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NoWaste: waste heat re-use for greener truck

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Abstract

The present paper summarizes the key points of the European NoWaste Project, which aims at developing Rankine cycle systems for integration into long-haul trucks with the aim to convert the waste heat of the exhaust gases into useful energy usable in mechanical or electrical form. The first part of the paper describes the ORC system architectures defined for two different truck engines: one with EGR and the other one without EGR. For both engines, different cycle configurations and working fluids are compared in terms of energy performance and technical constraints. For both ORC systems, the paper shows the final technical choices made in terms of main components: boiler, condenser, expander and pump. The second part of the paper presents preliminary experimental results carried out on demonstrators of the two ORC systems. The objectives of these tests were to check the performance announced by the components' manufacturers. Finally, the last part of the paper compares the cost of both systems.

Keywords: Rankine cycle; No Waste; waste heat recovery; automotive application.

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1. Introduction

Automotive world is rapidly changing driven by the CO_2 emission regulations [1], [2] worldwide asking for a significant fuel consumption reduction. The internal combustion engine will be the principal powertrain concept for the upcoming decades, especially when it comes to road transportation. Even if the efficiency of the ICE's has increased within the last years, around 30-40% of the fuel indicated energy is still lost through waste heat (mainly in the exhaust gases and engine cooling system). This waste heat could be partially recovered via secondary cycles as the Rankine cycle, Brayton cycle or Stirling cycle. In a Rankine cycle system, a working fluid at high pressure and

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liquid state is heated, vaporized and superheated in a boiler. Heat provided to the boiler is that recovered from the waste heat of the engine. The high-pressure vapour is expanded through an expansion machine, which produces mechanical power. The low-pressure fluid at the expander exhaust is then condensed and cooled down in the condenser. Heat is rejected outside the vehicle. The low-pressure liquid is finally driven to the evaporator supply by means of a pump. The working fluid could be water or an organic fluid, such as a hydrocarbon or a synthetic refrigerant, characterized by lower boiling points. Preliminary studies have shown [3] that for a heavy duty Diesel application the Rankine cycle system offers the highest potential, over competing technologies, for efficient waste heat recovery. Another model-based comparison between Rankine cycle and other technologies has been proposed for passenger cars, but is of interest for long haul trucks [4]. The integration of Organic Rankine Cycles systems (ORC) on trucks has already been investigated in the seventies [5]. Such systems have been regaining interest during the last decade [6, 7, 8, 9, 10, 11, 12]. Current research investigates, among other things, the fluid selection, the cycle architecture, the design of the expansion machine, the performance on duty driving cycles and the control. However, there is still a lack of published results on prototypes of Rankine cycle systems designed for long-haul trucks.

The adoption of such technology in the automotive domain requires specific R&D activities to develop the components and identify the most appropriate system architectures and level of integration in order to achieve sustainable costs and the required level of reliability. In this context, the EU has funded in the frame of the 7th framework program the project NOWASTE: a collaborative project between several companies and institutions: Centro Ricerche Fiat S.C.p.A., Volvo Technology AB, Dellorto SPA, University of Liège, AVL List GMBH, Faurecia systèmes d'échappement SAS. This project has the goal to develop a waste heat recovery system based on Organic Rankine Cycle (ORC) for a Heavy Duty Truck (HDT) application with the aim to realize fuel economy savings. The objective of the project consisted in developing and validating two WHR Rankine cycle systems: for a VOLVO truck and for an IVECO truck. The first part of the project was dedicated to the simulation-based investigation of advanced cycle topologies, aiming at defining the cycle architecture (matching with the available heat sources and sinks), the selection of the working fluid and component technologies, as well as the WHR ORC control strategy with respect to the vehicle and engine environment. The result was the definition of two system architectures after 12 months. The second part of the project was focused on the development, realization and validation of the ORC system's components. The most appropriate suppliers have been identified and asked to realize customized components according to the specification defined previously. In addition, two different control systems were developed in order to set up the engine test benches for the subsequent ORC systems' testing activities. The last part of the project was dedicated to the design of the WHR units for on-board installation. All the vehicle aspects and the interactions with the other on-board systems and components were considered with special attention devoted to the vehicle engine cooling circuit. CRF and VOLVO ORC systems will be integrated on demonstrator devices for the final validation on the defined reference drive cycles. In parallel, a technological feasibility study was performed to analyze the opportunities to achieve sustainable costs and compatibility with a typical automotive supply chain.

This paper describes the key points of the waste heat recovery system concepts developed, the preliminary performance evaluated on engine test benches and a preliminary cost analysis performed taking into account the main cost drivers which can affect the return of investment period.

Nomenclature

η	Efficiency [-]
h	Specific enthalpy [J/kg]
$\dot{M}$	Mass flow rate [kg/s]
$\dot{Q}$	Thermal power [W]
$\dot{W}$	Electrical or mechanical power [W]

Subscripts

boil	Boiler
in	Inlet

out	Outlet
s	Isentropic
turb	Turbine

Acronyms

BSFC	Brake Specific Fuel Consumption
CAC	Charge Air Cooler
CRF	Centro Ricerche Fiat
EGR	Exhaust Gas Recirculation
HTR	High Temperature Radiator
ICE	Internal Combustion Engine
LTR	Low temperature Radiator
ORC	Organic Rankine Cycle
ROI	Return On Investment
SCR	Selective Catalytic Reduction
ULG	University of Liège
WHR	Waste Heat Recovery

2. Definition of waste heat recovery systems

The reference engine applications selected by CRF and VOLVO to define the WHR ORC systems are described in Table 1.

2.1. Volvo ORC system architecture

Since the engine layout for the VOLVO application contains a cooled EGR path, it has been decided to analyze a system combining waste heat recovery from the EGR cooler and the exhaust gases.

Table 1. Reference Engine Applications

Parameter	**VOLVO**	**CRF**
Name	US10	Cursor 11
Displacement [l]	12.7	11.1
Number of cylinders	6	6
Max power [kW] @ rpm	317 @ 1800	353@ 1900
EGR	yes	No, SCR only
EU category	Euro VI	Euro VI

Two possibilities have hence been identified to combine both heat sources: via a serial or parallel configuration. In both configurations, it has to be ensured that the EGR temperature at the outlet is sufficiently low in order to be reintroduced into the engine admission. Therefore, in the serial configuration the EGR heat exchanger needs to be placed upstream the exhaust heat exchanger. In the parallel configuration the working fluid mass flow through the EGR heat exchanger needs to be adapted in order to guarantee sufficient EGR cooling. Finally, even if the parallel configuration would have yielded a higher net power output, the serial configuration has been chosen in order to minimize the system's complexity and cost since the parallel configuration needed an additional number of actuators to control the working fluid mass flow and larger-capacity heat exchangers.

About the system's working fluid, the thermodynamic simulation analysis has shown that an ethanol-based cycle offers better results in terms of cycle efficiency, heat rejection and power recuperation than a refrigerant-based cycle. In addition, a water-ethanol mixture for reduced flammability and corrosivity compared to pure ethanol is preferable. Considering this working fluid, the system has been designed to work at a maximum system pressure and temperature of about 30 bar and 225°C respectively, and a condensation pressure of about 1bar (the condenser is vented to the ambient).

The whole system will implement the following devices as in the showed simplified layout (Fig. 1):

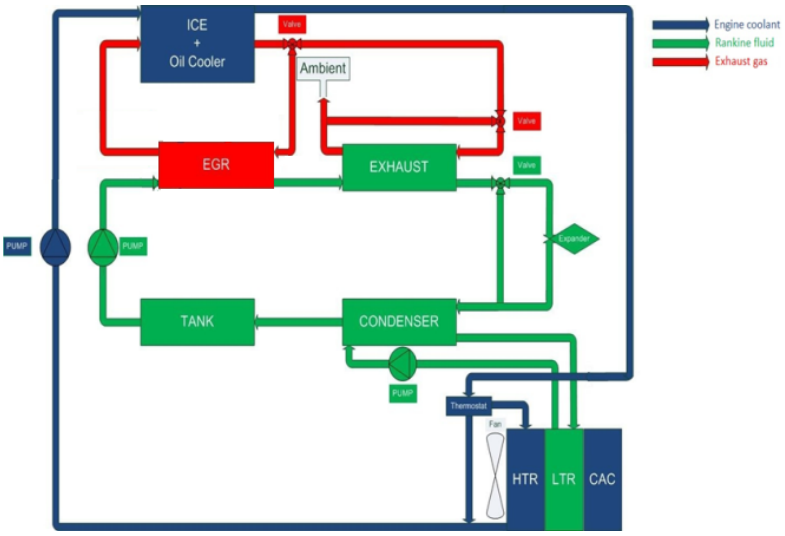

Fig. 1. (a) Schematic layout of the VOLVO Rankine system.

Regarding the heat rejection circuit, in real vehicle cooling conditions the low temperature coolant entering the condenser as cold sink is expected to be tempered at 60-70°C.

Finally, about the power output exploitation, the Volvo powertrain's architecture for the considered long haul application does not include hybridization, so it has therefore been decided to couple the recuperated energy mechanically to the driveline through a turbine connected to a reducer with the engine.

The final components selected for the VOLVO system are:

- An external gear pump as feed pump;
- An turbine as expander;
- A brazed stainless steel heat exchanger with a concept similar as the EGR cooler as EGR boiler,
- A brazed stainless steel (counter flow) heat exchanger based on plate type concept as tailpipe boiler,
- A brazed stainless steel (plate/plate counter flow) heat exchanger as condenser.

The range of technical boundary conditions for each component is outlined in the Table 2.

2.2. CRF ORC system architecture

CRF's approach for the ORC system design was not focused on the maximization of the WHR power output or efficiency, but on a trade-off between the maximum impact of the system on the overall vehicle efficiency and the system simplicity-volume-weight & cost. The ORC system has been designed using a holistic approach and with a strong focus on vehicle integration.

The reference diesel engine identified for CRF/ IVECO application does not include an EGR circuit, so only the exhaust gas waste heat will be recovered to feed the Rankine cycle. The after treatment system's architecture is a crucial constraint in a WHR system design because of the temperature level of the heat source available. Engine with EGR allows high temperature heat source so a "high temperature" WHR (high efficiency); engine without EGR (or with low EGR rate) have only low-medium temperature heat source (exhaust gas tailpipe), which leads to lower WHR efficiency.

These reasons lead to consider a system's working fluid suitable for medium-low heat sources; in addition a flammable fluid was not considered acceptable for safety reasons. The auto-ignition temperature of flammable hydrocarbons typically precludes their use in direct heat exchangers with high temperature exhaust gases that contain oxygen. For this reason, usually an intermediate oil loop is used to separate the hot gas from the flammable working fluid. The implementation of this option could cause an increase of installation space and components cost and was considered not acceptable. The organic working fluid chosen is Genetron ®245fa (1,1,1,3,3-Pentafluoropropane) produced and distributed by Honeywell. This non-flammable and non-ozone depleting fluid has high value of Global Warming Potential (~ 1000) but a very similar organic fluid named Solstice® R1233zd with very low GWP (< 5) is currently under development by Honeywell and could be considered as future replacement of ®245fa. In the frame of this project, ULG has performed some virtual simulations to make a comparison between these organic fluids and the preliminary results show that Solstice® R1233zd could offer even superior performances compared to ®245fa in terms of output power produced with an ORC system with the same external boundary conditions.

Regarding the heat rejection circuit design, a limitation on the maximum power to be rejected by the WHR System has been defined (35kW) in order to contain the overall heat to be rejected to the ambient at low temperature, considering the other loads installed on the vehicle (electronics components, A/C liquid cooled condenser, CAC liquid cooled condenser). In this condition, to reach a higher LT power rejection performance, the vehicle fan activation is needed, but the fan power consumption could be higher than the power benefit of the ORC system.

Finally about the power output exploitation, the CRF's architecture for the considered long haul application includes a partial hybridization (dual voltage boardnet, electric A/C compressor, electric air compressor, servo steering pump), so it has therefore been decided to couple the recuperated electrical energy to the vehicle electrical network thanks to an axial turbine connected to an electric generator through a reducer.

The design's result is a compact ORC unit integrating all the basic components (evaporator, turbine-generator, condenser, fluid pump).

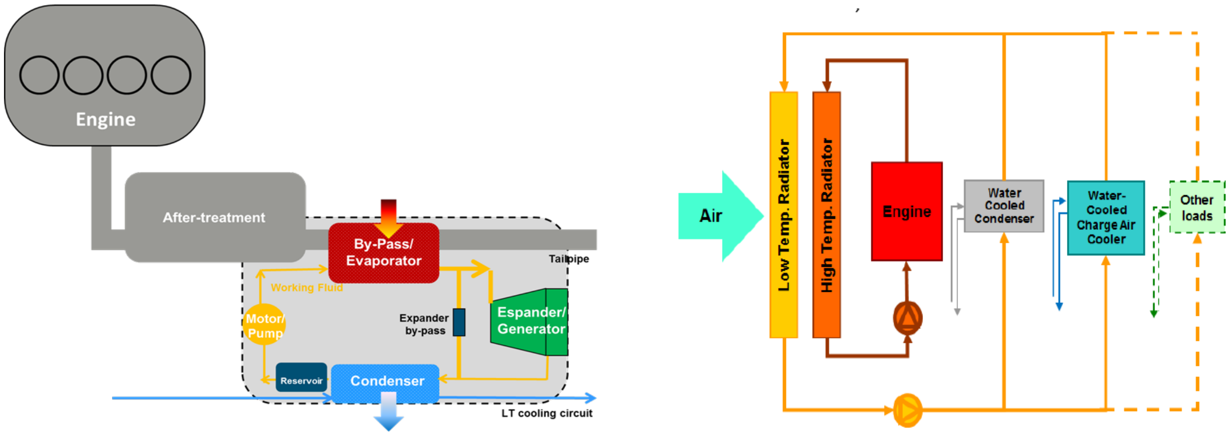

Fig. 2. (a) Schematic layout of the CRF Rankine system; (b) Schematic layout of the vehicle's new coolant circuit architecture.

Based on these boundary conditions, a preliminary estimation of the heat transfer rates exchanged have been performed to have a rough idea of what would be the overall system performances and to give some information to components suppliers. A vehicle speed cruise condition was then taken into account for this purpose and the results of these preliminary estimations are resumed in Table 2.

The final components selected for the CRF system are:

- An internal gear pump as feed pump;

- An axial impulse turbine coupled with an electric generator as expander;
- A stainless steel plate-fin heat exchanger as tailpipe boiler,
- An aluminum liquid-cooled plate heat exchanger as condenser.

Table 2. Component specifications of Volvo and CRF ORC systems.

Component	Technical boundary conditions	VOLVO	CRF
EGR boiler	Heat flow range (kW)	15-45	-
	EGR inlet temperature (°C)	400-500	-
	Working fluid pressure (bar)	25 - 40	-
	Working fluid inlet temperature (°C)	65	-
Exhaust boiler	Heat flow range (kW)	25-60	30-50
	Exhaust inlet temperature (°C)	320-350	200-300
	Exhaust mass flow (kg/s)	0.18-0.25	0.2-0.3
	Working fluid inlet temperature (°C)	65-215	63-73
Condenser	Heat flow range (kW)	50-85	25-45
	Working fluid pressure (bar)	1	5-7
	Working fluid inlet temperature (°C)	85-180	100-110
	Coolant inlet temperature (°C)	50-70	50-70
	Coolant mass flow (kg/s)	1-5	0.6-1
Expander	Inlet pressure (bar)	25-40	25-35
	Inlet temperature (°C)	200-280	140-160
Feed pump	Inlet pressure (bar)	1	5-7
	Inlet temperature (°C)	70-80	60-70
	Working fluid inlet mass flow (kg/s)	0.04-0.08	0.1 -0.2

3. Engine bench testing results

3.1. CRF application

The experimental activity performed has been useful to determine the system behavior in several steady state conditions of thermal engine load. During the experimental tests all the components have been characterized in order to verify the supplier's specifications and to obtain data useful to improve the simulation model. The working fluid thermodynamic states have been defined by measuring the temperature and pressure at the inlet/outlet of every component of the system. The generator power production has been determined by measuring the output current and the voltage while the mass flow rate and the pump electrical power absorption were regulated by controlling the pump rotational speed.

Regarding the components' performances, the internal gear feed pump has worked very well in all the test's conditions, no functional problems were detected in both the pump and in its brushless electrical motor. The heat exchangers performances respected the supplier's specifications; the maximum heat transfer rates exchangeable for both the evaporator and the condenser were reached. The main issues observed were related to the turbine&generator global efficiency, which was below the expected level; this fact had a significant impact on the ORC system performance and efficiency (Fig.3). This efficiency is defined as the ratio between the electrical power provided by the generator and isentropic power. The latter is the product of the fluid mass flow rate entering the turbine and the drop of specific enthalpy if the expansion was isentropic from turbine inlet to outlet.

$$\eta_{turb} = \frac{\dot{W}_{turb}}{\dot{M}_{turb}(h_{in,turb} - h_{out,turb,s})}$$

The ORC efficiency is the ratio between the electrical power provided by the generator and the thermal power consumed at the boiler.

$$\eta_{ORC} = \frac{\dot{W}_{turb}}{\dot{Q}_{boil}}$$

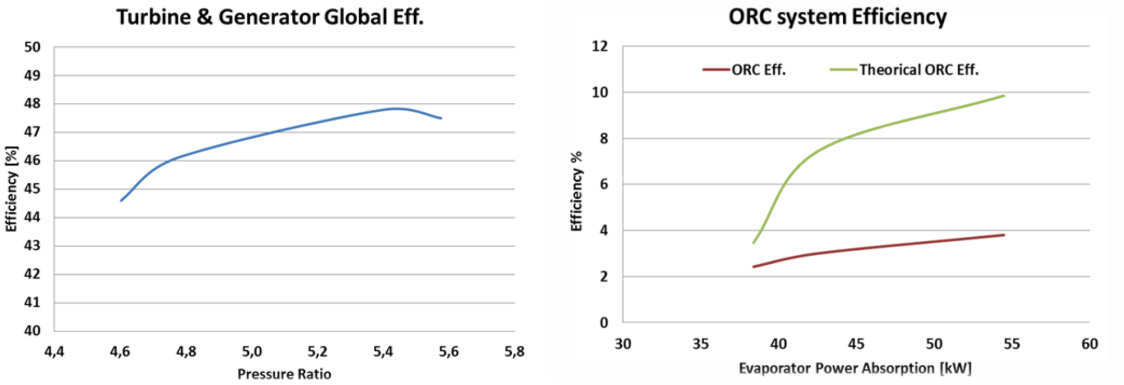

Fig. 3. (a) Turbine&Generator global efficiency; (b) Theoretical and measured ORC efficiency (CRF application).

The global efficiency of the expander machine in Fig.3 (a) includes the isentropic, mechanical and electrical efficiencies in function of the pressure ratio measured; the difference between the theoretical efficiency of the ORC system, that takes into account the isentropic efficiency only, and the real efficiency (red curve in Fig. 3 (b)) that takes into account also the mechanical and electrical energy conversions, shows how much these aspects affect the ORC benefits and that the component tested has to be improved.

The average results achieved in the steady state conditions considered are summarized in the next table.

Table 3. CRF Rankine system: performances measured on an engine test bench at different engine load levels.

Parameter	Engine load 70%	Engine load 80%	Engine load 90%	Engine load 100%
Evaporator heat recovery [kW]	38.4	42.6	48	54.5
Condenser heat rejection [kW]	36.2	40.8	46	51.8
Pump power absorption [kW]	0.27	0.32	0.38	0.43
Electricity generation [kW]	1.2	1.6	2	2.5
Mass flow rate [kg/s]	0.15	0.16	0.18	0.19
ORC global efficiency	2.4	3	3.3	3.8

3.2. VOLVO application

In a first approach the WHR system has been tested under steady state engine load points in order to validate components performance and to derive important information for the control system development. The system has been installed on an engine test rig, the Rankine cycle components have been placed in order to represent a future vehicle installation. A dedicated coolant loop (water-glycol mixture) has been used to control the heat rejection of the Rankine cycle. Unfortunately the tests have been performed without expander, i.e. the turbine has been replaced by a representative orifice. The heat ratio describes the fraction of heat recovered by the working fluid compared to the total heat loss of EGR and exhaust gases.

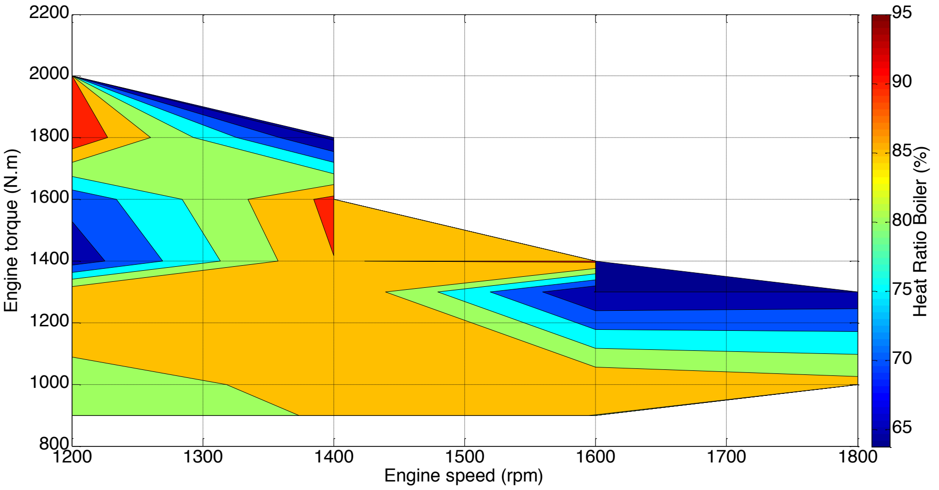

Fig. 4: Heat ratios Boilers VOLVO application

The heat ratio does not represent a boiler specific efficiency but mainly describes losses to the ambient. The present results indicate clearly that roughly 15-25% of the heat is lost under steady state conditions and could be recuperated by the working fluid if the heat exchangers are better insulated which would have an non-negligible influence on weight and cost.

Based on the measured working fluid states and mass flow rates at the expander orifice inlet and outlet, an estimation of cycle efficiency has been performed for the present set-up estimating a total turbine efficiency of 65%.

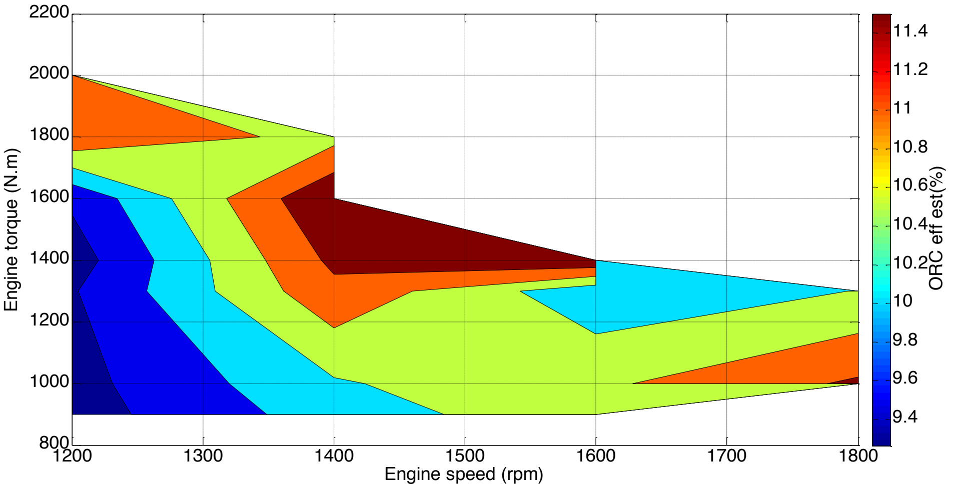

Fig. 5: Rankine cycle efficiency estimation VOLVO application

With an average efficiency estimation of 10% over a relatively wide range of engine working points the Ethanol based Rankine cycle shows its benefits. However, additional potential of cycle efficiency and power recuperation can be estimated when reducing the condensation temperatures and pressure levels as well as improving the expander total efficiency.

4. Cost Analysis

AVL investigated the Volvo and CRF systems in relation to overall system costs. The more complex Volvo system could be currently in a range of 2900 - 4000 Euros and the smaller, more reliable but less efficient CRF system is expected in a range between 2300 – 3000 Euros. These prices are estimated as production prices, no additional margins are considered because to bring the system on the market and to increase production the prices have to be low as possible. In the beginning, the number of possible suppliers will be also low, which will lead to increased component prices in a first period.

The following pie charts give an overview where the main cost drivers are located. In general it is always the expanders and the evaporators, followed by system support with all integrated piping's and fixations.

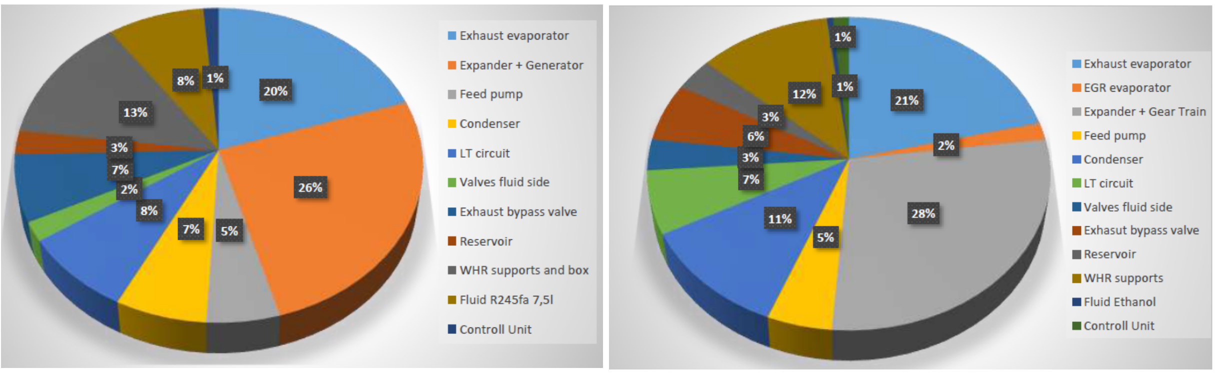

Fig. 6. (a) Cost's drivers overview for CRF system; (b) Cost's drivers overview for Volvo system.

Figure 7 shows that a ROI lower than 2 years could be achieved, considering the range of system cost given hereunder, provided that the brake specific fuel consumption (fuel consumption divided by the engine power) is reduced by around 2-3%. This figure is drawn under the following assumptions: a vehicle price of 95,000 EUR, a mileage of 150,000 km/year, an average fuel consumption of 35 l/km, and an average EU fuel price of 1.7 EUR/l.

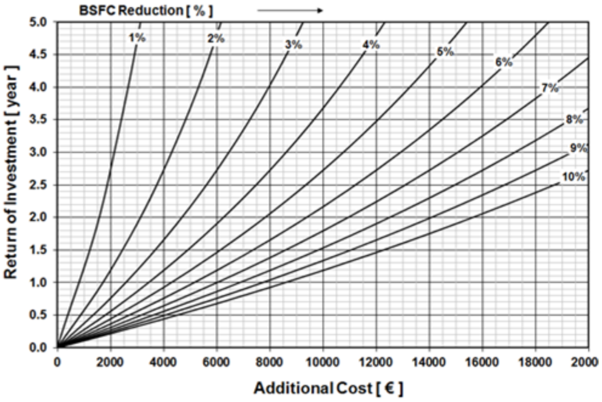

Fig. 7. Return on investment as a function of the WHR system cost and of the brake specific fuel consumption reduction

5. Conclusions

The main achievements of the No Waste Project can be summarized as:

- a relevant improvement in respect of the understanding of the system design and its integration on a heavy duty vehicle application;
- an increased motivation of the components' suppliers in the investment on specific component development;
- an increased motivation of the OEM involved in the project, but also other ones for internal investment on ORC developments;
- a new synergy of the OEM working on this topic that has driven the suppliers to increase their effort in the development of new and specific components;
- a demonstrated energy saving realized on the considered applications through a waste heat recovery system based on the ORC technology.

The WHR system developed by CRF, designed with the idea to be installed on a hybrid commercial vehicle application, has demonstrated that a simple ORC system, based on an energy recovery from the exhaust gas only, can achieve interesting results in terms of electricity power output (~2 kW) which could be improved with a more efficient turbine. This idea of cheap and "plug and play" system has a low impact on the vehicle's architecture because of its low global size and weight, and no impact on the powertrain's design.

The development of the VOLVO's WHR system showed that efficient EGR cooling and heat recovery can be combined for a long haul heavy duty application showing realistic cycle efficiencies around 10% on all measured engine working points, however the decrease of the condensation temperature and an optimal layout of heat exchangers as well as improved overall expander efficiency can lead to significant improvements in both power production and cycle efficiency.

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