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Organic Rankine Cycles (ORC) for mobile applications – Economic feasibility in different transportation sectors ☆

Roberto Pili [a,*], Alessandro Romagnoli [b], Kai Kamossa [c], Andreas Schuster [c], Hartmut Spliethoff [a], Christoph Wieland [a]

[a] Institute for Energy Systems, Technical University of Munich, Boltzmannstr. 15, 85748 Garching, Germany
[b] School of Mechanical & Aerospace Engineering, College of Engineering, Nanyang Technological University (NTU), 50 Nanyang Avenue, 637820, Singapore
[c] Orcan Energy AG, Rupert-Mayer-Straβe 44, 81379 Munich, Germany

HIGHLIGHTS

- Economic feasibility of ORC for different transportation sectors is analyzed.
- Trade-off between lower fuel costs and ORC mass and volume is considered.
- Significantly good economic performance is shown by ships.
- The limits for economic feasibility are slightly positively satisfied by trains and trucks.
- Large reduction in ORC weight and volume is required for city busses.

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ABSTRACT

Organic Rankine Cycles (ORC) offer a valuable alternative to recover waste heat from internal combustion engines (ICE) in transportation systems, leading to fuel energy savings and reduced emissions. Nevertheless, the additional weight of the ORC affects the net energy balance of the overall system and the ORC occupies additional volume that competes with vehicle transportation capacity. A lower income from delivered freight or passenger tickets will be therefore achieved. This work defines a benchmark for the economic feasibility of integrating an ORC into an ICE and the resulting economic impact of weight and volume in the transportation sector. It additionally investigates the current ORC situation on the market.

The applied methodology defines a maximum allowable change of transport capacity caused by the integration of the ORC. The procedure is applied to a typical city bus, a truck of 40 t of payload capacity, a middle-size freight train (1000 t), an inland water vessel (Va RoRo, 2500 t) and ocean vessel (25,000 t). The results are compared with commercial ORC products.

The findings of the present study are a theoretical and practical approach for the economic application of ORCs in the transportation sector. For maritime transportation, the situation appears highly favorable. For integration for trains and trucks appeared successful, but close to the limit line. For busses, a competitive integration requires a strong reduction in weight and volume.

In future works, the potential for volume and mass reduction of the ORC has to be addressed together with the integration of an economic assessment for the ORC.

1. Introduction

The transportation sector, dominated by the combustion of fossil fuels from internal combustion engines (ICE), contributes extensively to global environmental pollution. According to [1], the transportation sector in the U.S. accounted for 24% of overall greenhouse gas emissions in the country in 2014, second behind the electricity sector at 30%. In the European Union, the CO_2-emissions from transportation in the same year reached 23.2% [2]. The most typical fuels for ICE are petrol and diesel, but also kerosene, ethanol and heavy oil are used [3]. More stringent regulations limit the allowed emissions down to values that common engine configurations can no longer reach, and some intervention is necessary to alleviate the problem. The amount of emitted

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* Corresponding author.
E-mail address: roberto.pili@tum.de (R. Pili).

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Nomenclature

Symbol	unit of measure
LF	load factor, [–]
m_F	weight of transported freight, [t]
k_F	vehicle weight capacity, [t]
v_F	volume of transported freight, [m^3]
V_F	vehicle volume capacity, [m^3]
EF	empty trip factor, [–]
d_E	unloaded distance, [km]
d_F	loaded distance, [km]
CU_N	net capacity utilization factor, [–]
m_E	empty vehicle weight, [t]
CU_G	gross capacity utilization factor, [–]
$e_{tkm,N}$	net specific energy consumption, $[\frac{l}{tkm}]$
$e_{tkm,G}$	gross specific energy consumption, $[\frac{l}{tkm}]$
m'_E	empty vehicle weight with ORC, [t]
LF'	load factor with ORC, [–]
$m_{F'}$	transported freight with ORC, [–]
σ	stowage factor, $[\frac{m^3}{t}]$
η_m	power system efficiency, [–]
$\eta_{m'}$	power system efficiency with ORC, [–]
η_{ORC}	efficiency of the ORC, [–]
P_{ICE}	ICE power output, [kW]
P_{ORC}	ORC power output, [kW]
$R_{tkm,N}$	revenues per unit net ton of freight and km of covered distance, $[\frac{€}{tkm}]$
$R_{t,N}$	revenues per unit net ton of freight, $[\frac{€}{t}]$
R	revenues, [€]
R'	revenues with ORC, [€]
$c_{fuel,tkm,N}$	costs per unit net ton of freight and km of covered distance, $[\frac{€}{tkm}]$
$c_{fuel,l}$	costs per unit liter of fuel, $[\frac{€}{l}]$
C_{fuel}	fuel costs, [€]
C'_{fuel}	fuel costs with ORC, [€]
X	economic performance ratio, [–]
Z	fuel impact ratio, [–]
$Q_{in,ORC}$	heat input rate, [kW]
V_{ORC}	ORC volume, [m^3]
m_{ORC}	ORC weight, [t]

pollutants is proportional to the fuel energy required for transportation. This is why techniques to improve the efficiency of the energy conversion process “from tank to wheel” are still under investigation. Several techniques try to reduce emissions by using high quality fuels, controlling the mixing of combustion agents, optimizing the combustion process and improving post-combustion treatments [4–8]. Despite all the commitment, current ICEs can convert a maximum of 40–45% of the fuel energy into mechanical energy at the engine shaft, while 50% (or more) is found in the exhaust flue gas and the cooling medium [9,10]. One promising solution is to recover the heat available from the engine exhaust. A detailed description of the available engine heat recovery (EHR) techniques can be found in [11,12]. In exergy terms, hot flue gases seem more attractive than common low temperature water cooling. [13] showed that for a 2L gasoline engine 26% of the fuel exergy was still available in the flue gas (at high temperature) with respect to 3% in the coolant (at low temperature). Turbocompounds, thermoelectric and thermo-acoustic system have been proposed, but especially the last two solutions show high cost and low efficiency [11].

Organic Rankine Cycles (ORC) are Rankine cycle systems that make use of the relatively high flexibility in the choice of organic working fluids to achieve higher efficiencies than common steam Clausius-Rankine cycles, when the waste heat source has a temperature below 400 °C. For higher heat source temperatures, several studies showed that water is the best working medium in terms of thermodynamic performance [14,15]. Water has, in addition, incredible advantages in terms of availability and environmental impact. For lower temperatures and small-scale systems, organic fluids seem to perform better [16]. Thermal efficiencies up to 25% have been reported for heat source temperatures below 400 °C [17,18]. Typical fluids that have been proposed for waste heat recovery from transportation systems are Ethanol, a Water/Ethanol mixture and R245fa [19]. The most basic design of an ORC includes an evaporator, an expander, a condenser and a pump. From this basic layout more complex architectures with their advantages and drawbacks have been described in [12,17,20]. In the case of dry fluids, the efficiency of the ORC might be improved by integrating a recuperator [17,21]. The recuperator cools down the vapor at the expander outlet to preheat the working fluid before it enters the evaporator. Supercritical ORCs have been studied by [22] and for mobile applications in [23]. These systems can reach higher efficiencies than subcritical ORCs, reducing especially the exergy destruction in the evaporator. Dual cycles have also been investigated [24,25], where two separate cycles are used to achieve a better matching between the temperature of the heat source and the evaporating working fluids.

Despite the higher efficiency that more complex ORC configurations might promise, it must be considered that the installation of an ORC increases the weight of the vehicle and requires a certain volume [26]. The weight decreases the net energy recovery because of the increased vehicle load. The heat recovery evaporator also has a negative impact on the engine performance since it increases the ICE backpressure. The evaporator compactness and the engine backpressure are generally inversely correlated: if the evaporator is smaller, a smaller cross section is available for the exhaust gas flow, leading to an increased pressure drop. Several works have addressed the importance of the weight and compactness of the ORC for transportation systems. In [27], the size and weight of the ORC heat exchangers for water and D_4 are assessed by means of an automated design procedure, which was previously validated experimentally. It has been shown that, given the same pressure drop losses, the heat exchangers for D_4 would be comparatively larger in comparison with water. In [28], a design procedure for waste heat recovery from heavy-duty trucks is developed, where a maximum available space is set as constraint for the heat exchanger design. The procedure is applied to water and R245fa as working fluids. R245fa could allow for a more compact system, at the expense of lower efficiency. An optimization method for mini-ORCs recovering exhaust heat from a long-haul truck is also described in [26], where thermodynamic optimization, heat exchangers and expander design are integrated in a single code. The genetic algorithm is used for system optimization, having the maximization of the net power output, the minimization of the flue gas pressure drop at the evaporator, and the minimization of the core weight of the evaporator and recuperator as objective functions.

The drawbacks of the ORC integration, such as increased weight, volume and engine backpressure, could even completely annihilate the energy recovery, especially at low rpm as shown in [4]. Furthermore, most of the means of transportation have restriction in terms of size, which accounts in particular for road transportation [29]. As a result, the required volume of the ORC competes with the transportation capacity of the vehicle. Because of this, some

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