise ship energy systems[10]

5.1 Pinch analysis

The analysis of the composite curves allows identifying potential for improvements to the energy systems, in particular for what concerns its heat integration and the improvement of the internal heat exchanges. In this section, an example of the use of pinch analysis to this purpose is presented, with relation to the case study.

In theory, composite curves can be plotted for each of the time steps. However, analyzing in detail each of the 48 composite curves would prove challenging in practice. Hence, only the composite curves of the system for four reference conditions will be represented here:

- Winter day, sailing
- Winter day, port
- Spring day, sailing

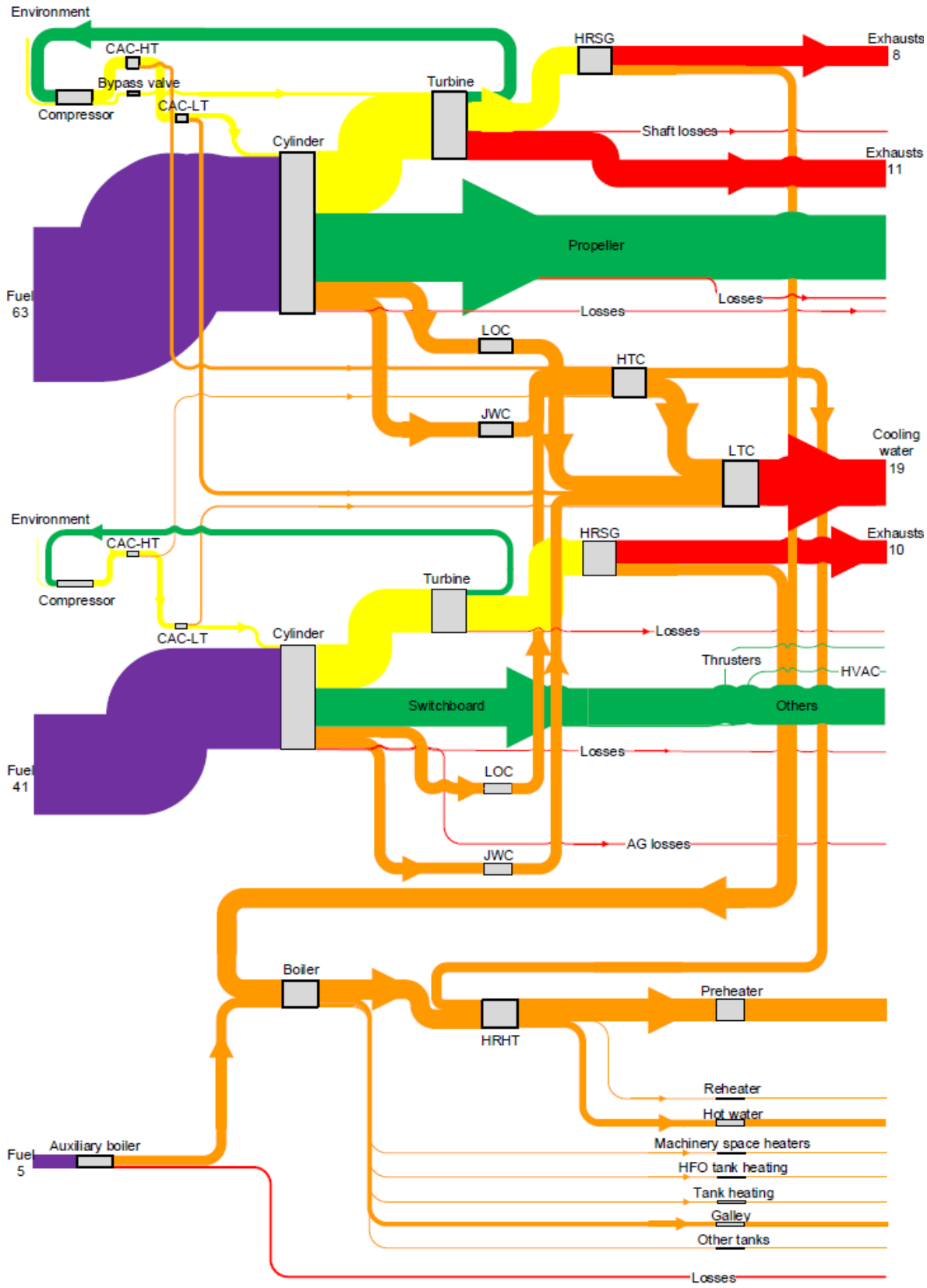


Figure 3: Sankey diagram for the case study ship, representing the average yearly energy flows. Reproduced with permission from [8]

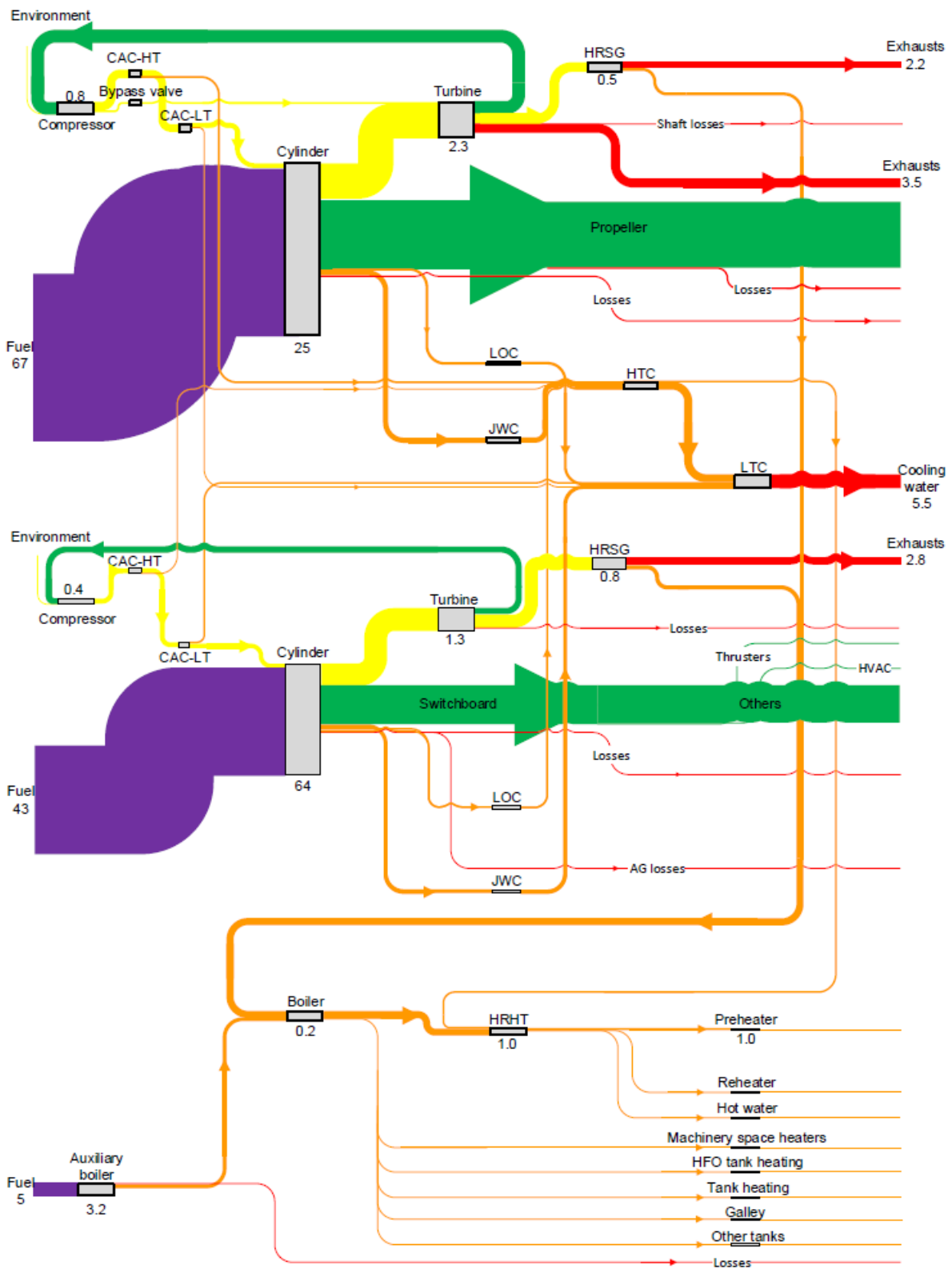


Figure 4: Grassmann diagram for the case study ship, representing the average yearly exergy flows. Reproduced with permission from [8]

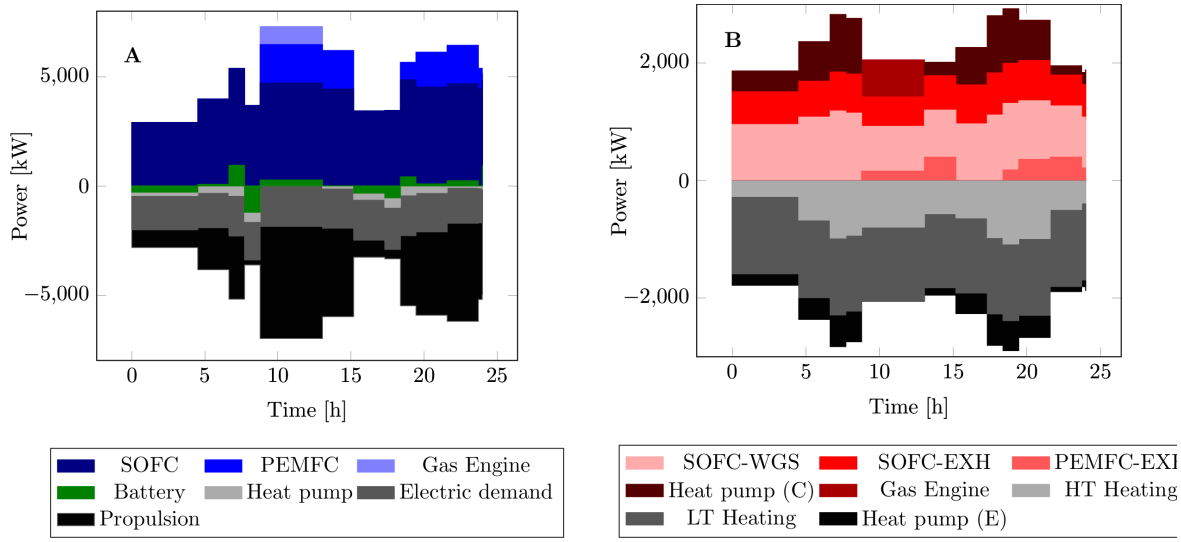


Figure 5: Energy demand of the case study ship represented in the forms of typical days. Reproduced with permission from [11]

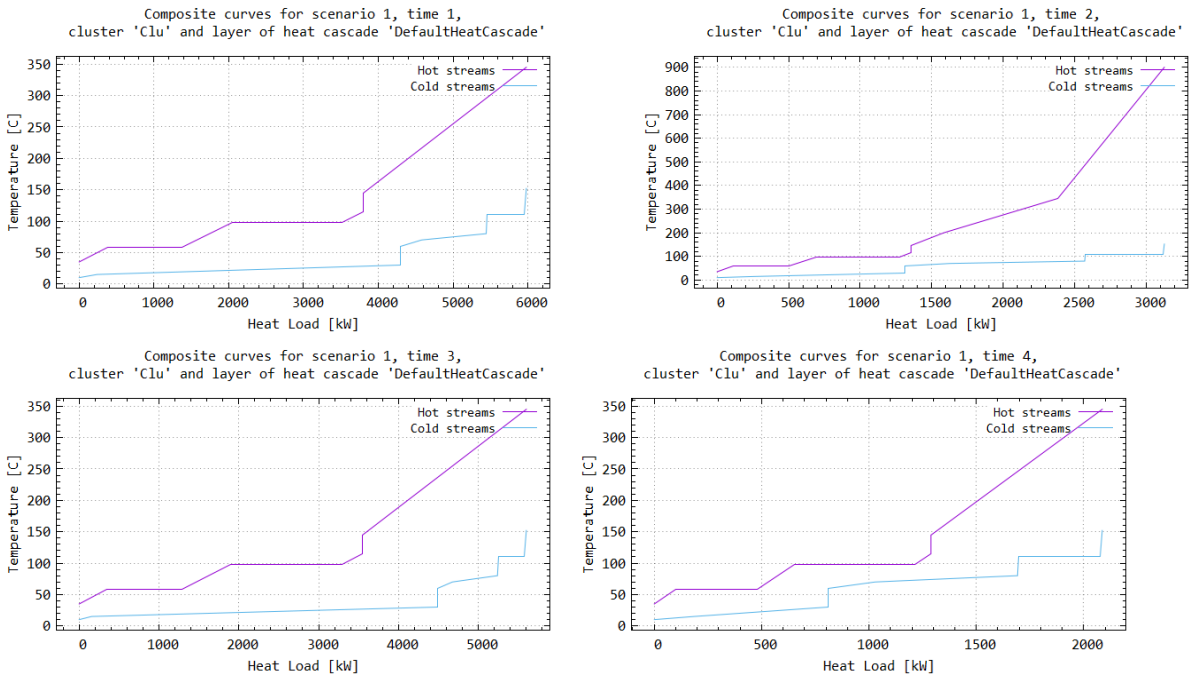


Figure 6: Application of pinch analysis to the case study

- Spring day, port

The composite curves for these operational conditions are represented in Figure 6. From their analysis we can observe that in most operational conditions there is a large temperature gap between the heat sources and the heat demand. This suggests that, although part of the heat is already recovered, there is potential for improving the heat integration within the system.

Type of WHR system	p_{con}	p_{eva}	dT_{sh}	Savings
Steam (cogen)	1.7	20	125	3.5%
Steam (power)	0.2	9	164	4.8%
ORC (ethanol)	0.2	60	100	6.9%

Table 2: Results of the analysis for different types of WHR system. Savings are compared with no WHR

5.2 Ship with Diesel engines + WHR

The analysis of the composite curves presented in the previous section highlighted the presence of a potential for a more efficient use of the waste heat available on board.

In most studies related to the application of WHR to ship energy systems, the designer makes a choice a priori about what sources are available for the conversion to electricity (see, for instance, [1] and [36]). This practice is justified in most cases for merchant ships, where the heat demand on board is limited. In the case of cruise ships, however (and particularly of the one considered in this study, that operates in relatively cold areas), there is a significant demand of heat that is today mostly fulfilled using the waste heat from the engines, and is hence competing with the conversion to electricity.

In this case, the use of process integration can help to identify the best choice of utilities and the most convenient choices for the heat exchanges among different utilities and processes. As shown in the previous section, the ship energy systems are already designed to recover most of the high-grade waste heat. In this case, the advantages of using heat-to-power WHR systems are not fully clear, while there is evidence of a potential for improving the efficiency of the system by making larger use of low-temperature heat

To test this hypothesis, this work included the test of optimization-based proces integration techniques for the design of a heat-to-power WHR system on board. This included the following, alternative options:

- A steam-based Rankine cycle in cogeneration mode (with condensation pressure above the maximum required temperature of the heat demand)
- A steam-based Rankine cycle optimized for maximum power output
- An ORC with ethanol as working fluid

The assumption of not limiting the heat exchange between the different parts of the system was made. While this is not entirely realistic, it allows to identify the maximum potential for energy efficiency on board, which can then be used as reference.

The results are shown in Table 2 and in Figure 7, where the chosen operating conditions in terms of condensation pressure, evaporation pressure and superheating temperature are shown. It can be observed that the ethanol-based ORC performs remarkably better than the alternatives, with an estimated 6.9% fuel savings over one year of operations compared to the 4.8% of the steam-based Rankine cycle. It should be noted that, on the other hand, the steam-based system operates at a much lower pressure, and using a completely unhazardous and non-flammable working fluid.

In the ORC case, although ethanol was identified as one of the most realistic fluids for these applications [36], the high required operational pressure (60 bar) and its flammability imply that it might not be possible to locate the exchange surfaces in direct contact with the exhaust gas.

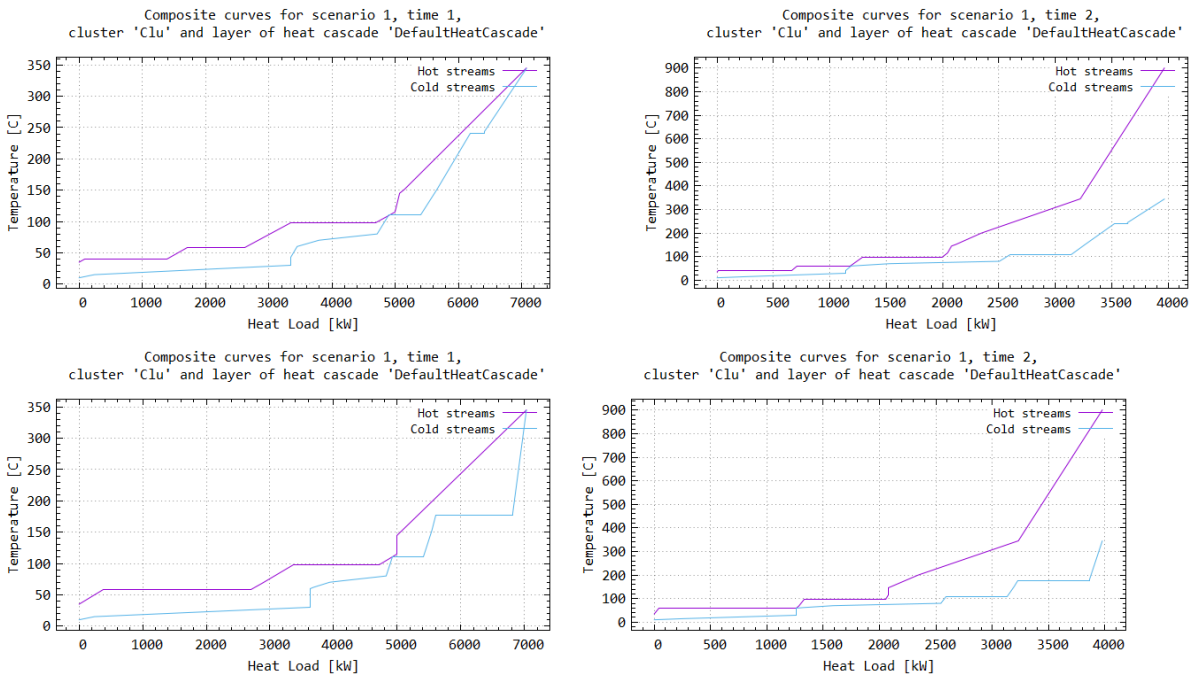


Figure 7: Composite curves for the case study in presence of a heat-to-power WHR system. The top row refers to the case of a conventional Rankine cycle, while the bottom row refers to the case of an ORC

The composite curves for winter operational conditions for the ORC (ethanol) and the Steam (power) cases are shown in Figure 7. Here it can be observed that the composite curves are closer together in the sailing cases compared to the port cases. This is due to the choice of optimizing the WHR operating temperatures and pressures to one single value for the entire operational profile. When in port, the use of boilers is required, and heat at higher temperature is available, thus suggesting that, in these conditions, a higher evaporation pressure and superheating temperature could be achieved. It should be noted, however, that the amount of energy available in port is substantially lower than during sailing, end the lost potential due to this simplification of the optimization would not substantially affect the total potential savings.

5.3 Ship with Fuel cells

As presented in Section 2.1 fuel cells represent an innovative technology that shows the potential to lead to significant reductions in emissions of ship energy systems. Part of the project, hence, dealt with understanding what are the potential benefits resulting from an extensive application of fuel cells on board of a ship.

Given the difficulty of using hydrogen as ship fuel, in particular with relation to its low energy density, the core of this work focused on the use of SOFCs as main energy conversion unit, particularly because of their potential of using natural gas as fuel, either directly or with an intermediate reforming stage, without the need for high-purity hydrogen of PEMFCs.

The results show that for the selected case study, the use of fuel cells can lead to a reduction of up to 25% of ship direct emissions, when compared to the use of Gas engines, in addition to the benefits earned from the use of natural gas as fuel when compared to Diesel-type fuels. This emission reduction is, however, achieved at a much higher investment cost when compared to the standard (gas engines) solution: more than twice more expensive. When aiming for a

more cost-competitive solution, it can be shown that while only marginally increasing the total annaualized cost (+3.3%) it is possible to reduce emissions by approximately 12% thanks to an extensive use of SOFCs in the on board energy generation

In this case, the investment costs are dominated by three items:

- The gas turbine, which is required to have a high design power as a consequence of the requirement for the ship to be able to deliver, even if for short periods, a very high eletric power for high-speed propulsion.
- The SOFC, mostly as a consequence of the high cost per kW of this component (it should be noted that the annualized investment cost is almost the same for the SOFC and the gas turbine, while the latter has an installed power more than twice as large as the SOFC).
- The batteries, which are needed to respect the constraint of the SOFC being on at all times. It should be noted that, even if there's no shore connection included in the concept and, hence, batteries do not have any net contribution to the ship's energy demand, they account for the largest share of the costs in this scenario.

From the above, it appears that failing to include operational limits of SOFCs in such an optimization problem would lead to a substantial underestimation of the investment costs, with the consequent strong risk of converging to a sub-optimal design solution.

In this project, we proposed one conceptual alternative for mitigating the high investment costs for energy storage required to mitigate the fluctuations in power demand. While still being based on the use of a SOFC as the main energy source of the polygeneration system, the proposed system includes in the design other systems more suitable for load following. The system hence includes:

- A SOFC, equipped with a hydrogen purification system, as the main energy source of the system
- A battery for fast transients and peak shaving
- A hydrogen storage system combined with a PEMFC for medium-slow load transients

The hybrid SOFC (H-SOFC) is the main unit of the system and is able to generate both electrical power and waste heat for cogeneration purposes. In this paper we assume the use of the system structure proposed by [**?**]. In this configuration, the anode off-gas goes through a series of steps: a two-stage water-gas shift (WGS) reactor to enhance the hydrogen content, and a pressure swing absorption (PSA) unit for achieving high H_2 purity. The purified hydrogen flow from the PSA is pressurized and stored in hydrogen storage tanks. The unreacted gas after the PSA is combusted and the generated heat is recovered both internally and for onboard heat demand. The prence of a burner, that can run directly on the inlet natural gas feed, ensures the heat balance of the system at all times. In addition to the electric power and hydrogen output, the H-SOFC also provides waste heat for cogeneration purposes, coming from the cooling of the anode gas between the two WGS reactors ($\dot{Q}_{\mathrm{H-SOFC,WGS}}$) and from the cooling of the exhaust gas ($\dot{Q}_{\mathrm{H-SOFC,WGS}}$) of the burner.

The results of the use of this system are shown in Figures XX to XX. As the round-trip efficiency of the hydrogen storage is lower compared to that of electric storage, the overall fuel consumption is marginally higher, as shown by the higher operational costs, although this largely depends on the choice of the units providing the power for peak demands. However, the major improvement of the selected system can be seen in the reduction of the investment cost, both of the SOFC and of the batteries.

It should be mentioned that the results largely depend on the assumptions for specific investment costs of the different units, and particularly of the SOFC and of the batteries. The specific investment cost for batteries was 300 EUR/kWh in REF and approximately 950 EUR/kWh in REF. Similarly, the cost for the SOFC was assumed to be approximately 2200 EUR/kW in REF and 1500 EUR/kW in REF. These differences, a result of the high uncertainty on current and future prices for these fast-developing markets, can be observed in the difference in the results presented in the two papers. It should be noted, however, that while the specific numbers are different, the overall trend is similar: in both cases, the use of the proposed hybrid system allows mitigating the high investment cost of the SOFC and of the batteries, regardless of the operational costs.

As the investment costs of SOFCs and batteries are expected to decrease even further in the future, the optimal solution might change as a result of these new boundary conditions to be taken into account. The effect of the evolution of the SOFC technology might also sufficiently reduce the start-up time to the point of eliminating the need of keeping them constantly running, and hence dramatically reduce the need for energy storage. This does not influence however the conclusions of this study: if the results of the optimization are to be realistic and trustworthy, these aspects need to be taken into account.

5.4 Optimal control

In the case of energy storage, the linear optimization problem includes the optimization of the state of charge of the storage (batteries, hydrogen storage, etc.) at any given time step of the optimization problem. This state of charge, together with the operating power of all utilities is optimized in a single optimization process, hence based on the assumption that the operations of the ship are known from the beginning.

This can be considered a strong assumption, depending on the type of ship and, more particularly, how predictable its operations are. In the case of the ship that was taken into account in this study, the ship operates according to daily cruises that are, apart from a few exceptions, repeated every day in a very similar manner. In the second part of the project, a simple predictive control system was developed to investigate how deviations from the scheduled operations would impact the efficiency of a hybrid propulsion system.

The EMS proposed in this paper is made of an offline and an online control layer. The offline layer refers to the computations which take place before starting any new cycle and is further subdivided into three main interconnected parts:

Clustering : Past operational data are used to provide an estimation for the upcoming operation based on the analysis of past measured operational profiles. This is done using clustering algorithms, such as k-means and k-medoids.

Segmentation : Clustered data are simplified using an adaptive piecewise constant approximation (APCA) to reduce the dimensionality of the data-set. This is done to reduce the computational time in the optimization section.

Optimization : The segmented profile sent to a MILP optimizer with the aim of identifying the optimal power share for the upcoming operational cycle.

In the online layer of the EMS, the information of the optimal state of charge (SOC) of the ESS is sent to the control system of the ESS and used as a reference value in a proportional-integral (PI) controller. The scheme of the proposed EMS is shown in figure 8.

The results of this investigation were that the proposed control system, despite its relative simplicity, was able to perform convincingly also with relatively large variations from the "average" cycle: in almost all the investigated cases the actual consumption was less than 10% worse

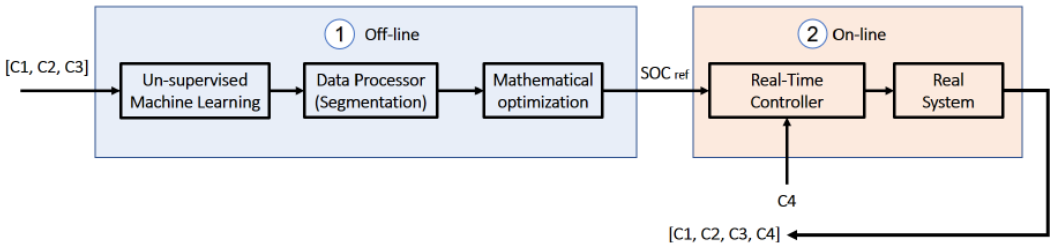


Figure 8: Scheme of the EMS proposed in the second part of the project

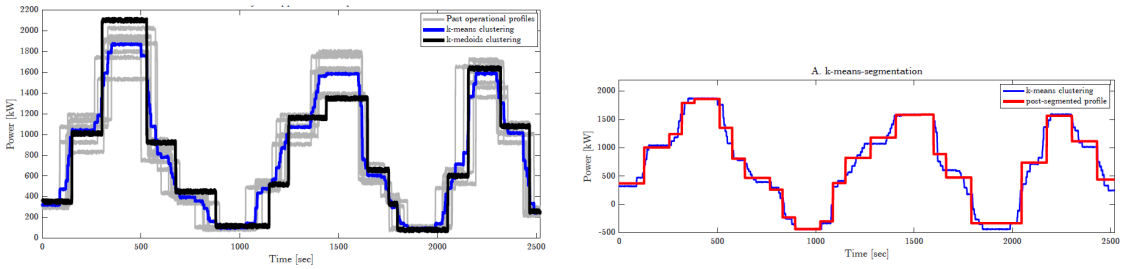


Figure 9: Example of the clustering and segmentation process

Variation	5 cycles		10 cycles	
	k-means	k-medoids	k-means	k-medoids
Time variation				
5%	97.6%	96.6%	98.7%	96.7%
10%	96.4%	94.0%	98.0%	96.3%
20%	93.3%	94.2%	97.2%	90.2%
Power variation				
5%	98.7%	99.3%	95.9%	96.5%
10%	97.8%	97.5%	99.2%	99.2%
20%	98.2%	96.4%	98.1%	98.9%
Time and power variation				
5%	96.2%	94.5%	97.3%	96.1%
10%	96.0%	91.8%	97.8%	95.1%
20%	97.4%	93.8%	98.0%	87.5%
Time and power variation in presence of noise				
5%	95.5%	95.0%	99.0%	94.7%
10%	97.0%	93.8%	98.6%	93.7%
20%	96.3%	89.7%	99.0%	98.0%

Table 3: Ideal versus real controller, comparison of the K-medoids and the K-means algorithms

when compared to the one achieved when full knowledge of the operational cycle was available. Particularly, the control system based on the K-medoids clustering algorithm (see Table 3 for more detailed results) consistently performed with a loss of efficiency lower than 5%.

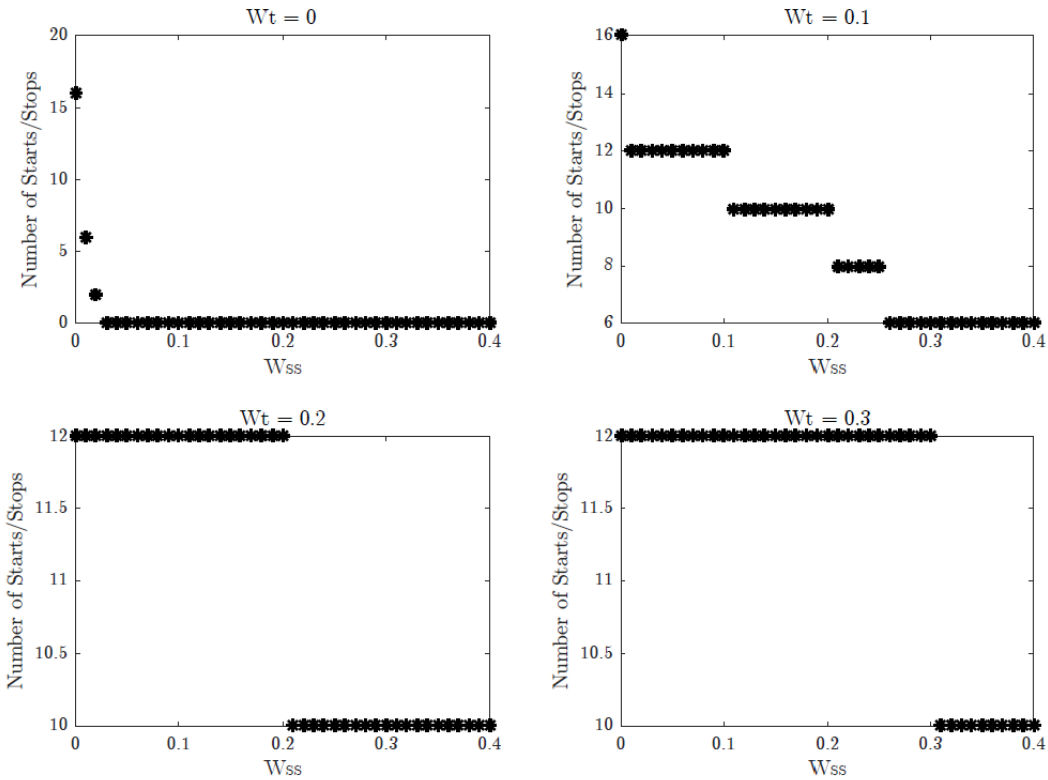


Figure 10: Effect of weight factors on the number of engine starts and stops

The controller also included elements for the penalization of the number of start-ups and stops of the engines, that are considered to be detrimental to the durability of the engines. The results are shown in Figure 10, providing evidence that additional operational elements, not necessarily connected to the minimization of fuel consumption, can be included in the controller.

These results allowed to conclude that, at least in the case of cyclical operations, it is reasonable to assume that the results of an optimization based on the full knowledge of the operational cycle can be considered as representative of the actual operations of the system. These results are also confirmed by other similar efforts in the literature, such as [25].

6 Acknowledgments

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References

[1] Fredrik Ahlgren, Maria E. Mondejar, Magnus Genrup, and Marcus Thern. Waste heat recovery in a cruise vessel in the Baltic Sea by using an Organic Rankine Cycle: A case study. *Journal of Engineering for Gas Turbines and Power*, 138(1):011702, 2016.

[2] J. Ahn, S.H. Park, Y. Noh, B.I. Choi, J. Ryu, D. Chang, and K.L.M. Brendstrup. Perfor-

mance and availability of a marine generator-solid oxide fuel cell-gas turbine hybrid system in a very large ethane carrier. *Journal of Power Sources*, 399:199–206, 2018.

[3] M. A. Ancona, F. Baldi, M. Bianchi, L. Branchini, F. Melino, A. Peretto, and J. Rosati. Efficiency improvement on a cruise ship: Load allocation optimization. *Energy Conversion and Management*, 164:42–58, May 2018.

[4] A. Armellini, S. Daniotti, P. Pinamonti, and M. Reini. Evaluation of gas turbines as alternative energy production systems for a large cruise ship to meet new maritime regulations. *Applied Energy*, 211:306–317, February 2018.

[5] Cruise Lines International Association. 2018 Cruise Industry Outlook. Technical report, 2017.

[6] F. Baldi, F. Maréchal, and K. Tammi. Process integration as a tool for the improvement of cruise ships energy efficiency. In *Proceedings of the Shipping in Changing Climate Conference*, London, United Kingdom, September 2017.

[7] Francesco Baldi, Fredrik Ahlgren, Francesco Melino, Cecilia Gabrielii, and Karin Andersson. Optimal load allocation of complex ship power plants. *Energy Conversion and Management*, 124:344–356, September 2016.

[8] Francesco Baldi, Fredrik Ahlgren, Tuong-Van Nguyen, Marcus Thern, and Karin Andersson. Energy and Exergy Analysis of a Cruise Ship. *Energies*, 11(10):2508, September 2018.

[9] Francesco Baldi, Ulrik Larsen, and Cecilia Gabrielii. Comparison of different procedures for the optimisation of a combined Diesel engine and organic Rankine cycle system based on ship operational profile. *Ocean Engineering*, 110:85–93, December 2015.

[10] Francesco Baldi, Ligang Wang, and Francois Maréchal. Integration of solide oxide fuel cells in cruise ship energy systems. Guimaraes, Portugal, 2018.

[11] Francesco Baldi, Ligang Wang, Mar Pérez-Fortes, and François Maréchal. A Cogeneration System Based on Solid Oxide and Proton Exchange Membrane Fuel Cells With Hybrid Storage for Off-Grid Applications. *Frontiers in Energy Research*, 6, 2019.

[12] S Bengtsson, K Andersson, and E Fridell. A comparative life cycle assessment of marine fuels: liquefied natural gas and three other fossil fuels. *Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment*, 225(2):97–110, May 2011.

[13] BMI. Manufacturing cost analysis of 100 and 250 kW fuel cell systems for primary power and combined heat and power applications. Technical Report DOE Contract No. DE-EE005250, Battelle, 2016.

[14] Selma Brynolf, J. Fredrik Lindgren, Karin Andersson, Magda Wilewska-Bien, Francesco Baldi, Lena Granhag, Hannes Johnson, Philip Linné, Erik Svensson, and Maria Zetterdahl. Improving Environmental Performance in Shipping. In *Shipping and the Environment*, pages 399–418. Springer, 2016.

[15] Annamaria Buonomano, Francesco Calise, Massimo Dentice d'Accadia, Adolfo Palombo, and Maria Vicidomini. Hybrid solid oxide fuel cells–gas turbine systems for combined heat and power: A review. *Applied Energy*, 156:32–85, October 2015.

[16] Fabio Burel, Rodolfo Taccani, and Nicola Zuliani. Improving sustainability of maritime transport through utilization of Liquefied Natural Gas (LNG) for propulsion. *Energy*, 57:412–420, August 2013.

[17] G. Cinti, G. Discepoli, E. Sisani, and U. Desideri. SOFC operating with ammonia: Stack test and system analysis. *International Journal of Hydrogen Energy*, 41(31):13583–13590, 2016.

[18] George G. Dimopoulos and Christos A. Frangopoulos. Synthesis, design and operation optimization of the marine energy system for a liquefied natural gas carrier. *International Journal of Thermodynamics*, 11(4):203–211, 2008.

[19] George G. Dimopoulos, Chariklia A. Georgopoulou, and Nikolaos MP Kakalis. The introduction of exergy analysis to the thermo-economic modelling and optimisation of a marine combined cycle system. In *Proceedings of the 25th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems (ECOS)*, pages 26–29, 2012.

[20] George G. Dimopoulos, Iason V. Stefanatos, and Nikolaos MP Kakalis. A process modelling approach to the evaluation of ship machinery configuration alternatives of LNG carriers. *International Journal of Thermodynamics*, 19(3):146–156, 2016.

[21] B. Dziurdzia, Z. Magonski, and H. Jankowski. Commercialisation of Solid Oxide Fuel Cells - Opportunities and forecasts. volume 104, 2016.

[22] M.C. Díaz-de Baldasano, F.J. Mateos, L.R. Núñez-Rivas, and T.J. Leo. Conceptual design of offshore platform supply vessel based on hybrid diesel generator-fuel cell power plant. *Applied Energy*, 116:91–100, 2014.

[23] Eke Eijgelaar, Carla Thaper, and Paul Peeters. Antarctic cruise tourism: the paradoxes of ambassadorship, "last chance tourism" and greenhouse gas emissions. *Journal of Sustainable Tourism*, 18(3):337–354, April 2010.

[24] C. Ezgi, M.T. Çoban, and Ö. Selvi. Design and thermodynamic analysis of an SOFC system for naval surface ship application. *Journal of Fuel Cell Science and Technology*, 10(3), 2013.

[25] R.D. Geertsma, R.R. Negenborn, K. Visser, and J.J. Hopman. Design and control of hybrid power and propulsion systems for smart ships: A review of developments. *Applied Energy*, 194:30–54, May 2017.

[26] H. Ghezel-Ayagh, S. Jolly, K.E. Davis, M. Lukas, J. Nagar, C. Willman, C. Howard, M. DiNitto, M. Pastula, B. Nuttall, and O. Grande. Air-independent hybrid SOFC-battery energy system for undersea vehicles. volume 56, pages 23–28, 2013.

[27] H. Ghezel-Ayagh, S. Jolly, R. Sanderson, J. Hunt, K.E. Davis, M. Lukas, C. Willman, and C. Howard. Hybrid SOFC-battery power system for large displacement unmanned underwater vehicles. volume 51, pages 95–101, 2013.

[28] H. Ghezel-Ayagh, S.T. Junker, J.A. Peters, T.F. Miller, J. Martin, and D. Lowe. Development of solid oxide fuel cell power systems for underwater applications. volume 12, pages 707–711, 2008.

[29] Mirko Grljušić, Vladimir Medica, and Gojmir Radica. Calculation of Efficiencies of a Ship Power Plant Operating with Waste Heat Recovery through Combined Heat and Power Production. *Energies*, 8(5):4273–4299, May 2015.

[30] Costante Mario Invernizzi. *Closed power cycles: thermodynamic fundamentals and applications*. Number 11 in Lecture notes in energy. Springer, London, 2013. OCLC: 873385178.

[31] IPCC. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Technical report, IPCC, Geneva, Switzerland, 2014.

[32] Zhenzhong Jia, Jing Sun, Herb Dobbs, and Joel King. Feasibility study of solid oxide fuel cell engines integrated with sprinter gas turbines: Modeling, design and control. *Journal of Power Sources*, 275:111–125, February 2015.

[33] Jiří Jaromír Klemeš, editor. *Sustainability in the process industry: integration and optimization*. Green manufacturing & systems engineering. McGraw-Hill, New York, 2011. OCLC: ocn656213162.

[34] Jiří Jaromír Klemeš and Zdravko Kravanja. Forty years of Heat Integration: Pinch Analysis (PA) and Mathematical Programming (MP). *Current Opinion in Chemical Engineering*, 2(4):461–474, November 2013.

[35] Jiří Jaromír Klemeš and Petar Sabev Varbanov. Heat integration including heat exchangers, combined heat and power, heat pumps, separation processes and process control. *Applied Thermal Engineering*, 43:1–6, October 2012.

[36] Ulrik Larsen, Leonardo Pierobon, Fredrik Haglind, and Cecilia Gabrielii. Design and optimisation of organic Rankine cycles for waste heat recovery in marine applications using the principles of natural selection. *Energy*, 55:803–812, June 2013.

[37] B. Linnhoff and E. Hindmarsh. The pinch design method for heat exchanger networks. *Chemical Engineering Science*, 38(5):745–763, 1983.

[38] George A. Livanos, Gerasimos Theotokatos, and Dimitrios-Nikolaos Pagonis. Techno-economic investigation of alternative propulsion plants for Ferries and RoRo ships. *Energy Conversion and Management*, 79:640–651, March 2014.

[39] MEPC. Meeting Summary of the Marine Environment Protection Committee (MEPC), 72nd Session. Technical Report, Maritime Environmental Protection Committee (MEPC), part of the International Maritime Organisation (IMO), London, United Kingdom, 2018.

[40] M. E. Mondejar, J. G. Andreasen, L. Pierobon, U. Larsen, M. Thern, and F. Haglind. A review of the use of organic Rankine cycle power systems for maritime applications. *Renewable and Sustainable Energy Reviews*, 91:126–151, August 2018.

[41] P. Nehter, B. Wildrath, A. Bauschulte, and K. Leites. Diesel based SOFC demonstrator for maritime applications. volume 78, pages 171–180, 2017.

[42] D.J. Palmer and W.J. Sembler. Environmentally friendly very large Crude carriers. *Journal of Ocean Technology*, 4(3):73–90, 2009.

[43] J. Rechberger, R. Schauperl, J.B. Hansen, and P.K. Larsen. Development of a methanol SOFC APU demonstration system. volume 25, pages 1085–1092, 2009.

[44] R. E. Rosli, A. B. Sulong, W. R. W. Daud, M. A. Zulkifley, T. Husaini, M. I. Rosli, E. H. Majlan, and M. A. Haque. A review of high-temperature proton exchange membrane fuel cell (HT-PEMFC) system. *International Journal of Hydrogen Energy*, 42(14):9293–9314, April 2017.

[45] E. Sadeghinezhad, S. N. Kazi, Foad Sadeghinejad, A. Badarudin, Mohammad Mehrali, Rad Sadri, and Mohammad Reza Safaei. A comprehensive literature review of bio-fuel performance in internal combustion engine and relevant costs involvement. *Renewable and Sustainable Energy Reviews*, 30:29–44, February 2014.

[46] Gunter Sattler. Fuel cells going on-board. *Journal of Power Sources*, 86(1):61–67, March 2000.

[47] T W P Smith, J P Jalkanen, B A Anderson, J J Corbett, J Faber, S Hanayama, and Et Al. Third IMO GHG Study. Technical report, International Maritime Organisation, London, UK, 2014.

[48] Marco Soffiato. Design and performance evaluation of an Organic Rankine Cycle system exploiting the low grade waste heat of the main engines in a LNG carrier. 2014.

[49] Siri Solem, Kjetil Fagerholt, Stein Ove Erikstad, and Øyvind Patricksson. Optimization of diesel electric machinery system configuration in conceptual ship design. *Journal of Marine Science and Technology*, 20(3):406–416, September 2015.

[50] Maria Taljegard, Selma Brynolf, Maria Grahn, Karin Andersson, and Hannes Johnson. Cost-Effective Choices of Marine Fuels in a Carbon-Constrained World: Results from a Global Energy Model. *Environmental Science & Technology*, 48(21):12986–12993, November 2014.

[51] Gerasimos Theotokatos and George Livanos. Techno-economical analysis of single pressure exhaust gas waste heat recovery systems in marine propulsion plants. *Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment*, 227(2):83–97, May 2013.

[52] L. van Biert, M. Godjevac, K. Visser, and P.V. Aravind. A review of fuel cell systems for maritime applications. *Journal of Power Sources*, 327:345–364, September 2016.

[53] J. Van Herle, Y. Membrez, and O. Bucheli. Biogas as a fuel source for SOFC co-generators. *Journal of Power Sources*, 127(1-2):300–312, 2004.

[54] Wolf Vielstich, Hubert A. Gasteiger, and Harumi Yokokawa. *Handbook of Fuel Cells: Fundamentals Technology and Applications: Advances in Electrocatalysis, Materials, Diagnostics and Durability.* John Wiley & Sons, 2009. Google-Books-ID: qG7VeAB94u4C.

[55] Yuedong Zhan, Youguang Guo, Jianguo Zhu, and Hua Wang. Intelligent uninterruptible power supply system with back-up fuel cell/battery hybrid power source. *Journal of Power Sources*, 179(2):745–753, May 2008.