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RESEARCH ARTICLE

# Exergy and economic assessments of an organic rankine cycle module designed for heat recovery in commercial truck engines

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## Abstract

**Objectives:** To evaluate the energy and exergy performances of a designed ORC system and to quantify loses within the system and measure its output. The study also assesses the economic performance of the ORC system to determine the feasibility of the business. **Methods:** Thermodynamic analysis assessing the energy performance and cost estimation using manufacturers' prices to generate generic equations for estimating costs of the components of the designed ORC system. **Findings:** The results of the exergy evaluation of the ORC show a system thermal efficiency of 6.39%, net power output of 3.10$kW_e$, exergy destruction of 9.07kW, and exergy efficiency of 54.6%. The economic estimation has a capital investment cost of £8,381.98, a specific investment cost of £2,754.36/$kW_e$, annual savings of £1,233.34, and a payback period of 6.8years. **Novelty**: The use of exergetic method of analysis and the assessment of the potential economic benefits of installing the module in commercial trucks which form part of the acceptance-criteria, using prevailing market prices of the ORC system is an obvious novelty in this study. In addition, the generation and use of curve-fitting plots to obtain the generic equations for computing the approximate costs of the individual components of the system is an integral part of the novelty of this work.

**Keywords:** Organic Rankine cycle; exergy and economic assessment; specific investment cost; capital investment cost; payback period; exhaust heat recovery

## 1 Introduction

Efficiency improvements and reduction in $CO_2$ emissions are the focus of research trends in internal combustion engines aimed at mitigating climate threats from exhaust gases and meeting tight emerging emissions regulations. Several solutions to these threats, such as exhaust gas recirculation (EGR) and selective catalytic reduction (SCR), are already developed and in the market, while some are still developing. However, one attractive option with great potential is the Organic Rankine Cycle technology for waste heat recovery. This concept is seen as crucial, with 60 to 65% of fuel energy lost as heat to the environment via exhaust gas, engine cooling systems, and charge air cooler (CAC); with exhaust gas accounting for a significant proportion of the exergy,[(1)]. Recovering the heat in the exhaust gas waste stream would bring about considerable efficiency improvement and fuel saving. Organic Rankine Cycle system is a promising candidate option for recovering energy from exhaust gases. In the process, the embedded energy in the exhaust is transferred to the working fluid, which further expands to produce mechanical power at the shaft. ORC is considered a deployable technology in recovering energy from low -to-medium grade heat sources (230-to- 650°C),[(2)].

In this study, the ORC model is programmed to recover exhaust heat from a Yuchai diesel engine fitted with EGR and SCR exhaust after-treatment systems[(3)]. The ORC system has a shell and tube heat exchanger employed as the evaporator, while the condenser is a plate heat exchanger, and the expander a radial inflow turbine coupled to a generator. The module also has a recuperator which preheats the working fluid with heat extracted from the superheated vapor exiting the turbine outlet. The system arrangement also has a bypass valve, which shuts it down when the exhaust conditions are below the minimum requirement and helps in the turbine warm up. The working fluid adopted in this study is R245fa due to its proven effectiveness in ICE ORC systems application,[(4)],[(5)]. The recovered exhaust energy is converted to mechanical power, where it can be transformed into electricity in a generator or reinjected back into the driveline via belt drive or mechanical coupling and a damping device. The principle works by transferring heat from the engine exhaust to the working fluid via the evaporator. The vaporized high-pressure working fluid then expands in the turbine coupled with a generator to produce the desired electrical power. After expansion, the low-pressure vapor is condensed and returns to the reservoir as saturated liquid, and the cycle is repeated. The coolant expels some of the system's heat through the cooling system to the outside environment[(6)],[(7)].

Although waste heat recovery economic feasibility and potentials have been reported in several articles and reliable results obtained, the concept must prove a good return on investment and safety when eventually adopted commercially. This present study focuses on evaluating the performances of the module by the method of exergy analysis and assessing the economic benefits of such a conceptual model design for heat recovery from the engine of highway trucks. The work is delineated into three sections; the first section describes the designed module, relevant parameters, and boundary conditions used in the subsequent section. The second part evaluates the system's effectiveness in terms of thermodynamics and exergy analyses, and the final segment deals with the economic assessment of the ORC system for heat recovery applications in truck engines. In this case, the potential capital investment costs, specific investment costs, and payback period of deploying the ORC module for heat recovery in highway trucks are evaluated.

## 2 Materials and Methods

### 2.1 Module description

An ORC system coupled to a diesel engine for exhaust heat recovery application was designed and simulated on a GT-Suite platform using R245fa as a working fluid for an operating speed of 66-132km/h. The ORC model was developed to generate additional thermal energy with no additional fuel consumption by the truck engine. The exergy analysis and economic assessment concern with evaluating the heat energy and the potential economic performance quantifiable from the truck engine's exhaust gas expelled to the environment. The model for this study corresponds to a Yuchai diesel engine with characteristics shown in Table 1 commonly used in trucks and other heavy-duty vehicles. These assessments were investigated at the maximum operating speed of 132km/h, as depicted in Figure 1. The study is not intended to detail the developed system's recovery process but focuses on the exergy and economic aspects. Figures 2 and 3 depict the schematic layout and the t-s diagram of the module, and at the same time, Table 1 presents the necessary experimental parameters used in the exergy evaluation and costs assessment of the ORC module, as described in the subsequent sections.

### 2.2 Performance evaluation of the ORC system

A brief outline of the thermodynamic equations governing the ORC system, and used in evaluating the system performance are as follows:

The electrical output equation of the unit is given as:

$$\dot{W}_{elec} = \eta_{mech}\eta_{gen}\dot{W}_{tur} - \frac{\dot{W}_p}{\eta_M} \tag{2.1}$$

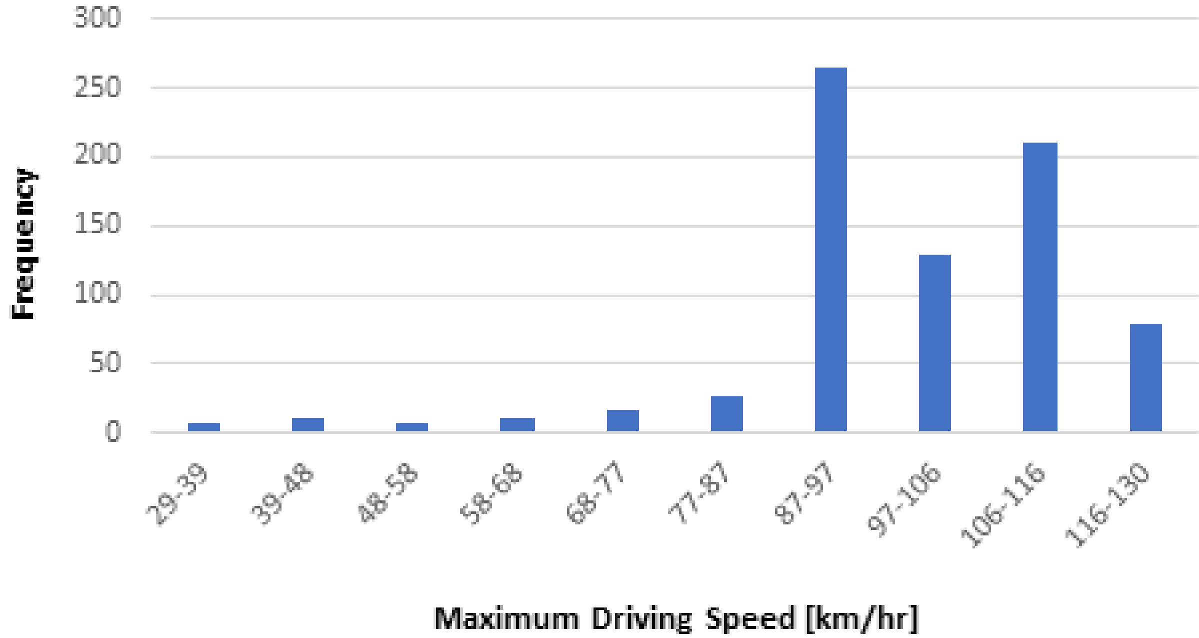


**Fig 1.** Commercial trucks maximum driving speed [km/hr], [8].

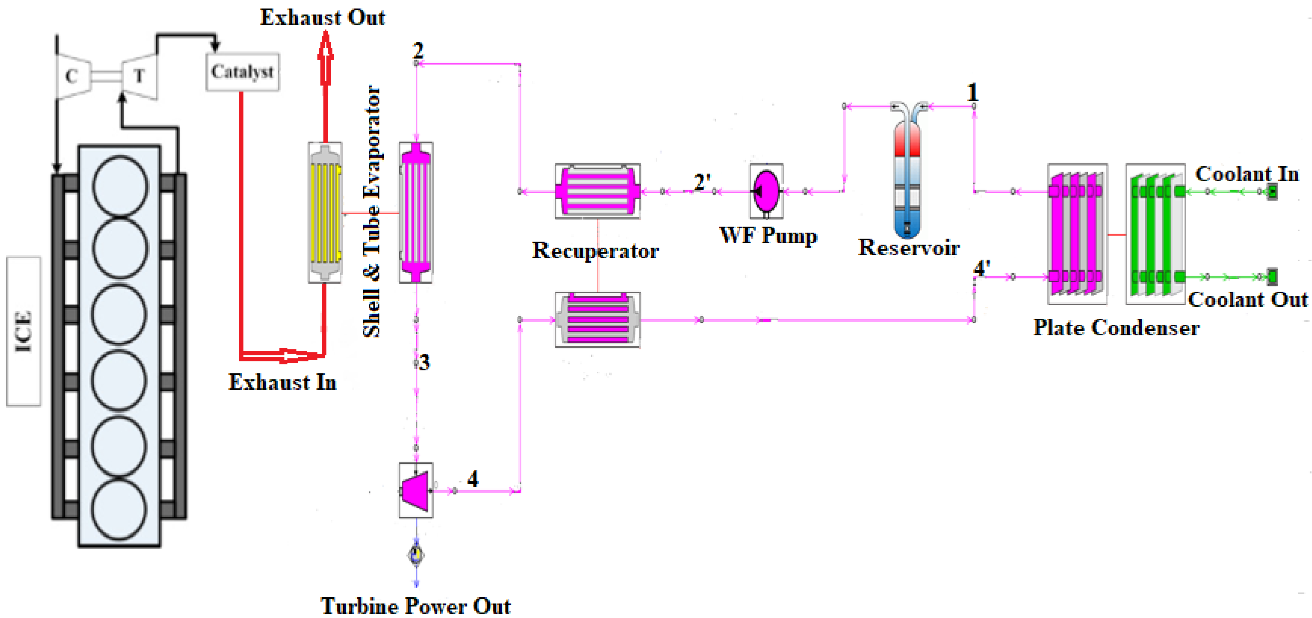


**Fig 2.** Schematic layout of the designed model

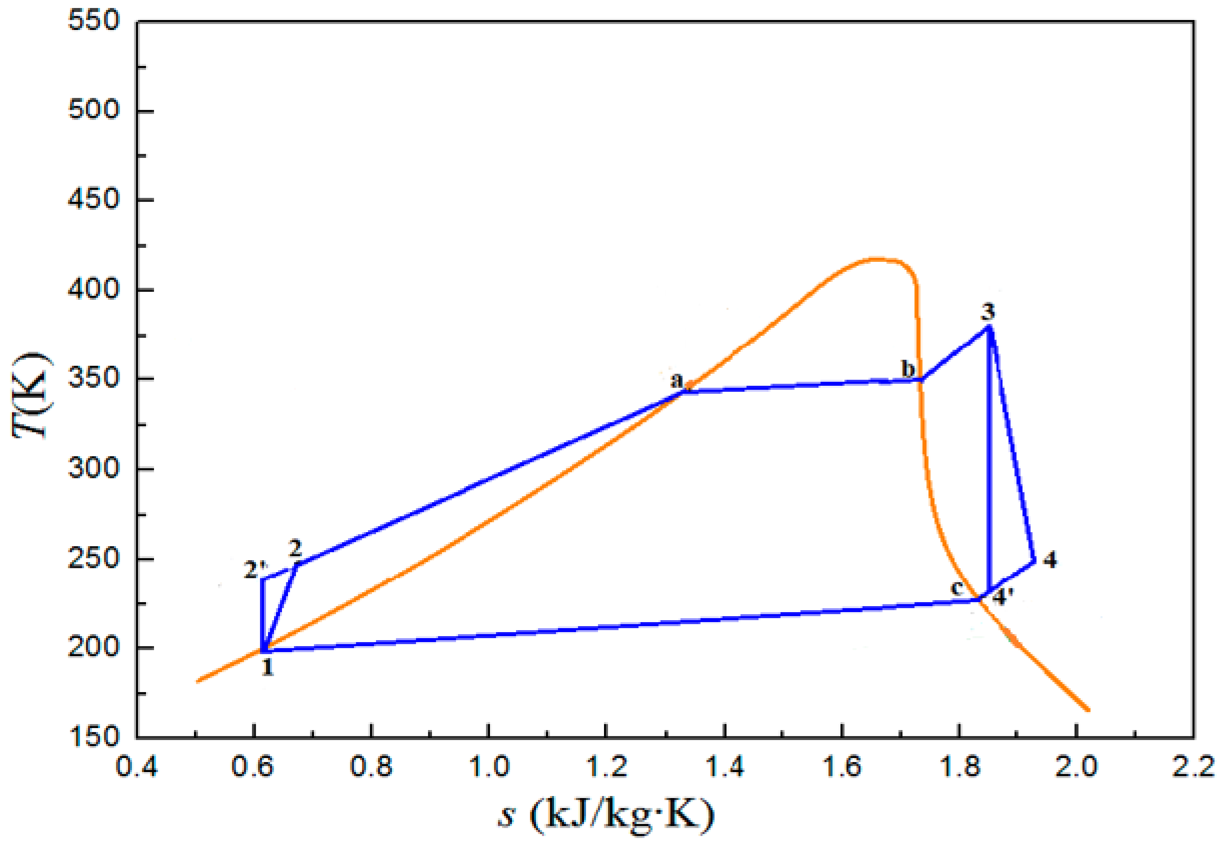


**Fig 3.** T-s diagram for R245fa refrigerant used

**Table 1.** Yuchai 7.26l characteristics ,[3]

| ITEM | SPECIFICATION |
|---|---|
| Model | YC6A280-30 |
| Displacement (l) | 7.26 |
| Stroke (mm) | 132 |
| Bore (mm) | 108 |
| Compression ratio | 17.5 |
| Number of Cylinder | 6 |
| Number of Valves | 4 |
| Maximum Torque | 1100 Nm @ 1400-1600rpm |
| Maximum Power | 206 kW @ 2300 rpm |
| Emission | EURO III (bsfc $\leq$ 205g/kWh) |

**Table 2.** Experimentally generated parameters for exergy analysis

| Parameter | Condition |
|---|---|
| Truck Speed (km/h) | 119 |
| Brake Power (kW) | 90.42 |
| Ambient Temperature (°C) | 26.85 |
| Mass flow rate of working fluid (kg/s) | 0.234 |
| Mass flow rate of exhaust gas (kg/s) | 0.125 |
| Exhaust gas Specific Heat (kJ/kgK) | 1.0829 |

**Table 3.** Module performance results

| Indicator | Value | Unit |
|---|---|---|
| Electric Output ($\dot{W}_{elec}$) | 3.1 | $kW_e$ |
| Turbine Power ($\dot{W}_{turb}$) | 3.37 | kW |
| Pump Power ($\dot{W}_{pump}$) | 0.36 | kW |
| Evaporator Heating Load ($\dot{Q}_{evap}$) | 47.12 | kW |
| Condenser Cooling Load ($\dot{Q}_{cond}$) | 43.74 | kW |
| Evaporator Effectiveness ($\varepsilon$) | 0.86 | - |
| ORC Thermal Efficiency ($\eta_{th}$) | 6.36 | % |

Where $\dot{W}_{elec}$, $\dot{W}_{tur}$ and $\dot{W}_p$ are electricity output, turbine power out and pump consumption, $\eta_{mech}$, $\eta_{gen}$ and $\eta_M$ are mechanical efficiency, generator efficiency and mechanical efficiency of the pump.

The heat expelled from the system via the condenser is given by the equation:

$$\dot{Q}_{out} = \dot{m}_{wf}\left(h_4 - h_1\right) = \dot{m}_w C p_w \triangle T_w \tag{2.2}$$

Where $\dot{m}_{wf}$ and $\dot{m}_w$ are working fluid and cooling water mass flowrates, $h_4$ *and* $h_1$ are enthalpies at the various points in Figure 3, $Cp_w$ is the specific heat capacity of the cooling water and $\triangle T_w$ is the change in temperature of the cooling water

The heat input to the working fluid via the evaporator is given as:

$$\dot{W}_{in} = \dot{m}_{exh}\left(h_{exh_{in}} - h_{exh_{out}}\right) = \dot{m}_{wf}\left(h_3 - h_2\right) \tag{2.3}$$

Where $\dot{m}_{exh}$ = mass flowrate of exhaust gas, $\dot{m}_{wf}$ = mass flowrate of working fluid, $h_{exh_{in}}$, $h_{exh_{out}}$, $h_2$, *and* $h_3$ are enthalpies of exhaust and working fluid as defined in Figure 3.

The evaporator effectiveness is calculated from equation 2.4,

$$\varepsilon = \frac{\dot{Q}_{Evap,in}}{\dot{m}_{exh} C_{p,\,exh}\left(T_{exh,\ in} - T_{wf,\,in}\right)} \tag{2.4}$$

Where $\dot{Q}_{Evap,in}$ is the heat absorbed by the working fluid, $\dot{m}_{exh}$ *and* $C_{p,\,exh}$ are mass flow and specific heat of the exhaust gas, $T_{exh,\ in}$ is exhaust gas temperature inlet and $T_{wf,\,in}$ is the evaporator working fluid inlet temperature.

Thermal efficiency of the ORC unit is given as

$$\eta_{th} = \frac{\dot{W}_{tur} - \dot{W}_p}{\dot{Q}_{in}} \tag{2.5}$$

## 2.3 Exergy analysis

The second law analysis in thermodynamic cycles evaluates the primary sources of energy loss in the system and provides performance assessment and efficiency improvement. Energy conversion systems follow conversion laws; however, energy destruction always occurs in practical systems. This destruction process is referred to as irreversibility in systems and measures the inefficiency of the process. In each system component, irreversibility is a mirror image of exergy losses resulting from irreversibility factors,[9–14] . In ORC systems, exergy efficiency highlights the importance of net output and the degree of efficient energy use. These include:

Exergy balance in the ORC unit

$$E_{in} - E_{out} = \dot{W}_{elec} + E_{heat} + I \tag{2.6}$$

Where $E_{in}$, $E_{out}$ and $E_{heat}$ represent inlet, outlet, and total heat exergies of the system respectively, and I is the total irreversibility of the unit.

Overall exergy efficiency of the ORC system is given as:

$$\eta_{ex,\,ORC} = 1 - \frac{I_{evap} + I_{cond} + I_{turb} + I_{pump}}{\dot{m}_{exh}\left[\left(h_{exh,\,in} - h_{exh,\,out}\right) - T_{amb}\left(S_{exh,\,in} - S_{exh,\,out}\right)\right]} \tag{2.7}$$

Irreversibility in the components are given as expressed,[15].

$$\begin{cases} I_{\text{evap}} = T_{amb}\left[\dot{m}_{wf}\left(S_3 - S_2\right) - \dot{m}_{\text{exh}}\left(S_{\text{exh,in}} - S_{\text{exh,out}}\right)\right] \\ I_{\text{cond}} = \dot{m}_{wf}\left[\left(h_4 - h_1\right) - T_{amb}\left(S_4 - S_1\right)\right] \\ I_{\text{turb}} = \dot{m}_{wf}\left[\left(h_3 - h_4\right) - T_{amb}\left(S_3 - S_4\right)\right] - \dot{W}_{\text{turb}} \\ I_{\text{pump}} = \dot{W}_{\text{pump}} - \dot{m}_{wf}\left[\left(h_2 - h_1\right) - T_{amb}\left(S_2 - S_1\right)\right] \end{cases} \tag{2.8}$$

## 2.4 ORC system cost assessment

The ORC system's cost assessment in this study assumes that the power generation from the system has the same cost price with the general cost of electric energy in the market. However, the electricity from the system by default is used in powering electrical appliances on the truck or stored in batteries for further use. The costing process was carried using current year 2020 market prices of the ORC components obtained directly from manufacturers' sales websites. These were used to plot the generic equations for calculating the costs of the various system components. The price details of Bowman shell and tube heat exchanger,[16] were plotted on a curve-fitting tool to generate the equation for estimating the cost of the evaporator. While the brazed plate heat exchanger catalogue,[17] was used for the condenser and the Green turbine data[18] was used for estimating the cost of the turbine coupled with a generator and this was compared with prices for expansion turbines from[19], which showed a good level of comparability, and finally,[20] was used for evaluating the cost of the pump for the working fluid. The curve-fitting plots used for evaluating the ORC system units costs are presented in Figures 4, 5, 6 and 7.

Thus, the individual costs plus costs of piping and working fluid are summed up to get the ORC module capital investment cost for the heat recovery application.

The preciseness of the estimates depends on the system's technical intricacy, the costing method, and suitable contingencies. Increasing the detailing of the designed system show little variation of the evaluated cost from the actual.

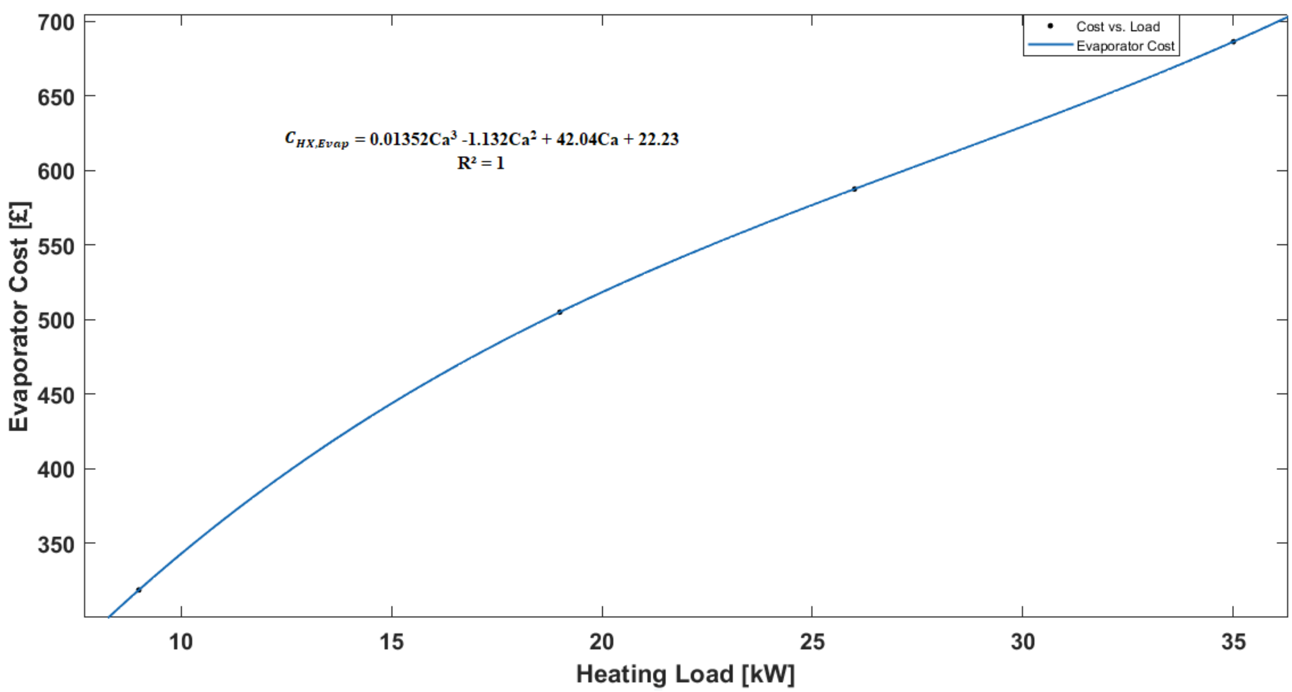


**Fig 4.** Fitting plot for evaporator cost estimation

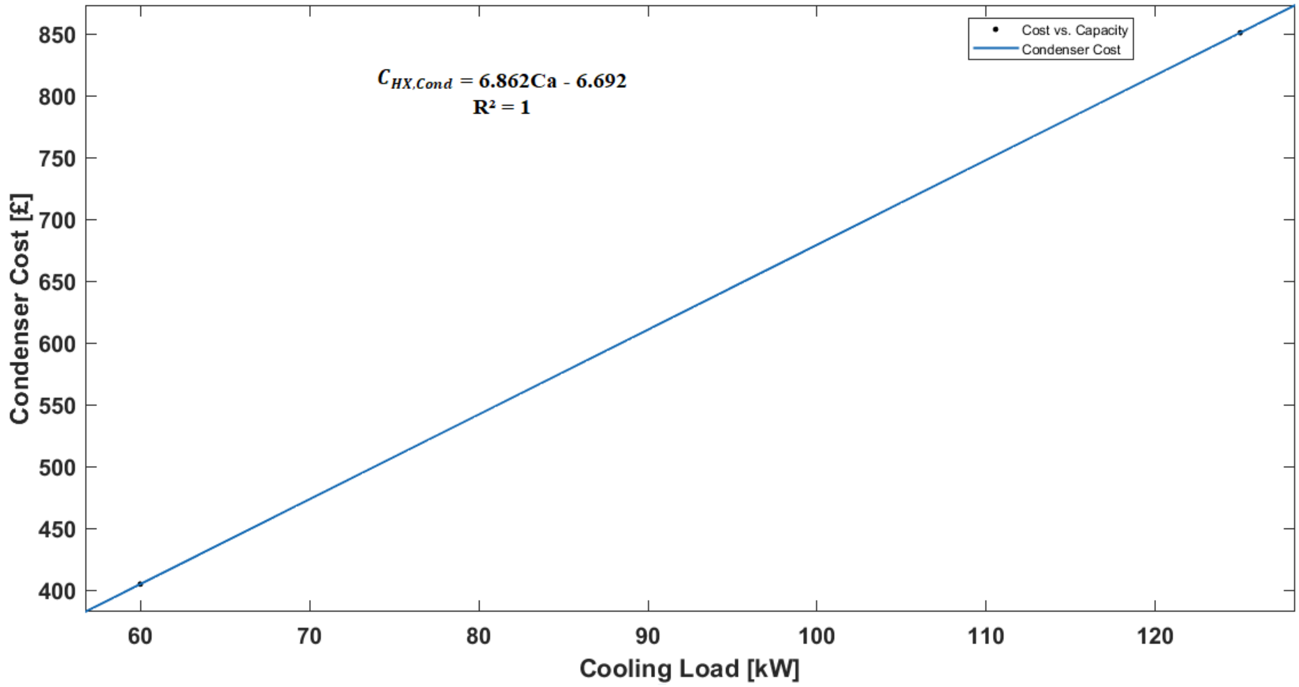


**Fig 5.** Fitting plot for condenser cost estimation

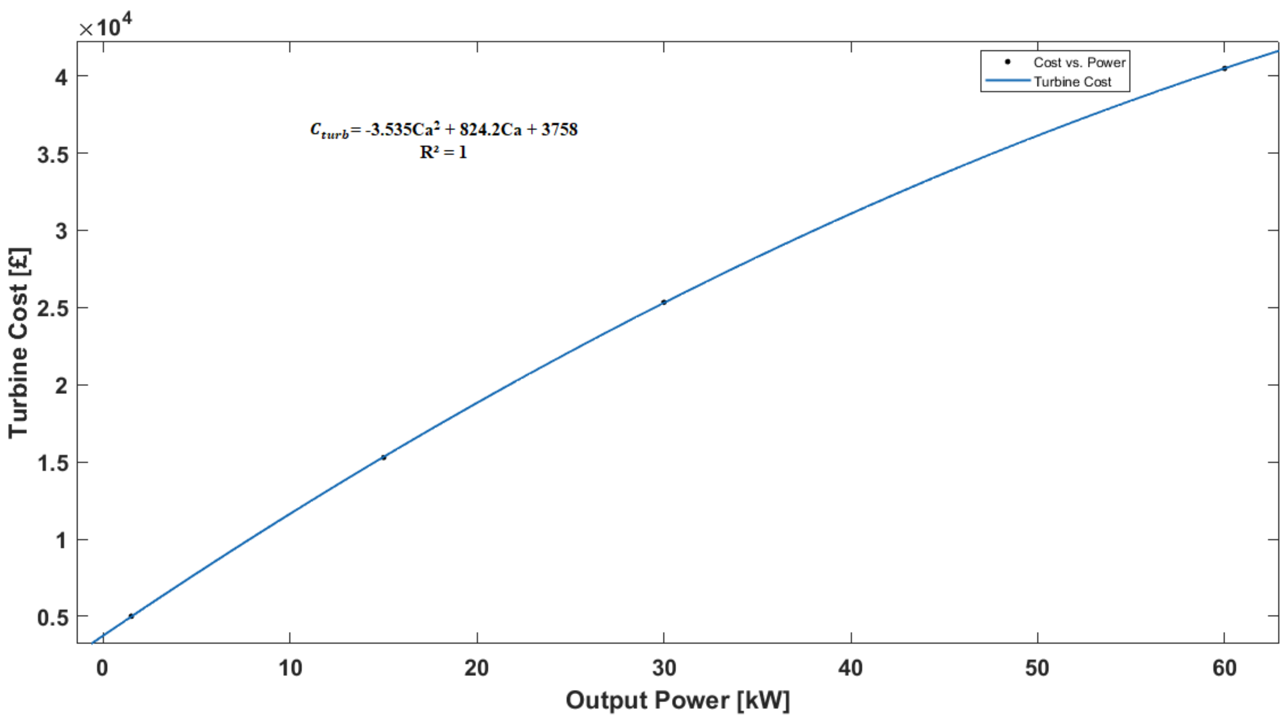


**Fig 6.** Fitting plot for turbine assembly cost estimation

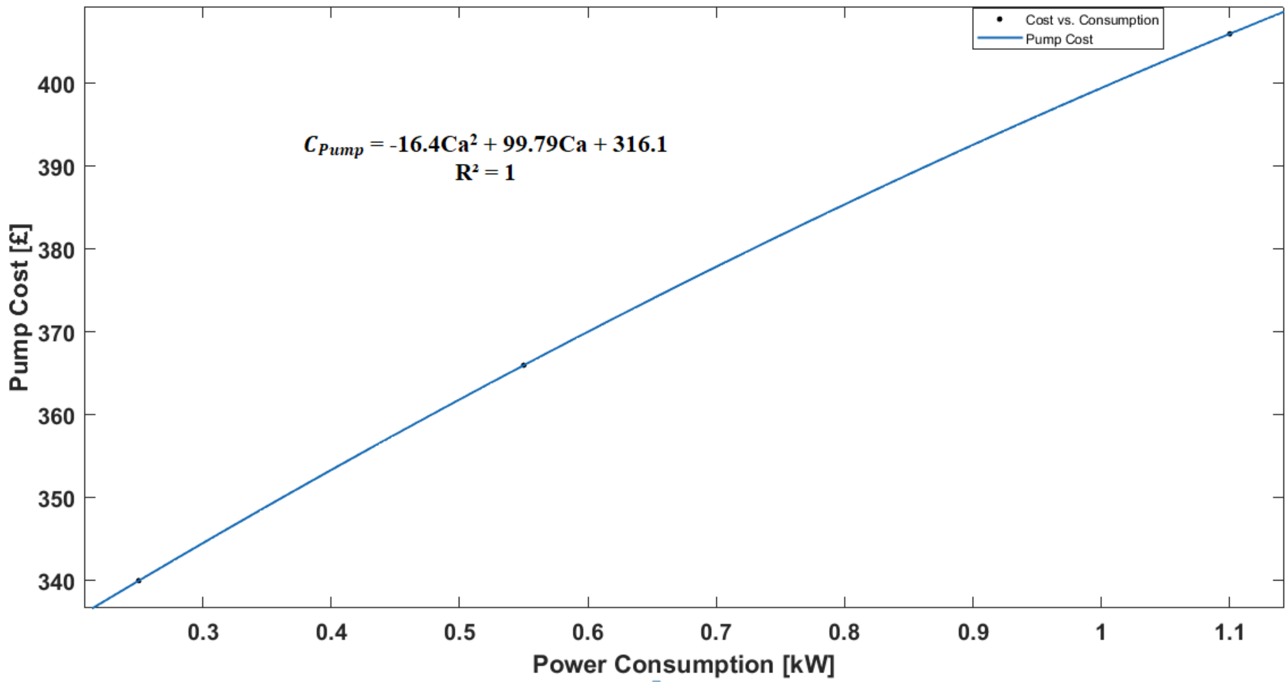


**Fig 7.** Fitting plot for pump cost

The cost estimations for the ORC primary components were expressed as follows.

$$\begin{cases} C_{HX,eva} = 0.01352\dot{Q}_{in}^3 - 1.132\dot{Q}_{in}^2 + 42.04\dot{Q}_{in} + 22.23 \\ C_{tur} = -3.535\dot{W}_{tur}^2 + 824.2\dot{W}_{tur} + 3758 \\ C_p = -16.4\dot{W}_p^2 + 99.79\dot{W}_p + 316.1 \\ C_{HX,con} = 6.862\dot{Q}_{out} - 6.692 \end{cases} \tag{2.9}$$

Where $C_{HX,eva}$ , $C_{HX,con}$, $C_{tur}$, & $C_p$= cost of ORC components (GBP), $\dot{Q}_{in}$and $\dot{Q}_{out}$= heating and cooling load, and $\dot{W}$ = power (kW), respectively.

The ORC cost estimation for sub-systems are realized from the following expressions: -

$$C_{Sys} = C_{HX,\,eva} + C_{HX,\,con} + C_{tur} + C_p \tag{2.10}$$

Cost of working fluid,[21]

$$C_{wf} = 10C_{rate} \tag{2.11}$$

Cost of piping[22]

$$C_{pipe} = 0.051C_{Sys} \tag{2.12}$$

Annual operation and maintenance cost,[23]

$$C_{O\&M} = 0.02C_{Sys} \tag{2.13}$$

Total cost of the ORC system elements

$$C_T = C_{Sys} + C_{pipe} + C_{wf} \tag{2.14}$$

The overall ORC module cost as considered in this work is presented thus:

$$C_{ORC} = C_T + C_{O\&M} \tag{2.15}$$

## 3 Results discussion

The results of the exergy analysis for each primary component of the ORC module are as discussed below.

### 3.1 Exergy performance

Exergy is the available maximum work of a thermodynamic system as it approaches the equilibrium state with its environment and enables the process inefficiency to be evaluated. Thus, exergy analysis is an essential tool used to determine the source, the location, and finally the level of inefficiencies in a thermodynamic process.

The results of the exergy performance analysis for this work are presented in- Table 4

**Table 4.** Irreversibility and exergy efficiencies in the ORC module

| Element | Irreversibility (kW) | Exergy Efficiency (%) |
|---|---|---|
| Evaporator | 6.11 | 70.2 |
| Condenser | 1.58 | 96.4 |
| Turbine | 1.25 | 62.9 |
| Pump | 0.13 | 64.5 |
| **ORC** | **9.07** | **54.6** |

### 3.2 Economic performance

The module costing results showed that a significant part of the costs is due to the turbine coupled with a generator, which takes up to 75% of the entire cost of the ORC module as shown in- Figure 8. This outcome highlights the evaporator as a crucial unit for potential cost optimization and then followed by the rest. The cost of the component units used for the estimations are all based on current market prices or as purchased from manufacturers. These results present a proxy version, which may slightly vary from the system's actual detailed cost. The concept used in this study to estimate the investment cost of the ORC system has already been outlined in the methodology.

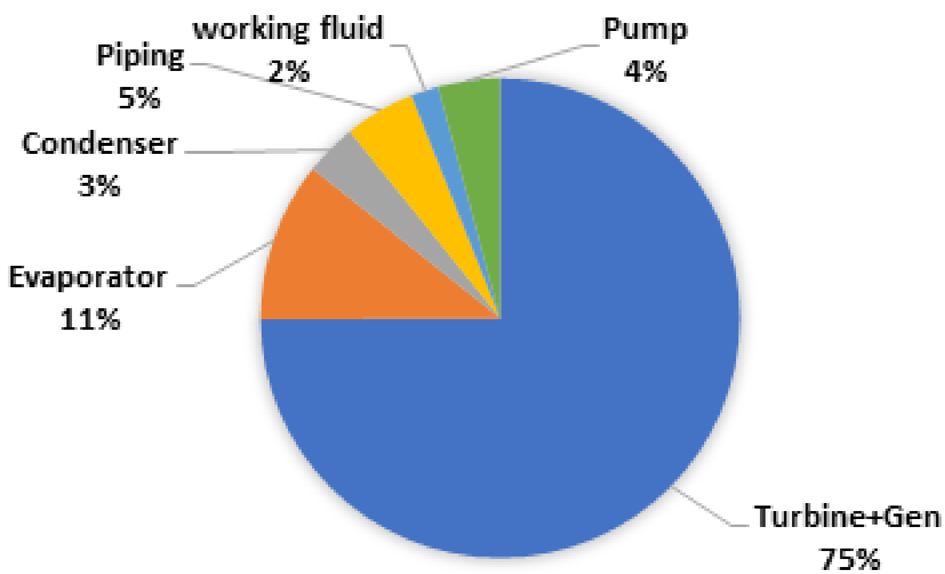


**Fig 8.** ORC module costing

Truck drivers are limited to a maximum of 10hrs driving time a day in the UK,[24]. The 10hr per day operation with the assumption of 26 days in a month was used to evaluate annual power recovery by the ORC system.

Monthly energy recovery is given as

$$26\,day \times \frac{10hr}{day} \times 3.1kW_e = 806kW_e hr \tag{3.1}$$

Annual electricity generation is

$$\frac{806kW_ehr}{month} \times \frac{12month}{year} = 9,672kW_ehr \tag{3.2}$$

The average electricity rate in the UK across the states is 14.37 pence/$kW_ehr$,[25]. Therefore, the annual cost of electric energy ($C_{an,\ elec}$) recovered by the designed ORC module will be

$$C_{an,\,elec} = \frac{9,672kW_ehr}{year} \times \frac{14.37\ pence}{kW_ehr} = 1,389.87 \tag{3.3}$$

*1 Specific investment cost (SIC)*

This section presents another option for determining the ORC system's performance besides the net power and system efficiency. The specific investment cost of the heat recovery unit in this study is evaluated from equation 3.4

$$SIC = \frac{C_T + C_{O\&M}}{\dot{W}_{net}} = \frac{8,381.98 + 156.53}{3.1} = \frac{2,754.36}{kW_e} \tag{3.4}$$

*2 Payback period*

The investment costs of small-scale ORC systems are substantially high compared to larger plants, and the costs of the small-scale modules range from £6,000 to £9,000,[12]. This assertion shows that the total investment cost of £8,456.61 obtained for the proposed model in this work falls within the range. The payback period (PBP) is commonly used for evaluating the financial performance of different systems in economics. The PBP for this work is calculated as

$$PBP = \frac{Initial\ Investment}{Net\ Cash\ Flow} = \frac{8,381.98}{1,233.34} = 6.8years \tag{3.5}$$

*3 Annual savings*

Annual fuel savings is an indicator for return on investment for truck owners if ORC system is installed for exhaust heat recovery.

Annual net saving (AS) for this module:

$$AS = C_{an,\ elec} - C_{O\&M} = 1,233.34 \tag{3.6}$$

*4 Electricity production cost (EPC)*

The cost of electricity production from ORC system according to[26] is given as

$$EPC = \frac{C_{O\&M} + \frac{i(1+i)^N}{(1+i)^N - 1} \times C_T}{\dot{W}_{net} \times hr_{op}} \tag{3.7}$$

Where $i$ = interest rate set at 5%, N = ORC system lifetime set 20yrs and $hr_{op}$= operating hours in a year

The economic performance of the ORC system has been assessed in terms of Specific Investment Cost (SIC), Payback Period (PBP), Annual Savings (AS), and Electricity Production Cost (EPC). The ORC system model was designed based on speed mode in which the model solver evaluates the engine model's performance and hence the ORC model using imposed truck speeds (66 to 119km/hr). These economic performance indicators were evaluated at the designed point (119km/hr) and design points to observe the system's performance at both design and off-deign points. Figure 9 shows that the electricity production cost (EPC) decreases from £0.831 to £0.086 with increasing truck speed while the electricity net output increases from 0.32kWe to 3.10kWe as the truck speed increases from 66km/hr to 119km/hr.

Figure 10 shows how the specific investment cost (SIC) and payback period (PBP) both decrease with increasing truck operating speed. This display is because as the shaft output power increases, the truck operating speed increases, thereby increasing the amount of electricity generation, which in turn reduces the specific investment cost and the number of years required for the payback. It can be inferred from this assessment study that,- if ORC system is considered for WHR in trucks, the module will potentially provide an annual savings of about £1,233.34 as shown in- Table 5.

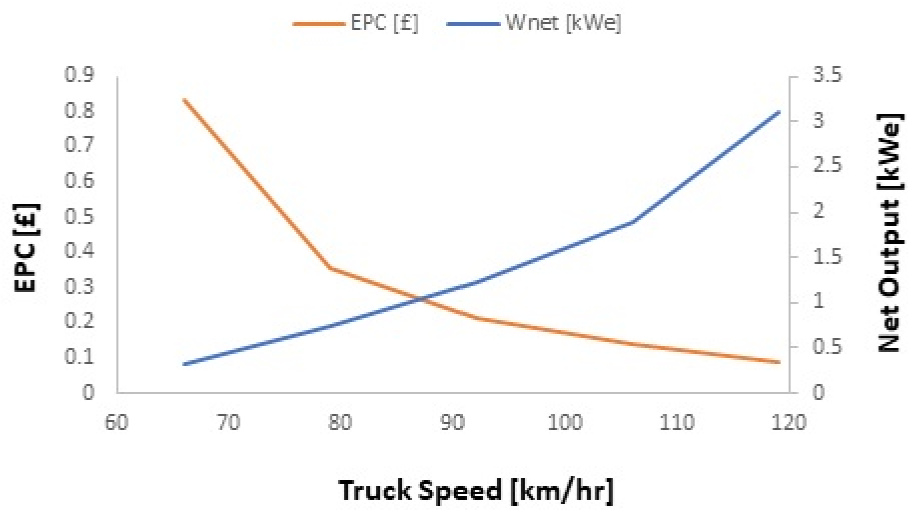


**Fig 9.** Influence of truck speed on EPC and net output

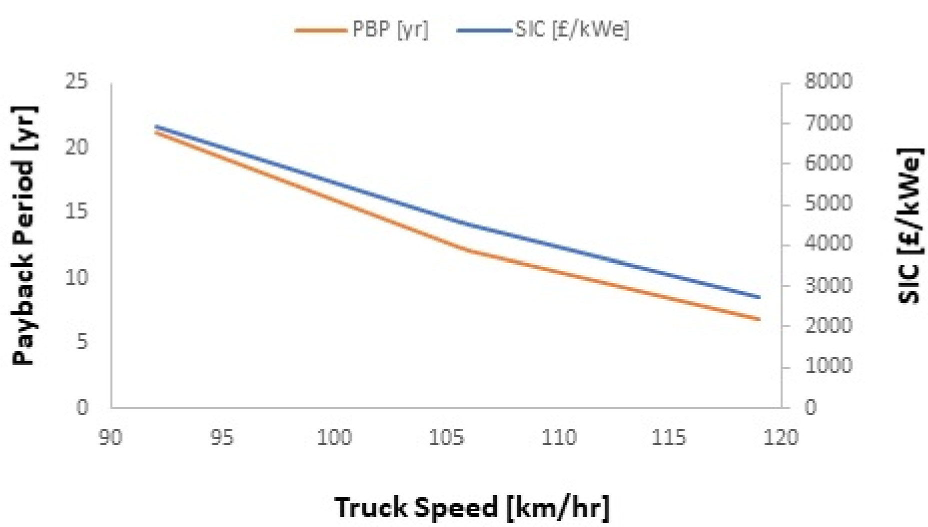


**Fig 10.** Influence of speed on payback period and specific investment cost

## 4 Conclusion

In this study, the thermodynamic and economic analyses of an ORC system designed for exhaust heat recovery from truck engines were evaluated. The recovered thermal energy which would have been exhausted into the environment is converted into electricity to supply power to electrical appliances on the truck or stored in batteries for future use. The quantified electricity cost and the savings show the potential economic viability of the installation of ORC system in highway trucks for waste heat recovery, thus justifying the primary objective function of the study. The results showed that the performance assessment at the designed point achieved 3.1kW as net output, 6.39% thermal efficiency, and 54.6% overall system exergy efficiency. Furthermore, the economic assessment within the boundary of the assumptions is £8,381.98, £2,754.36/$kW_e$, £0.086, and £1,233.34 as capital investment cost, specific investment cost, electricity production cost, and annual saving, respectively, with a payback period of 6.8years. Though the cost estimation was done using correlations, the resulting costs do not deviate substantially from the ORC

**Table 5.** Results of ORC module cost estimation

| Component | Cost (£) |
|---|---|
| Evaporator | 904.24 |
| Turbine & Gen. | 9,279.05 |
| Condenser | 293.45 |
| Pump | 349.90 |
| Piping | 399.16 |
| Working fluid | 156.18 |
| **Operation & Maintenance** | **156.53** |
| **Total** | **8,381.98** |
| **Specific Investment Cost (£/$kW_e$)** | **2,754.36** |
| **Payback Period (year)** | **6.8 years** |

module's actual purchased costs, considering the ORC system's primary components' market prices. The results of the economic assessment of ORC systems with respect to heat exchangers found in literature, compare favourably with those obtained in this study as referenced in the text. It should however be mentioned that vehicle weight and space requirements due to added ORC system are crucial challenges in WHR application in on-board vehicles resulting in the need for more traction efforts to accelerate the vehicle and increase tire rolling resistance. The additional weight also results in high fuel consumption, especially in light-duty vehicles, nonetheless, these additional loads and space restrictions are of minimal consequences in heavy-duty trucks and off-road vehicles due to their inherent structural design.

Furthermore, a change in mass flowrate and temperature of the exhaust gas logically will impact the power output (off-design) and may affect the result of the thermo-economic assessment. This notwithstanding, the present study based on a designed and simulated ORC system on a GT-suite platform with operating speed range of 66-119km/h using R245fa as working fluid can be considered as a benchmark and appropriate for feasibility study estimation using the performance indicators.

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