PROCESS INTEGRATION AS A TOOL FOR THE IMPROVEMENT OF CRUISE SHIPS ENERGY EFFICIENCY

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ABSTRACT

The growing trend of the cruise ship industry, together with increasing concerns over its impact on the environment, makes these ships a much relevant target for efforts toward increasing ship energy efficiency, thus ultimately reducing fuel consumption and emissions of carbon dioxide and other air pollutants.

In this work, we propose the application of process integration methods to the case of a cruise ship operated in the Baltic Sea. Given the basic energy demand of the ship and its expected operational profile, we optimize the design and operations of its power plant.

The results of the application of process integration show that, for the specific case of interest:

- A larger number of engines (8), subdivided in two different sizes, allows reducing fuel consumption by up to 3% when compared to a smaller number (4) of equally sized engines.
- The application of pinch analysis allows identifying potential for heat integration within the system, and particularly shows how the exhaust gases provide a particularly significant potential for improved use on board.
- The installation of a waste heat recovery system allows to achieve savings of up to 4.8% for a steam-based Rankine cycle and of up to 6.9% for an organic Rankine cycle based on ethanol as a working fluid
- Using batteries for engine load levelling as a potential of up to 1.6% fuel savings.

Keywords: process integration, energy efficiency, heat integration, linear programming

1. INTRODUCTION

The challenge of ensuring progress in society while reducing the impact of human activities on the environment has gained a strong relevance in the latest years. As in the case of other industries, society is asking the shipping sector to improve its sustainability and, hence, to reduce its emissions of gases that contribute to the greenhouse effect. Cruise ships are a particular relevant case, given the growing trend of the business, the high-energy requirements and the complexity of the power plant.

Although cruise ships are already in the top end of the scale in terms of the efficiency of marine power plants, there is still potential for improvement. The design and operations of the ship's power plant, with particular reference to the optimal management of the waste heat from the engines, is a subject that has proven to be of particular relevance (Baldi, 2015a; Baldi, 2015b).

Process integration includes a number of tools and methods used to improve the efficiency of energy systems. 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. 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 (Linhoff, 1983), 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 (Klemes, 2011).

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* (Klemes, 2013).

In this paper, we propose the application of process integration to the optimization of the design and the operations of a cruise ship.

2. METHODOLOGY

In process integration, units are divided among processes and utilities.

- **Processes** represent the fixed demands of the system, and are not associated to any optimization parameters
- **Utilities**, on the other hand, might or might not be used, and their operational mode is a result of the optimization procedure.

As a representative example, the propeller can be considered a process (propulsion power) while the engine functions as a utility (provides propulsion power to the propeller). Consequently, only defining variables related to utilities are considered as optimization parameters.

2.1 OVERALL APPROACH

The basis of the problem is presented as a mixed integer-linear programming (MILP) problem, where the main optimization parameters are:

- The choice of the installation of a unit (one variable per unit)
- The design size of a unit (one variable per unit)
- The choice of the use of a unit (one variable per unit and per time step)
- The operating load of a unit (one variable per unit and per time step)

The problem is defined as a multi-period MILP with 48 time steps, referring to four typical days (one for each season), each subdivided in 12 time steps of variable length. The MILP is defined within the Osmose (Boiliger, 2010; Tock, 2013) modelling framework in AMPL language (Fourer, 2002) and solved using the CPLEX solver. Each run of the MILP optimization required 5-10 seconds for convergence depending on the number and type of components included on a Dual core Intel i7-6600U 2.6 GHz processor.

2.2 UNIT MODELS – PROCESSES

The energy demand is defined in the form of four typical days optimized based on the energy analysis of the selected case study as described in previous work by the authors (Baldi, 2015b) and is represented in Figure 1. It should be noted that, although the heat demand is here represented in aggregated form, it is constituted of a number of different users requiring heat at different temperatures. In an optimization based on process integration, the temperature of heat streams is fundamental for a correct integration between different streams. The inlet and outlet temperatures of all the heat flows are summarized in Table 1.

Table 1: Cold stream list with inlet and outlet temperatures

Heat flow	T_{in}	T_{low}
Hot water heating	70	80
HVAC preheater	10	30
Fuel heating	70	150
Tank heating	60	80
Steam demand	110	110

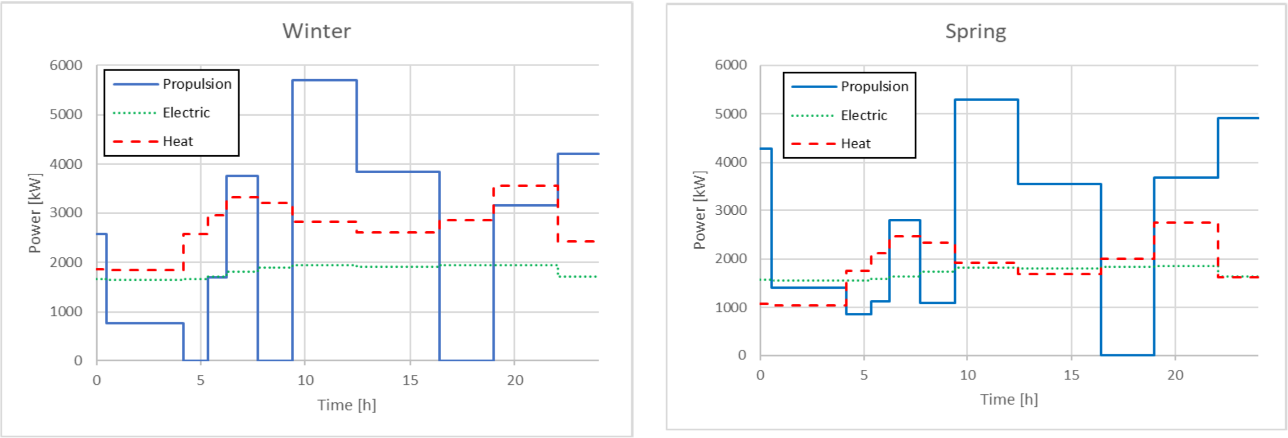
2.3 UNIT MODELS - UTILITIES

Each of the utilities that can be selected in the MILP optimization are modelled as linear components. Each component is defined by a number of streams (i.e. energy flows).

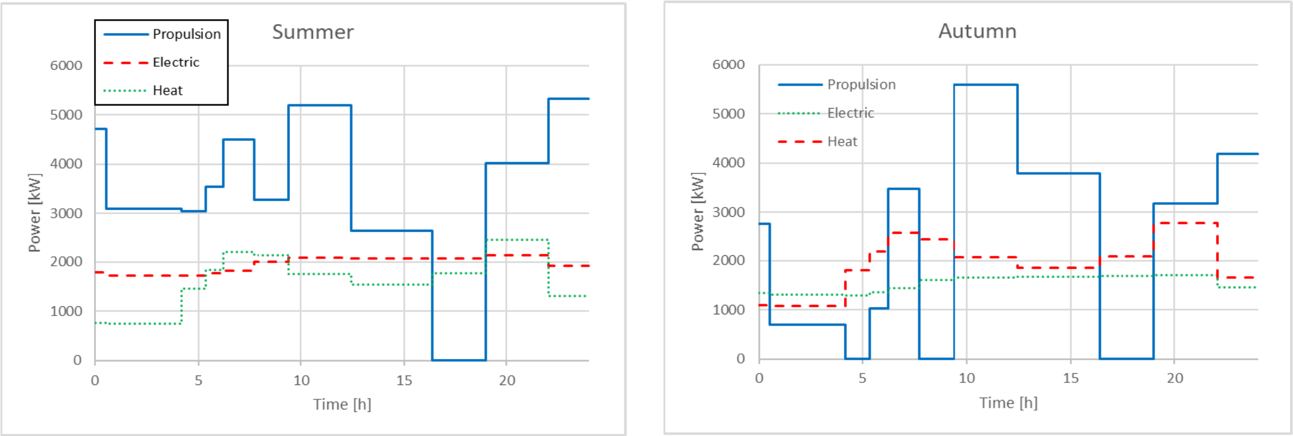
2.3(a) Diesel engines

Diesel engines are only unit on board that can provide mechanical power that is converted from an input of the form of Diesel-type fuel. Part of the energy input is rejected in the form of waste heat. The resulting streams, together with their design values and linear coefficients are provided in Table 2, while the resulting load-dependent efficiencies are represented in Figure 2. The engine minimum and maximum loads are set to 20% and 90% respectively. The values of a_0 and a_1 are used as described in Equation 1:

$$\dot{E}_i = \left(a_0 + a_1 \frac{\dot{W}}{\dot{W_{max}}}\right)\dot{E}_{i,max} \tag{1}$$



(a) Winter (b) Spring



(c) Summer (d) Fall

Figure 1: Energy demands for the four typical days

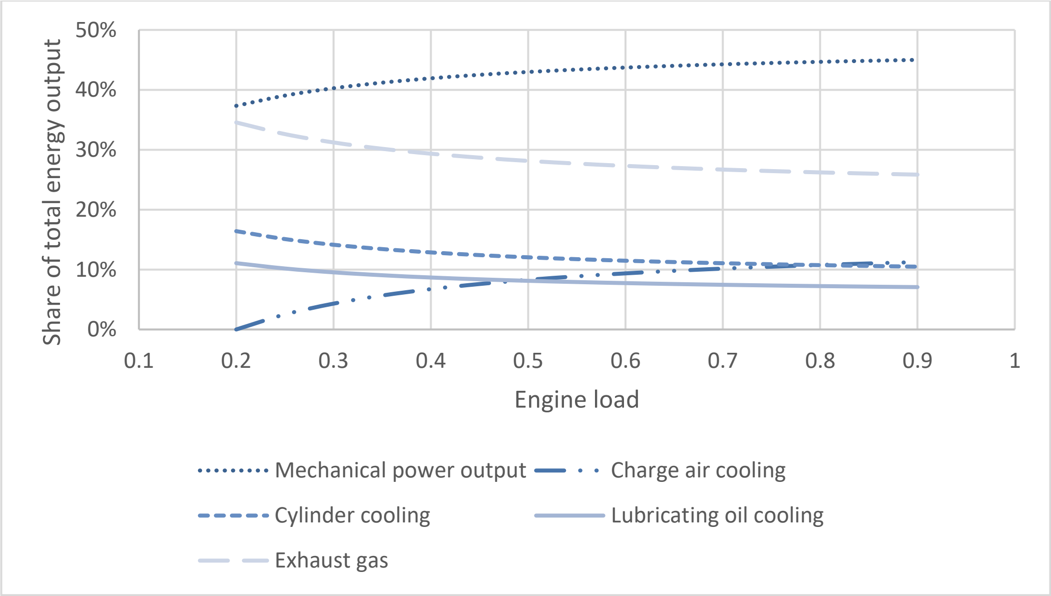


Figure 2: Share of energy output as a function of the engine load

Table 2: Model parameters for the Diesel engine model

Stream	Type	Design value	T_{in}	T_{out}	a_0	a_1
Power output	Work	0.450	-	-	0.0	1.0
Fuel input	Chemical energy	1.000	-	-	0.053	0.930
Charge air cooling	Heat	0.140	120	40	-0.20	1.0
Cylinder cooling	Heat	0.086	100	100	0.28	0.90
Lubricating oil cooling	Heat	0.058	60	50	0.28	0.90
Exhaust gas	Heat	0.270	350	160	0.15	0.79

The upper limit to the load was included since the linear form of the problem does not allow including the decreasing efficiency for higher loads. In addition, marine engines, in normal operations, are rarely operated above this load to prevent overloading. It should also be noted that some temperatures, and particularly that of the exhaust gas and of the charge air after the compressor, can change remarkably over the load range of the engines. The values provided in Table 2 are the result of a compromise between averaging between the different available temperatures, while maintaining a conservative stance as to not overestimate the potential for energy recovery.

The model was tuned based on the performance of a MaK 8M32C (MaK, 2010), and it is considered as representative of a generic 4-stroke marine Diesel engine. Although it is known to the authors that each engine has its own specific performance, it should be noted that the model efficiently catches the general trends.

2.3(b) Hot utilities

Apart from the waste heat from the engines, other utilities are included meant for providing heat for the on board energy demand.

Oil fired boilers are modelled as a utility converting fuel chemical energy to heat. The efficiency of the boiler is assumed to be equal to 0.8 as a reference value resulting from a compromise of what reported by Cohen et al. [0.83-0.89] (Cohen, 1962) and Mrzljak et al. [0.7 - 0.79] (Mrzljak, 2017). The heat flow is modelled as entirely resulting from the cooling of the exhaust gas from 900°C to 200°C. The boilers are assumed to be able to operate down to 10% of their design load.

Electric heaters are also considered as a potential alternative solution for on board heat generation, particularly because they can generate heat at constant high temperature and do not have load limitations. The electric heaters are assumed to generate heat at 95% efficiency and at a temperature of 1000°C.

Finally, heat pumps are also considered as heat sources, based on their ability of transferring heat to a higher temperature at very high efficiencies. Since the optimal condensing and evaporation temperatures are not known beforehand, we assumed a reference exergy efficiency for the generic heat pump of 40% (Hepbasli, 2010) and we derived the corresponding COP according to Equation 1:

$$\mathrm{COP} = \eta_{\mathrm{ex}} \frac{\mathrm{T_{con}}}{\mathrm{T_{con}} - T_{eva}} \tag{2}$$

2.3(c) Waste heat recovery

Rankine cycles are often used as a way to recover waste heat from other processes and convert it to electricity. In this initial study, we also wanted to test the possibility of using the models developed in this framework to integrate an (organic) Rankine cycle in the energy system, thus improving its efficiency.

As the objective of the study is not the optimization of an ORC for ship applications (for more information on the subject, see for instance (Larsen, 2013; Baldi, 2015c; Soffiato, 2015; Mondejar, 2016)), we decided to simplify the problem of the optimization of the ORC parameters by, in particular, pre-selecting an appropriate fluid for the purpose. Based on the work proposed by Larsen et al., we selected ethanol as a potential fluid (Larsen, 2014). It should be noted that, although the choice of the fluid has a rather significant impact on the performance of the system, the optimization procedure that we employed in this work can easily be adapted to other fluids.

The operating parameters of the ORC (condensation pressure, evaporating pressure, superheating temperature) cannot be optimized in the standard MILP optimization framework described in the previous part of the paper, as considering these variables as optimization parameters makes the problem nonlinear. For this reason, in the specific case of the ORC optimization, the problem was split into a master optimization (where the ORC optimization parameters are optimized) and a slave optimization (where the operational optimization parameters of the rest of the system are optimized). The master optimization is nonlinear, and solved using the Matlab in-built particle swarm optimization (PSO) solver (Mathworks, 2017), while the slave optimization, being defined as a MILP, is solved using the standard solver.

Fluid properties are calculated using Coolprop (Bell, 2014). The isentropic efficiency of the expander, the efficiency of the pump and the efficiency of the electric generator were assumed to be equal to 0.7, 0.7 and 0.95 respectively.

2.3(d) Electric energy storage

Given the relatively short operational cycle of the case study and the alternation of high and low load operations, we also tested the energy saving potential of electric energy storage. The installation of batteries on board of short-sea vessels has proven to have a potential both in academic literature (Dedes, 2012; Han, 2014; Zahedi 2014), and in practical applications (see, for instance, the applications listed on (Corvus Energy, 2017)).

In this work we modelled energy storage based on the assumption of installing lithium-ion batteries, today considered the industrial standard for this type of application. The battery is modelled as a simple input-output box. Given the well-known tendency of lithium-ion batteries to deteriorate when discharged below a certain threshold, we assumed a maximum depth of discharge of 70% (that is, the battery state of charge was only allowed to vary between 30% and 100%). In addition, we assumed 5% losses in the charge/discharge cycle to generally account for all processes causing energy losses.

Battery sizes were tested for a range between 0 and 8 MWh. It should be noted that electric energy storage installations or ships can be documented for up to more than 4 MWh (ABB, 2016).

2.3 VESSEL DESCRIPTION

The methods presented in the previous section are applied to a specific cruise ship. It is a small cruise ship/passenger ferry that operates based on daily cruises between Stockholm and the island of Åland, in the Baltic Sea. The ship is 176.9 m long 28.6 m wide and was designed for a maximum speed of 21 knots. The ship is able to accommodate up to 1800 passengers and is provided with a wide number of facilities, such as bars, restaurants, pools, saunas, and nightclubs.

The reference values for the demand of mechanical, electric and thermal power are taken from the analysis performed in (Baldi, 2015a), as can also be seen in the profile presented in previous work by the authors where we optimized the operational schedule of the vessel (Baldi, 2016).

3. RESULTS AND DISCUSSION

3.1 BASE DESIGN OPTIMIZATION – ENGINE CONFIGURATION

The first step of the optimization aimed at defining the sizing of the engines. It was assumed, in this part of the problem, that the system is designed as a fully Diesel-electric system, where all engines are equipped with an electric generator, and the propellers are provided the required torque by electric motors. This is a configuration frequently seen on cruise ships, as it allows combining greater flexibility, efficiency and redundancy.

The main element to be optimized in this phase was the number and size of the Diesel engines. The total installed power was calculated, for each possible configuration, as the one required by the ship in the most demanding conditions in terms of propulsion and electric power demand as recorded during 2014 (respectively 21000 kW and 5000 kW), knowing that the power plant should be able to generate this power with one engine out of order and all other engines running at 90% load. The validity of this working assumption is confirmed by the fact that the installed power on the original vessel shows to roughly follow this pattern (34000 kW).

Table 3 shows the design power of the engines and the resulting total yearly energy demand (compared to the case with four engines) for power plants based on a number from 4 to 8 engines. The results highlight how having a larger number of smaller engines results more convenient from an energy efficiency perspective. It should be noted that this result was obtained assuming that the efficiency of the engines does not depend on their size, while it is generally accepted that larger engines are more efficient. However, we estimate that the advantage generated by a more balanced load sharing among the engines is larger than the benefit related to the higher efficiency of more powerful engines.

Table 3: Results of the analysis for different numbers of equally sized engines. Savings compared to the baseline (four engines)

Number of engines	Engine power	Savings
4	9700	0.0%
5	7300	1.2%
6	5800	1.1%
7	4900	1.5%
8	4200	2.4%

In the discussion above, we assumed all engines to be of the same size. It is however not uncommon to have engines of two different sizes on board of the same vessel (albeit rarely no more than that, since every new engine model/size require a new set of spare parts that would increase costs significantly). Hence. we also tested for the influence that this assumption has on the average efficiency of the system in the case where 8 engines are installed. As shown in Table 4 the influence is small, but not negligible, and highlights how having engines of two different sizes leads to lower fuel consumption compared to have all of them of the same size. We consequently used the (3360 - 5040) configuration in the remaining part of this work. It should be also noted that the current configuration of the vessel (4x5850 and 4x2760) is not much dissimilar from the chosen combination of engine sizes.

Table 4: Results of the analysis for eight engines with two different sizes. Savings compared to the baseline (eight engines of same size)

Power share	Engine power (high)	Engine power (low)	Savings
0.5 – 0.5	4200	4200	0.0%
0.6 – 0.4	5040	3360	1.2%
0.7 – 0.3	5880	2520	1.1%
0.8 – 0.2	6720	1680	1.2%

3.2 ANALYSIS OF THE COMPOSITE CURVES

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 theory, composite curves can be plotted for each of the time steps. The detailed analysis of each of the 48 composite curves would prove challenging, both in practical terms and to represent in this paper. Hence, we will represent here only the composite curves of the system for four reference conditions:

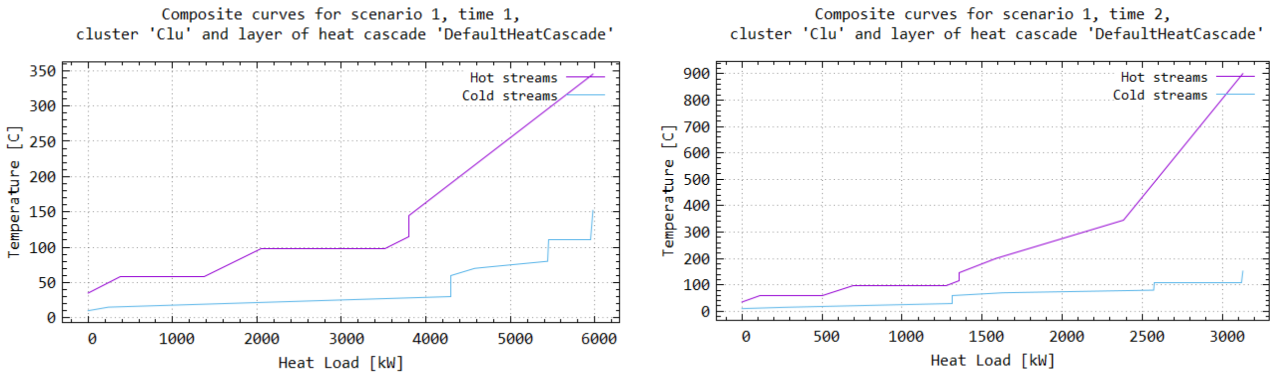
- Winter day, sailing
- Winter day, port
- Spring day, sailing
- Spring day, port

The composite curves for these operational conditions are represented in Figure 3. 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.

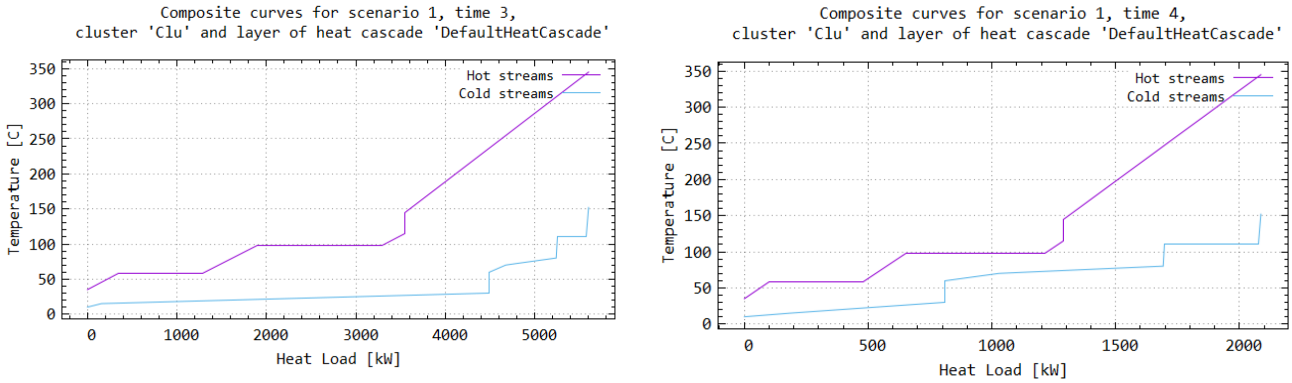
3.3 WASTE HEAT RECOVERY

Because of the results shown in the previous section, we also took into account the possibility of installing a WHR system to convert part of the high-temperature heat in the exhaust gas to electricity. We tested three main alternatives against the baseline of a system with no WHR installed:

- 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.

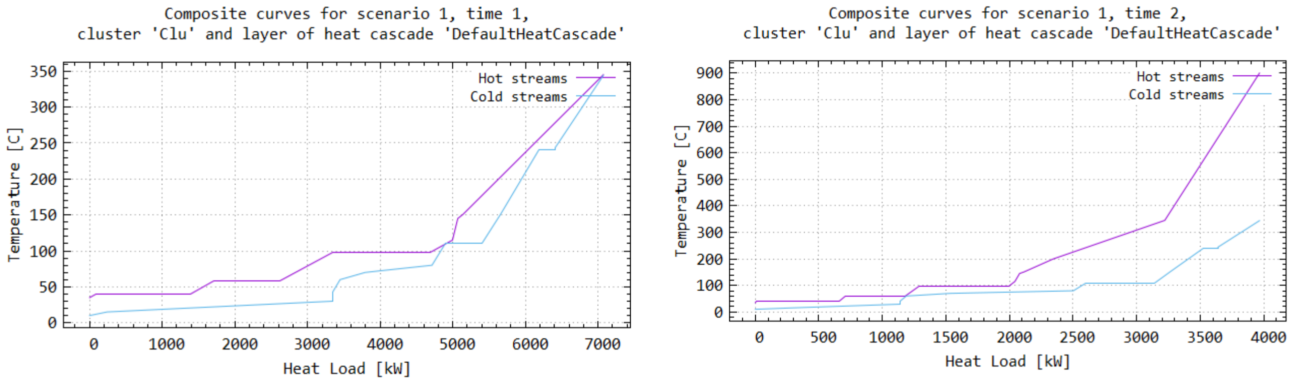


(a) Winter sailing (b) Winter port

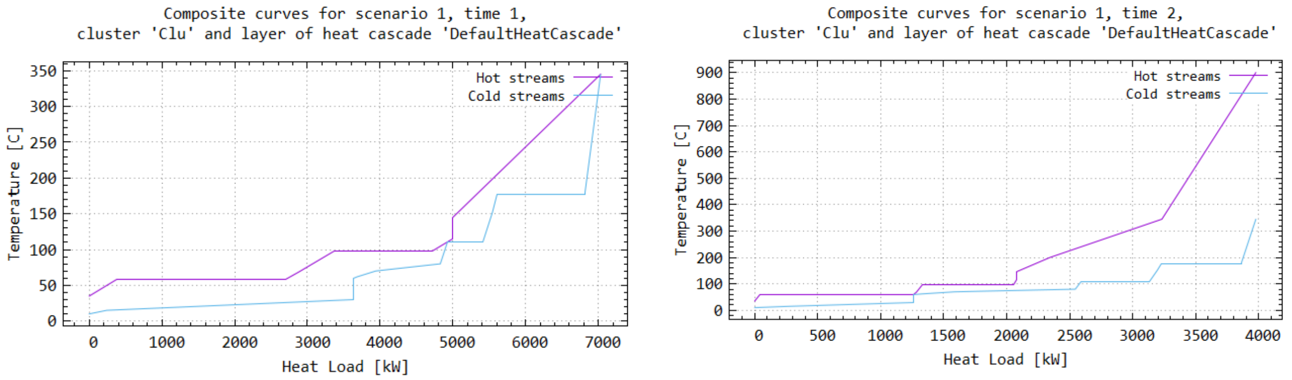


(c) Summer sailing (d) Summer port

Figure 3: Composite curves for four representative operational conditions



(a) ORC, Winter, Sailing (b) ORC, Winter, Port



(c) Steam, Winter, Sailing (d) Steam, Winter, Port

Figure 4: Composite curves for the winter representative operational conditions when the system is equipped with a WHR systems

The results are shown in Table 4, 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 (Larsen, 2014), it still would need to operate at high pressure (60 bar) and is flammable, meaning that it might not be possible to locate the exchange surfaces in direct contact with the exhaust gas.

The composite curves for winter operational conditions for the ORC (ethanol) and the Steam (power) cases are shown in Figure 4. 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.

Table 5: Results of the analysis for different numbers of equally sized engines. Savings compared to the baseline (four engines)

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%

3.4 ELECTRIC ENERGY STORAGE

The presence of large load fluctuations, particularly in the case of the propulsion power demand, suggests that the use of batteries could be beneficial towards a more uniform engine load distribution, hence allowing to operate the engines closer to the load at which they show the highest efficiency.

The results of testing the installation of electrical energy storage on the case study are shown in Figure 5. Results are shown both for the case with WHR installed (steam based, optimized for maximum power output) and without, shown as percentage savings compared to the case with no batteries installed.

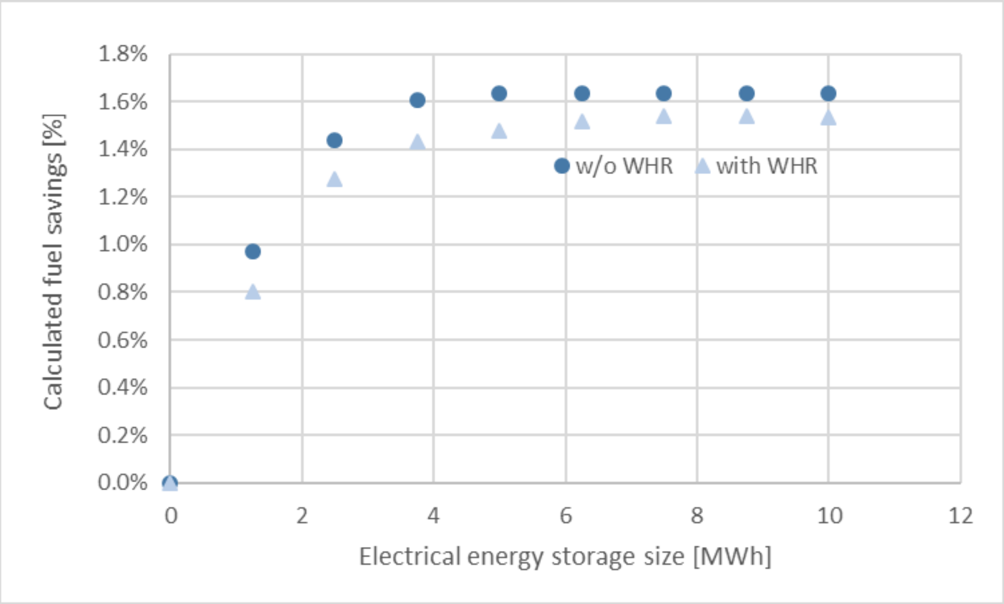


Figure 5: Estimated yearly fuel savings compared to the no-battery case for different values of the total installed battery capacity

It can be observed that the potential for savings reaches a maximum at around 4-5 MWh in both cases. However, given the large amount of engines installed and the full-electric nature of the power plant, it appears that the savings are quite limited (maximum 1.6%) and would hardly justify the purchase cost of the batteries. Other considerations, such as the prevention of harmful emissions in port, the reduced amount of engine start-ups, the decreased engine wear due to more fixed-load operations all provide additional support to the installation of batteries, but are outside the scope of this work. Also, batteries could be considered as an additional source of power, and hence the installation of batteries could be associated with a lower total installed Diesel engine power, which in turn could represent a reduction in the required investment.

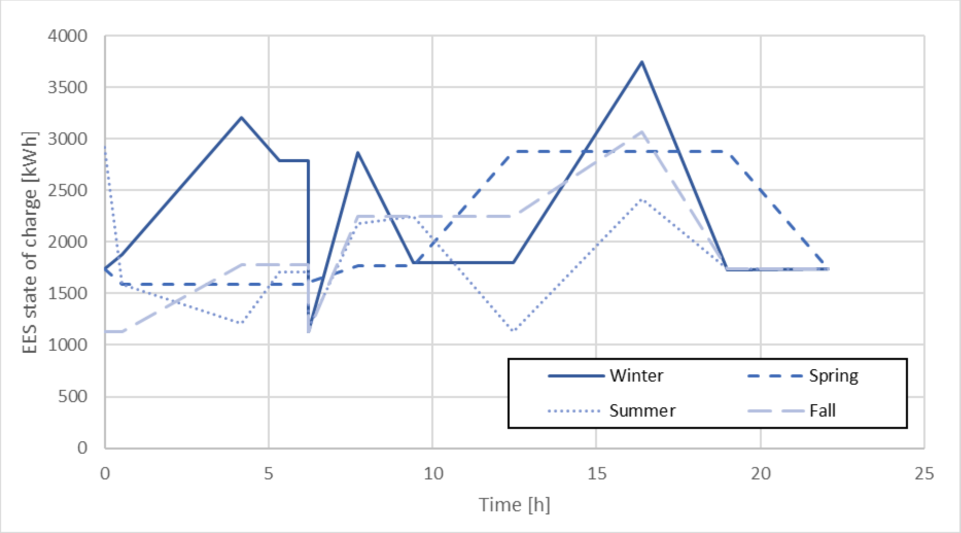


Figure 6: Evolution of the state of charge for the four reference days. Total battery capacity: 3.75 MWh, no WHR installed

4. CONCLUSIONS

In this paper, we presented the case of the application of process integration methods to the optimization of the energy system of a cruise ship. These methods were used to simultaneously optimize the design of the system and its operations.

The application of process integration proved useful as an effective and reliable way of analysing the potential for performance improvement of ship power plants and of testing the application of different technologies for improving the energy efficiency of the system under realistic operational conditions. The work presented in this paper thus aims at opening the way of using these methods for the optimization of ship power plants.

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