



Investigation of Waste Heat Recovery Systems for Improving Energy Efficiency in Internal Combustion Engines

Mahfuz Jeongmin

Department of Computer Science and Engineering, Mindoro International School of Engineering and Management, Philippines
mahfuz.jeongmin@misem-ph.org

Peer Review Information

Submission: 02 Jan 2021
Revision: 18 Feb 2021
Acceptance: 05 March 2021

Keywords

*Waste heat recovery,
Internal combustion
engine, Organic Rankine
cycle, Thermoelectric
generator, Energy
efficiency*

Abstract

Internal combustion engines convert only part of the fuel chemical energy into useful brake work, while a substantial fraction is rejected through exhaust gases, coolant and other thermal pathways. This paper develops a compact methodology for investigating waste heat recovery (WHR) systems intended to improve engine energy efficiency. The approach combines a first-law engine energy balance, exhaust heat availability estimation, screening of Organic Rankine Cycle (ORC), thermoelectric generator (TEG) and turbocompounding options, and a detailed ORC performance model. A generic 45 kW compression-ignition engine operating at 25-100% load is used as the methodological case. Exhaust heat is calculated from mass flow rate, specific heat and exhaust-to-ambient temperature difference; recoverable heat is then corrected for heat-exchanger effectiveness and conversion efficiency. The model predicts that net ORC power increases from about 0.53 kW at 25% load to 4.48 kW at full load, raising brake thermal efficiency from 37.5% to about 41.2% at the rated point. The comparison shows that ORC offers the strongest efficiency potential for sustained medium-to-high loads, TEG provides compact solid-state recovery at lower conversion efficiency, and turbocompounding can be attractive where exhaust pressure energy is high. The methodology is suitable for preliminary design, sensitivity analysis and subsequent experimental validation.

Introduction

Internal combustion engines (ICEs) remain important in road transport, heavy-duty mobility, distributed power generation and industrial equipment. Their principal limitation is that combustion heat cannot be completely transformed into shaft work. A large fraction of fuel energy leaves the engine through exhaust gas, coolant, charge-air cooling and radiation. Saidur et al. (2012) reviewed exhaust heat recovery technologies and identified ORC, thermoelectric generation and advanced turbocharging/turbocompounding as major routes for recovering this otherwise lost energy. Sprouse and Depcik (2013) similarly showed

that Rankine-based systems are particularly suitable for low- to medium-grade exhaust heat because a separate working fluid can be selected to match the thermal source.

Waste heat recovery can improve the effective brake thermal efficiency without increasing in-cylinder combustion severity. For vehicle applications, however, the useful thermodynamic gain must be balanced against additional mass, cost, packaging volume, exhaust backpressure, cooling demand and transient behavior. Aghaali and Ångström (2015) emphasized that turbocompounding can recover exhaust pressure and enthalpy, but excessive

backpressure can increase engine pumping work. Thermoelectric systems avoid moving parts and convert temperature difference directly to electricity, yet their performance is strongly affected by thermoelectric material quality and heat-exchanger design (Meng et al., 2016).

Recent reviews have shifted attention from simple maximum-efficiency calculations to system integration, working-fluid selection, off-design operation and dynamic control. Xu et al. (2019) noted that simulation studies often predict larger ORC power than experiments because real heat losses, component efficiencies and transient constraints reduce the available benefit. Tian et al. (2021) further identified backpressure, system weight, component design and off-design control as central barriers to commercialization. Therefore, a useful methodology should not only calculate theoretical waste heat, but should also impose realistic heat-exchanger and conversion efficiencies and compare alternative recovery paths.

The objective of this paper is to develop such a methodology for ICE waste heat recovery and demonstrate it through a simulation-based case study. The specific objectives are to: (i) quantify exhaust heat availability at multiple engine loads; (ii) compare the suitability of ORC, TEG and turbocompounding; (iii) model the ORC as the principal heat-to-power option; and (iv) evaluate the resulting gain in recovered power and brake thermal efficiency. The numerical results presented are model-generated values for a representative engine and are intended as a design methodology rather than as experimental measurements.

Literature Review

Early WHR studies established that the exhaust stream is attractive because it combines relatively high temperature with substantial mass flow. Macián et al. (2013) proposed a systematic bottoming-cycle methodology in which available heat and exergy are first quantified, followed by working-fluid and cycle optimization under practical limits. Their heavy-duty diesel example showed that the best thermal solution is not necessarily the easiest to package, making system-level selection essential. Amicabile et al. (2015) expanded this design logic by combining heat-source selection, candidate-fluid screening and optimization of alternative

subcritical and supercritical ORC layouts; the study demonstrated that economic and component constraints can change the preferred configuration.

The literature also shows that no single WHR technology dominates all operating conditions. Aghaali and Ångström (2015) reported that turbocompounding is mechanically simpler than a secondary thermodynamic loop and is especially attractive for high exhaust-flow engines, but backpressure and turbine matching must be controlled. Orr et al. (2016) reviewed car-based TEG and heat-pipe concepts and emphasized their solid-state simplicity together with material-temperature and conversion-efficiency limits. Meng et al. (2016) developed a multiphysics automotive TEG model and showed that module placement, cooling pattern and temperature non-uniformity have a strong effect on electrical output and reliability. Morgan et al. (2016) compared Rankine-cycle recovery with an intra-cycle concept and demonstrated that different recovery architectures must be assessed on both conversion performance and integration complexity. Lion et al. (2017) reviewed ORC deployment in on- and off-highway heavy-duty engines and stressed that design-point selection should reflect the actual engine speed-load profile rather than a single rated condition.

More recent reviews provide a stronger basis for integrated design. Hoang (2018) synthesized diesel-engine ORC research across heat-source selection, working fluids, components and thermodynamic-economic considerations. Xu et al. (2019) summarized heavy-duty diesel ORC architectures, expanders, heat exchangers, working fluids and control methods, noting a consistent gap between optimistic simulation outputs and experimental recovery power. Tian et al. (2021) organized the Rankine-cycle problem around working-fluid properties, cycle configuration, key components and real application penalties. Varshil and Deshmukh (2021) concluded that single-loop ORCs are generally attractive for vehicular diesel engines because they reduce weight, space and cost, whereas more complex dual-loop systems can recover more heat when packaging constraints are less severe. These findings motivate the present methodology: screening all major WHR options but applying a detailed single-loop ORC model for a vehicle-relevant engine.

Table 1. Selected literature used to define the present methodology

Study	WHR focus	Main methodological contribution	Relevance here
Saidur et al. (2012)	ORC, TEG, turbo systems	Technology-level review of exhaust recovery	Defines screening alternatives
Macián et al. (2013)	Bottoming Rankine cycle	Heat/exergy source selection and cycle optimization	Basis for energy-balance workflow
Amicabile et al. (2015)	Automotive ORC	Fluid/layout screening with practical constraints	Supports single-loop ORC design
Meng et al. (2016)	Automotive TEG	Coupled thermal-electrical system optimization	Provides TEG comparison criteria
Xu et al. (2019)	Heavy-duty ORC	Architecture, component and control review	Adds realistic efficiency penalties
Tian et al. (2021)	Rankine ICE-WHR	Challenges, working fluids, components, off-design issues	Frames implementation limitations

Methodology

The investigation is organized as a six-step simulation workflow so that the procedure can later be repeated with experimental engine data.

Step 1 - Define engine operating points. A representative turbocharged compression-ignition engine with a rated brake power of 45 kW is considered at a constant speed of 2000 rpm and at 25%, 50%, 75% and 100% load. For each operating point, brake power, fuel-energy input, exhaust temperature and exhaust mass flow are specified. The baseline brake thermal efficiency is calculated as $\eta_b = P_b / Q_f$, where P_b is brake power and Q_f is the fuel-energy rate.

Step 2 - Quantify exhaust heat availability. The sensible exhaust heat rate is calculated from $Q_{exh} = m_{exh} c_p (T_{exh} - T_{amb})$. A mean exhaust-gas specific heat $c_p = 1.08 \text{ kJ kg}^{-1} \text{ K}^{-1}$ and ambient temperature $T_{amb} = 30 \text{ }^\circ\text{C}$ are used. The method can be extended to coolant and EGR sources when measured temperature and flow data are available, consistent with the source-screening logic of Macián et al. (2013).

Step 3 - Screen WHR technologies. Three technologies are compared: ORC, TEG and turbocompounding. The screening criteria are source-temperature suitability, conversion efficiency, packaging, mass, maintenance, backpressure sensitivity and transient response. ORC is retained for detailed calculation because it can utilize medium-grade sensible heat and can be optimized using working-fluid and heat-exchanger parameters, as emphasized by Amicabile et al. (2015) and Lion et al. (2017).

Step 4 - Model the single-loop ORC. The ORC is represented by pump, exhaust evaporator/heat exchanger, expander and condenser. The exhaust

heat actually transferred to the working fluid is $Q_{HX} = \epsilon_{HX} Q_{exh}$. Heat-exchanger effectiveness is increased from 0.62 at low load to 0.72 at full load to represent improved thermal driving force. The net ORC conversion efficiency η_{ORC} is taken from 7% to 12% across the load range after accounting for expander output and pump/parasitic power. Net recovered power is $P_{rec} = Q_{exh} \epsilon_{HX} \eta_{ORC}$. These conservative values are consistent with the need to avoid idealized simulation assumptions highlighted by Xu et al. (2019) and Tian et al. (2021).

Step 5 - Calculate efficiency improvement. Recovered power is assumed to offset shaft or electrical demand and is added to useful output. The integrated efficiency becomes $\eta_{sys} = (P_b + P_{rec}) / Q_f$. The absolute efficiency gain is $\Delta\eta = \eta_{sys} - \eta_b$. If the recovered power is electrical, generator and power-electronics efficiencies should be inserted before this step; if mechanical, drivetrain efficiency should be included.

Step 6 - Evaluate practical constraints and sensitivity. A viable WHR system must preserve acceptable exhaust backpressure, provide adequate condenser heat rejection and respond safely to transient engine operation. The methodology therefore requires sensitivity checks on ϵ_{HX} , η_{ORC} , exhaust temperature and mass flow. For TEG, module temperature limits and cooling non-uniformity are important (Meng et al., 2016); for turbocompounding, the turbine pressure ratio and pumping-loss penalty must be included (Aghaali & Ångström, 2015). A 2021 exhaust-turbine generator simulation by Xu et al. (2021) also demonstrates why generator speed, turbine matching and the electrical conversion path should be modeled explicitly when power-turbine recovery is selected.

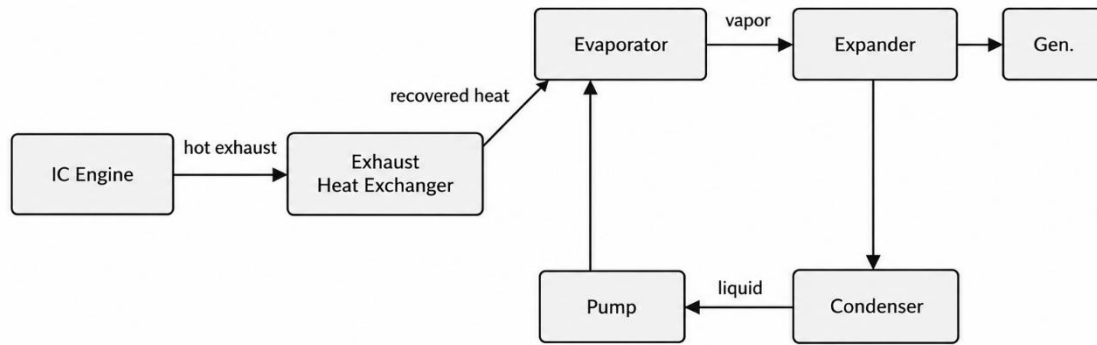


Figure 1. Methodology schematic for exhaust-based ORC waste heat recovery.

The controlled inputs used in the illustrative model are summarized in Table 2. They are not experimental measurements; they are selected

values used to demonstrate the calculation sequence and can be replaced directly by dynamometer data in a validation study.

Table 2. Model variables and assumed ranges

Variable	Assumed range / value	Role in calculation
Engine load	25-100%	Defines operating point
Brake power	11.25-45 kW	Baseline useful output
Fuel-energy input	40-120 kW	Denominator of BTE
Exhaust temperature	280-510 °C	Thermal driving potential
Exhaust mass flow	0.045-0.100 kg/s	Determines available heat rate
Heat-exchanger effectiveness	0.62-0.72	Fraction of exhaust heat captured
ORC net conversion efficiency	0.07-0.12	Heat-to-useful-power conversion

Results

Table 3 presents the calculated results. Exhaust thermal availability increases rapidly with engine load because both exhaust mass flow and temperature rise. At 25% load, the model gives approximately 12.15 kW of sensible exhaust heat, but only 0.53 kW becomes net recovered

ORC power because the temperature difference and cycle efficiency are comparatively low. At full load, exhaust heat reaches 51.84 kW and the recovered net power increases to 4.48 kW. The recovered fraction of the gross exhaust heat remains modest because the calculation includes both heat-exchanger and thermodynamic conversion losses.

Table 3. Model-generated ORC waste heat recovery results

Load (%)	Exhaust T (°C)	Q_exh (kW)	P_rec (kW)	Baseline BTE (%)	BTE with WHR (%)	Gain (points)
25	280	12.15	0.53	28.13	29.44	1.32
50	350	22.46	1.33	32.14	34.05	1.91
75	430	35.42	2.57	35.53	38.23	2.7
100	510	51.84	4.48	37.5	41.23	3.73

The efficiency trend in Figure 2 shows that WHR becomes more attractive as the engine approaches sustained medium-to-high load. The baseline brake thermal efficiency rises from 28.1% to 37.5% because the engine itself operates more efficiently at higher load. Adding the ORC raises the calculated system efficiency to 41.2% at full load, an absolute increase of 3.73 percentage points. Expressed relative to the baseline efficiency, this is approximately a 10% increase in useful energy conversion at the rated point. Such a magnitude is consistent with the range discussed in the ORC literature, although

the exact benefit in a real vehicle depends on duty cycle, heat-exchanger pressure drops, component efficiencies and transient control (Varshil & Deshmukh, 2021; Tian et al., 2021).

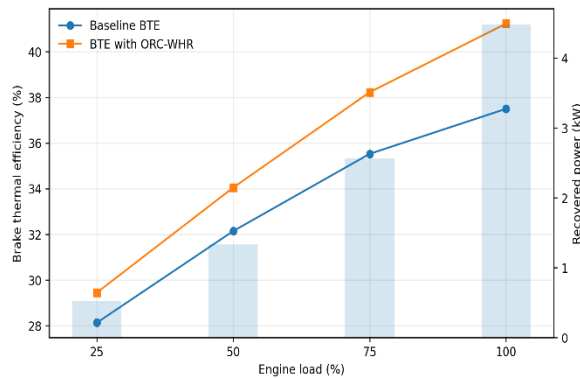


Figure 2. Predicted brake thermal efficiency and recovered ORC power versus engine load.

For technology selection, ORC provides the highest modeled recovery potential in this study because it can exploit the exhaust temperature over a broad range. TEG remains attractive when compactness, reliability and direct electrical output are more important than peak conversion efficiency, while turbocompounding is favorable for engines with high exhaust-flow energy and sufficient tolerance for pressure-ratio management. Therefore, technology choice should be based on the operating profile rather than on rated-point efficiency alone.

Conclusion and Discussion

The developed methodology provides a practical sequence for investigating ICE waste heat recovery without assuming that all exhaust energy can be converted into useful power. It begins with engine operating data, calculates available exhaust heat, applies technology screening, and then uses explicit heat-exchanger and conversion efficiencies to estimate net recovered power. This structure follows the design logic of prior ORC studies while remaining simple enough for a preliminary engineering paper. The illustrative case indicates that load strongly controls WHR value. At low load, exhaust temperature and flow are insufficient to justify a large bottoming system, while at full load the modeled ORC recovers about 4.48 kW and increases brake thermal efficiency from 37.5% to 41.2%. This confirms why heavy-duty highway engines, stationary generators and other sustained-load applications are frequently targeted for Rankine-cycle recovery. However, the benefit should not be interpreted as a guaranteed experimental result. Real systems experience additional heat loss, finite expander efficiency, pump and fan demand, working-fluid limits, condenser constraints, control delays and packaging penalties. Xu et al. (2019) specifically cautioned that simulations often overpredict experimental recovery power, and Tian et al.

(2021) emphasized the importance of off-design behavior and system integration. TEG and turbocompounding should not be excluded. TEG can provide maintenance-light electrical recovery and may be suitable for hybrid electrical architectures, while turbocompounding can deliver efficient pressure-energy recovery when turbine matching and backpressure are properly managed. The most appropriate system may therefore be application-dependent or hybrid. Future work should validate the methodology on an engine dynamometer using measured exhaust mass flow, temperature, pressure and fuel consumption; include exergy analysis; model transient driving cycles; optimize working fluid with environmental constraints; and perform cost, weight and payback analysis. Within these limitations, the proposed procedure is a defensible starting point for evaluating how WHR can raise the effective energy efficiency of internal combustion engines.

References

- Saidur, R., Rezaei, M., Muzammil, W. K., Hassan, M. H., Paria, S., & Hasanuzzaman, M. (2012). Technologies to recover exhaust heat from internal combustion engines. *Renewable and Sustainable Energy Reviews*, 16(8), 5649-5659. <https://doi.org/10.1016/j.rser.2012.05.018>
- Sprouse, C., III, & Depcik, C. (2013). Review of organic Rankine cycles for internal combustion engine exhaust waste heat recovery. *Applied Thermal Engineering*, 51(1-2), 711-722. <https://doi.org/10.1016/j.applthermaleng.2012.10.017>
- Macián, V., Serrano, J. R., Dolz, V., & Sánchez, J. (2013). Methodology to design a bottoming Rankine cycle, as a waste energy recovering system in vehicles. Study in an HDD engine. *Applied Energy*, 104, 758-771. <https://doi.org/10.1016/j.apenergy.2012.11.075>
- Amicabile, S., Lee, J.-I., & Kum, D. (2015). A comprehensive design methodology of organic Rankine cycles for the waste heat recovery of automotive heavy-duty diesel engines. *Applied Thermal Engineering*, 87, 574-585. <https://doi.org/10.1016/j.applthermaleng.2015.04.034>
- Aghaali, H., & Ångström, H.-E. (2015). A review of turbocompounding as a waste heat recovery system for internal combustion engines. *Renewable and Sustainable Energy Reviews*, 49,

813-824.
<https://doi.org/10.1016/j.rser.2015.04.144>

Meng, J. H., Wang, X. D., & Chen, W. H. (2016). Performance investigation and design optimization of a thermoelectric generator applied in automobile exhaust waste heat recovery. *Energy Conversion and Management*, 120, 71-80.
<https://doi.org/10.1016/j.enconman.2016.04.080>

Orr, B., Akbarzadeh, A., Mochizuki, M., & Singh, R. (2016). A review of car waste heat recovery systems utilising thermoelectric generators and heat pipes. *Applied Thermal Engineering*, 101, 490-495.
<https://doi.org/10.1016/j.applthermaleng.2015.10.081>

Morgan, R., Dong, G., Panesar, A. S., & Heikal, M. R. (2016). A comparative study between a Rankine cycle and a novel intra-cycle-based waste heat recovery concepts applied to an internal combustion engine. *Applied Energy*, 174, 108-117.
<https://doi.org/10.1016/j.apenergy.2016.04.026>

Lion, S., Michos, C. N., Vlaskos, I., Rouaud, C., & Taccani, R. (2017). A review of waste heat recovery and Organic Rankine Cycles (ORC) in on-off highway vehicle Heavy Duty Diesel Engine applications. *Renewable and Sustainable Energy*

Reviews, 79, 691-708.
<https://doi.org/10.1016/j.rser.2017.05.082>

Hoang, A. T. (2018). Waste heat recovery from diesel engines based on Organic Rankine Cycle. *Applied Energy*, 231, 138-166.
<https://doi.org/10.1016/j.apenergy.2018.09.022>

Xu, B., Rathod, D., Yebi, A., Filipi, Z., Onori, S., & Hoffman, M. (2019). A comprehensive review of organic Rankine cycle waste heat recovery systems in heavy-duty diesel engine applications. *Renewable and Sustainable Energy Reviews*, 107, 145-170.
<https://doi.org/10.1016/j.rser.2019.03.012>

Tian, H., Liu, P., & Shu, G. (2021). Challenges and opportunities of Rankine cycle for waste heat recovery from internal combustion engine. *Progress in Energy and Combustion Science*, 84, 100906.
<https://doi.org/10.1016/j.pecs.2021.100906>

Xu, Y., Cui, Y., Wang, Y., & Wang, P. (2021). Simulation study on exhaust turbine power generation for waste heat recovery from exhaust of a diesel engine. *Energy Reports*, 7, 8378-8389.
<https://doi.org/10.1016/j.egyr.2021.09.083>

Varshil, P., & Deshmukh, D. (2021). A comprehensive review of waste heat recovery from a diesel engine using organic Rankine cycle. *Energy Reports*, 7, 3951-3970.
<https://doi.org/10.1016/j.egyr.2021.06.081>