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# A feasibility analysis of waste heat recovery systems for marine applications

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ABSTRACT

The shipping sector is today facing challenges which require a larger focus on energy efficiency and fuel consumption. In this article, a methodology for performing a feasibility analysis of the installation of a WHR (waste heat recovery) system on a vessel is described and applied to a case study vessel. The method proposes to calculate the amount of energy and exergy available for the WHR systems and to compare it with the propulsion and auxiliary power needs based on available data for ship operational profile. The expected exergy efficiency of the WHR system is used as an independent variable, thus allowing estimating the expected fuel savings when a detailed design of the WHR system is not yet available. The use of the proposed method can guide in the choice of the installation depending on the requirements of the owner in terms of payback time and capital investment. The results of the application of this method to the case study ship suggest that fuel savings of 5%–15% can realistically be expected, depending on the sources of waste heat used and on the expected efficiency of the WHR system.



## 1. Introduction

Shipping business has been expanding almost continuously in the last decades [1], and is today responsible for between 80% and 90% of the overall global trade [2]. When we observe that today global trade, compared to 1950, is more than 100 times larger in terms of volume and value of goods transported [3], the importance and role of shipping in today's economy becomes apparent. However, shipping is now subject to important challenges. Bunker fuel prices are today three times higher than they were in the 80's [4] and fuel costs are estimated to account for between 43% and 67% of total operating costs depending on vessel type [5]. Moreover, upcoming environmental regulations on sulphur oxides, nitrogen oxides and greenhouse gases will exert an additional leverage on fuel costs [6]. This phenomenon will be more pronounced in present and future emission controlled areas, i.e. USA coastal waters, the Baltic Sea, and the North Sea, where regulations will be stricter.

Various fuel saving solutions for shipping are available and currently implemented. Operational measures include improvements in voyage execution, engine monitoring, reduction of auxiliary power consumption, trim/draft optimization, weather routing, hull/propeller polishing, slow-steaming. Design measures can relate to the use of more efficient engines and propellers, improved hull design, air cavity lubrication, wind propulsion, fuel cells for auxiliary power generation, waste heat recovery, pump frequency converters, cold ironing [6]. Several scientific studies have been conducted on these technologies, and a more detailed treatise would be out of the scope of this work, which focuses particularly on the use of WHR (waste heat recovery).

Despite their high brake efficiency Diesel engines waste large amounts of heat to the environment, especially (but not only) in the exhaust gas. Several alternative ways to recover the waste energy produced by Diesel engine on board ships have been proposed and applied in the past [7]. The focus of this paper lies however in the utilisation of WHR for the supply of mechanical/electrical power to the ship. In spite of their still rather limited application in the shipping industry, WHR systems for auxiliary power generation have been widely studied in literature. When four-stroke engines are employed, the relatively high temperature in the exhaust gas (~320 °C [8]) allows the employment of a standard steam cycle. This technology was explored, among others, by Theotokatos et al., who proposed a techno-economic evaluation of the application of a single-pressure steam cycle to bulk carriers [9] and to ferries [10]. Steam-based Rankine cycles have however been proposed also for

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**Nomenclature**

*Acronyms*

| | |
|---|---|
| AE | auxiliary engine |
| CMS | continuous monitoring systems |
| EGE | exhaust gas economiser |
| GB | gearbox |
| HT | high temperature (cooling) |
| JW | jacket water |
| LO | lubricating oil |
| LT | low temperature (cooling) |
| ME | main engine |
| ORC | Organic Rankine cycle |
| SG | shaft generator |
| SW | sea water (cooling) |
| WHR | waste heat recovery |

*Subscripts*

| | |
|---|---|
| 0 | reference conditions |
| air | air |
| Comp | compressor |
| Cool | after cooler |
| cyl | cylinder |
| eg | exhaust gas |
| in | inlet |
| max | maximum |
| out | outlet |
| prod | products |
| prop | propeller |
| S | shaft |
| Turb | turbine |

*Variables*

| | |
|---|---|
| $\beta$ | compression ratio |
| $\Delta T_{pp}$ | pinch point temperature difference [°C] |
| $\dot{m}$ | mass flow [kg/s] |
| $\dot{Q}$ | heat flow [kW] |
| $\eta$ | efficiency |
| $\eta_{en}$ | energy efficiency |
| $\eta_{ex}$ | exergy efficiency |
| $\eta_{pol}$ | polytropic efficiency |
| $\lambda$ | engine load |
| $c$ | specific heat (for liquids) [kJ/kgK] |
| $c_p$ | specific heat at constant pressure (for gases) [kJ/kgK] |
| $T_c$ | cold sink temperature [°C] |
| EX | exergy [kJ] |
| h | specific enthalpy [kJ/kg] |
| m | mass [kg] |
| N | number |
| P | power [kW] |
| s | specific entropy [kJ/kgK] |
| T | temperature [°C] |
| V | volume [$m^3$] |

application to two-stroke engines, in spite of the lower temperature of the exhaust gas after the turbocharger (~275 °C, [8]). Ma et al. proposed and evaluated a single-pressure design, both in design conditions and at part-load [11]. A detailed thermo-economic optimization of a WHR system for a two-stroke engine powered containership based on a steam cycle was proposed by Dimopoulos et al. [12], who also investigated the application of exergy analysis as a mean to improve the understanding of the combined cycle (Diesel engine and WHR system) efficiency and the optimization procedure [13]. Grimmelius et al. proposed a modelling framework for evaluating the waste heat recovery potential of Diesel engines and tested it to marine applications [14]. Steam-based WHR systems for both four- and two-stroke engines are available commercially, among others by MAN, Wärtsilä, Mitsubishi and Alfa Laval. Most of the proposed solutions also involve the use of a turbocharger bypass in connection with a power turbine, particularly effective at high engine load [12].

Organic Rankine cycles (ORCs) are considered as an alternative solution in the case of two-stroke engines given the low exhaust temperatures. ORCs are Rankine cycles employing a working fluid different from water in order to adapt evaporation and condensation temperatures to the heat source. Larsen et al. proposed a methodology for the simultaneous optimisation of the process design layout, working fluid and process parameters depending on the temperature of the heat source [15]; Choi and Kim analysed the performance of a dual-loop WHR system for a medium-sized containership under operational conditions [16], while Yang et al. analysed the performance at part-load and transient conditions for a larger vessel [17]. A comparison of conventional steam cycles with ORCs have been proposed by Hountalas et al. [18], while Larsen et al. also included Kalina cycles in the analysis [19,20]. These studies are of particular relevance since two-stroke engines are by far the most employed prime mover in the shipping industry in terms of installed power [21].

As seen in the previous paragraphs the exhaust gas is of major importance for the WHR potential of Diesel engines. Other sources of waste heat are also available, namely the cooling of combustion air after compression CAC (charge air cooling), lubricating oil, and cylinder wall cooling water JW (jacket water). The use of the exhaust gas alone is the most common configuration, and is often suggested both in scientific literature [11,15–17] and as a “baseline” case by manufacturers. The use of charge air cooling water for working fluid pre-heating is also often suggested in literature [9,10,12,14,18]. Finally, Larsen et al. and some manufacturers propose the utilisation of heat from cylinder cooling on top of charge air and exhaust gas [15,22].

With reference to different types of technologies, case studies, and designs, the previously mentioned works witness quite significant possibility for energy saving when WHR systems are employed, ranging from around 1% for single-pressure steam cycles applied to two-stroke engines [9] to more complex systems based on ORCs (up to 10% [18]) or including the cooling systems as a source for waste heat (over 10% [13]).

Despite the acknowledgement of the importance of ship operational profile on WHR systems performance, this aspect is seldom accounted for in the techno-economic or feasibility evaluation. Some of the authors do not include this part in their work [15,17,19,20]; when a techno-economic analysis is included, expected ship performance is often calculated based on a single operating point [11]. The approximation employed by Theotokatos and Livanos [9], Livanos et al. [10], Choi and Kim [16], and Dimopoulos et al. [12,13], which clearly identifies two or three operational speeds, is suitable for the ships operating according to fixed schedules (ferries [10] and container ships [12,13,16]); however,