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**Comparative and Hybrid Integration Study of
Thermoelectric Generators and Organic Rankine Cycle
for Waste Heat Recovery in heavy duty Internal
Combustion Engines in off grid regions**

Promoteur :

Pr. B. BOUMEDANE

Réalisé par :

BELHATHAT MOHAMED

ANIS SEBKHAOUI KHETTABI

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First of all I just want to say alhamdulillah god gave me everything, alhamdulillah all the times and forever, alhamdulillah.

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Al-Kindi Club My second home, a place where different minds meet, unique experiences unfold, and bonds are formed with truly remarkable people. To all the members who have stood by me, celebrated my victories even more than I did myself, offered unwavering support, and cheered me on every step of the way—thank you from the depths of my heart. Your presence in my life has meant more than words can express. Every beautiful chapter must eventually close, but we ended ours with the best possible ending.

To my future wife , you are late..

Though I have not met you yet, I believe you will be my partner in all that lies ahead. I dedicate this effort to you as a symbol of loyalty and love for the journey we will build together.

And finally, a note to my 35-year-old self: “You’re welcome.” Keep reflecting on life and enjoying it to the fullest, live the moment, hold to your deen, trust the process, I’m proud of you no matter what, and finally happiness was always a decision for u to choose everyday.

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اولا الحمد لله الذي بنعمته تتم الصالحات فهذا توفيق من عند الله

ما انا الا مخلوق مسير من عند الله لأكمل طريق هو اختاره لي بمشيئته و توفيقه فالحمد و الشكر لله رب العالمين
يارب انت استثناء اشكرك يا الله بقلب كان منكسرا فجبرته و كان بعيدا عنك فقربته و لن نوفيكَ حقك فنعمك علينا لا
تحصى

*اللهم لك الحمد كما ينبغي لجلال وجهك و لعظيم سلطانك *

●I dedicate this work to those who have been my support throughout a 19 year journey of education and growth.

To my beloved family ,my parents my brother I extend my deepest thanks and appreciation for your support, patience, and constant encouragement that lit my path.

●professor, Mr. Boumedane,

My sincere gratitude for not only the knowledge you shared, but also for the principles and unforgettable sayings you instilled in us

among them:

"Don't stress... someone once stressed... and died."

A simple yet profound reminder of the value of calmness and balance when facing life's challenges.

●To my future wife,Though I have not met you yet, I believe you will be my partner in all that lies ahead. I dedicate this effort to you as a symbol of loyalty and love for the journey we will build together.

●And to my future children,May this work be a small cornerstone in the foundation of a life I hope will make you proud, just as I know you will be my greatest pride one day.

●And to my future self you re welcome

Always look back at this achievement and the path you walked for 19 years with pride.

Never regret the decisions you made they are what shaped the person you've become,I'm certain you'll be in a good place, and I'm proud of you.

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Khettabi anis sebkhaoui

ABSTRACT

The thesis is a comparative and integrated study of Waste Heat Recovery (WHR) technologies for a diesel internal combustion engine. The Organic Rankine Cycle (ORC) and Thermoelectric Generators (TEG) were separately evaluated for their performance in recovering energy from engine subsystems. After their thermodynamic characteristics and recovery efficiencies were investigated, a hybrid ORC-TEG model was developed and integrated with a Cummins QSK19-G4 engine. Thermodynamic simulations and hand calculations were performed to examine energy recovery from exhaust gases, coolant, lubricating oil, and structural surfaces. The overall recovery efficiency of the hybrid system was 47.3%, of which 44.56% was converted into useful electricity. A simplified economic analysis was also performed, confirming the technical and economic feasibility of this system for industrial applications. The findings present the value creation through the integration of technologies to provide maximal waste heat recovery and optimal engine efficiency.

Ce mémoire présente une étude comparative et intégrative des technologies de récupération de chaleur perdue (WHR) appliquées à un moteur diesel à combustion interne. Les performances du cycle de Rankine organique (ORC) et des générateurs thermoélectriques (TEG) ont d'abord été évaluées séparément afin d'estimer leur potentiel de récupération énergétique à partir des sous-systèmes du moteur. Après l'analyse de leurs caractéristiques thermodynamiques et de leurs rendements, un modèle hybride ORC-TEG a été conçu et intégré au moteur Cummins QSK19-G4. Des simulations thermodynamiques et des calculs manuels ont permis d'évaluer la récupération de chaleur des gaz d'échappement, du liquide de refroidissement, de l'huile moteur et des pertes radiatives. Le système hybride a atteint une efficacité de récupération de 47,3 %, dont 44,56 % sous forme d'électricité. Une évaluation économique simplifiée a confirmé la faisabilité technique et financière de ce système pour des applications industrielles. Les résultats mettent en évidence l'intérêt de combiner ces technologies pour maximiser la récupération thermique et améliorer le rendement global du moteur.

يقدم هذا البحث دراسة مقارنة وتكاملية لتقنيات استرجاع الحرارة المهدورة (WHR) المطبقة على محرك ديزل داخلي الاحتراق. تم تقييم أداء كل من دورة رانكين العضوية (ORC) والمولدات الحرارية الكهربائية (TEG) بشكل منفصل أولاً لتحليل قدرتها على استرجاع الطاقة من الأنظمة الفرعية للمحرك. وبعد دراسة خصائصها الديناميكية الحرارية وكفاءتها، تم تطوير نموذج هجين يجمع بين ORC و TEG وربطه بمحرك Cummins QSK19-G4. أُجريت محاكاة حرارية وحسابات يدوية لتقدير الطاقة القابلة للاسترجاع من غازات العادم و نظام التبريد. أظهر النظام الهجين كفاءة استرجاع كلية تبلغ 47.3%، منها 44.56% تتحول إلى كهرباء قابلة للاستخدام. كما أُجري تحليل اقتصادي مبسط أكد الجدوى التقنية والمالية لتطبيق النظام في البيئات الصناعية. وتُظهر النتائج القيمة المضافة من دمج التقنيتين لاسترجاع أقصى قدر ممكن من الحرارة وتحسين كفاءة المحرك.

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SYMBOL LIST

$\dot{m}_{\text{fuel}}$ — Fuel mass flow rate (kg/s)

LHV — Lower Heating Value of diesel (MJ/kg)

$\dot{Q}_{\text{fuel}}$ — Thermal power input from combustion (kW)

ρ — Fuel density (kg/m³)

C_{fuel} — Fuel cost (DZD/h)

$\dot{Q}_{\text{exhaust}}$ — Heat from exhaust gases (kW)

$\dot{Q}_{\text{coolant}}$ — Heat removed by coolant (kW)

$\dot{Q}_{\text{loss}}$ — Total waste heat losses (kW)

T_{exh} — Exhaust temperature (°C or K)

$\dot{m}_{\text{exhaust}}$ — Exhaust gas mass flow rate (kg/s)

c_p — Specific heat capacity at constant pressure (kJ/kg·K)

η_{ORC} — Thermal efficiency of ORC cycle

η_{turbine} — Isentropic efficiency of turbine

η_{pump} — Isentropic efficiency of pump

$\dot{W}_{\text{net}}$ — Net work output of ORC (kW)

$\dot{W}_{\text{turbine}}$ — Power from turbine (kW)

$\dot{W}_{\text{pump}}$ — Power consumed by pump (kW)

h, h_s — Enthalpy / isentropic enthalpy (kJ/kg)

s — Specific entropy (kJ/kg·K)

T — Temperature (°C or K)

P — Pressure (bar or Pa)

$\dot{m}$ — Mass flow rate (kg/s)

η_{TEG} — Thermoelectric efficiency (dimensionless)

ZT — Thermoelectric figure of merit

α — Seebeck coefficient (V/K)

σ — Electrical conductivity (S/m)

κ — Thermal conductivity (W/m·K)

ΔT — Temperature difference across TEG (K)

V — Voltage output from TEG (V)

η_{el} — Electrical efficiency (e.g., 44.56%)

$\eta_{overall}$ — Total WHR efficiency (e.g., 47.3%)

$E_{recovered}$ — Electrical energy recovered (kWh)

$\dot{Q}_{recovered}$ — Total recovered heat (kW)

C_{elec} — Value of recovered electricity (DZD/kWh)

ROI — Return on Investment (%)

General Introduction

In the global quest for energy efficiency and sustainable development, the management of waste heat has become a critical focus area in engineering and applied energy systems. Internal Combustion Engines (ICEs), despite their widespread use and mechanical reliability, are notorious for their poor energy conversion efficiency—often dissipating more than half of the fuel energy as waste heat through exhaust gases and cooling circuits. This unutilized thermal energy not only reduces overall efficiency but also contributes to environmental degradation through excessive fuel consumption and heat rejection into the surroundings. With the rising cost of energy, the tightening of emissions regulations, and the global shift toward carbon neutrality, there is an urgent need to re-evaluate existing systems for better energy recovery and resource optimization. This context frames the relevance and necessity of advanced Waste Heat Recovery (WHR) technologies such as the Organic Rankine Cycle (ORC) and Thermoelectric Generators (TEG). These systems offer viable, scalable, and modular solutions to convert waste heat into usable energy—either in the form of electricity or thermal output.

The ORC system, based on traditional thermodynamic principles, uses an organic working fluid with low boiling points to convert low- and medium-grade heat into mechanical and subsequently electrical energy. It has proven to be efficient, adaptable, and relatively mature in industrial applications. On the other hand, TEGs, which exploit the Seebeck effect in thermoelectric materials, can directly convert heat differentials into electricity with no moving parts, minimal maintenance, and compact design, but often suffer from lower efficiency and require high-grade heat for optimal performance. Both systems exhibit unique advantages and limitations that make them suitable for different temperature ranges and operational contexts.

This thesis is dedicated to a comparative study and hybrid integration of ORC and TEG systems as applied to the waste heat of a diesel-powered Cummins QSK19-G4 engine. The research aims to numerically and thermodynamically evaluate the performance of each system, compare their effectiveness under various boundary conditions, and finally propose and simulate a hybrid architecture that combines their strengths while counteracting their individual limitations. In order to maximize the net recovery of the energy and the maximum utility of low-grade heat, the last refrigeration stage is integrated (using exhaust heat leftover of the ORC) thereby achieving cascaded energy usage framework involving electrical, mechanical, and refrigeration outputs.

The EES (Engineering Equation Solver) is employed for simulation and modelling of the TEG and ORC systems individually and in the hybrid mode based on actual thermodynamic parameters, temperature limits, pressure drops, and material limits (such as PbTe and Toluene limits) and inter-system thermal linkages. Extensive parametric analysis is also conducted to explore how operating temperatures, heat exchanger efficiencies, and mass flow rates influence system output and efficiency.

General Introduction

Through this multi-layered approach, the thesis addresses several key research objectives:

- To quantify the comparative efficiency and output of ORC and TEG systems under realistic ICE exhaust conditions.
- To evaluate the thermodynamic feasibility of a hybrid ICE/TEG/ORC system in terms of energy density, power production, and system integration.
- To introduce and validate the addition of an absorption chiller stage to utilize residual low-grade heat.

To simulate the complete WHR cascade system, analyze its behavior under different temperature nodes, and assess its potential for industrial application.

Ultimately, this work aspires to contribute to the development of smarter, more sustainable energy recovery systems that minimize losses, reduce emissions, and improve the overall performance of conventional power sources. The originality of this study lies not only in the hybrid integration of multiple WHR technologies but also in the careful thermodynamic and parametric justification of each stage, offering a pathway toward comprehensive energy optimization in heavy-duty engine applications.

CHAPTER I:

Bibliographic Research

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I.1 Introduction

I.1.1 Historical Background and the Role of Thermal Energy

Fire, heat, and thermal energy have long been fundamental tools in the development of human civilization. Since ancient times, fire has served as a cornerstone of progress, playing a crucial role in shaping societies. From prehistoric use of fire to drive metallurgy to the steam age, the control of heat has marked every industrial step forward. The internal combustion engine (ICE), first successfully demonstrated by Nikolaus Otto in 1876, represents a more advanced utilization of thermal energy, harnessed to serve the needs of modern life [1], [2]. It stands as a pivotal innovation of the Industrial Revolution, with its influence extending to nearly every aspect of daily human activity.

I.1.2 Classification of Thermal Engines

Combustion is a fundamental criterion used to classify thermal engines into external and internal types [1]. These engines are generally divided into two general categories: external combustion engines and internal combustion engines. External combustion engines, such as the early steam engine and the Stirling engine, operate by burning fuel outside the working cylinder, transferring heat indirectly to the working fluid. Unlike them, however, are internal combustion engines, which perform the process of combustion within the engine itself with the fuel actually burning right in the combustion chamber. Internal combustion engines can further be classified on the basis of how combustion happens. Among them is intermittent combustion where fuel and the oxidizer (air) are fed in, mixed, and then burnt in successive repeating cycles. This type includes engines like the conventional piston engine and the Wankel rotary engine. The second type is continuous combustion, having a continuous and uninterrupted combustion process in a continuous air stream. Jet engines, gas turbines, and rocket engines fall under this type because their combustion chambers possess a constant flame, as opposed to the periodic nature of continuous combustion systems.

I.1.3 Focus of the Study : Piston Engines

The subject of interest in this research is the piston engine. The engines of these kind are what separate them from all other kinds. The otto and the diesel cycle are most famously known.

I.1.3.1 The Otto cycle :

Also known as the gasoline engine, the Otto cycle was conceptualized by German engineer Nikolaus Otto in 1876 [1], [3]. The Otto cycle is the ideal thermodynamic cycle employed to describe the operation of a generic spark-ignition internal combustion engine that is widely used in gasoline engines. The Otto cycle consists of four processes:

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two isentropic (adiabatic reversible) and two isochoric (constant volume) processes. The cycle includes:

1. Isentropic compression (adiabatic compression)
2. Isochoric heat addition (combustion at constant volume)
3. Isentropic expansion (power stroke)
4. Isochoric heat rejection (exhaust at constant volume)

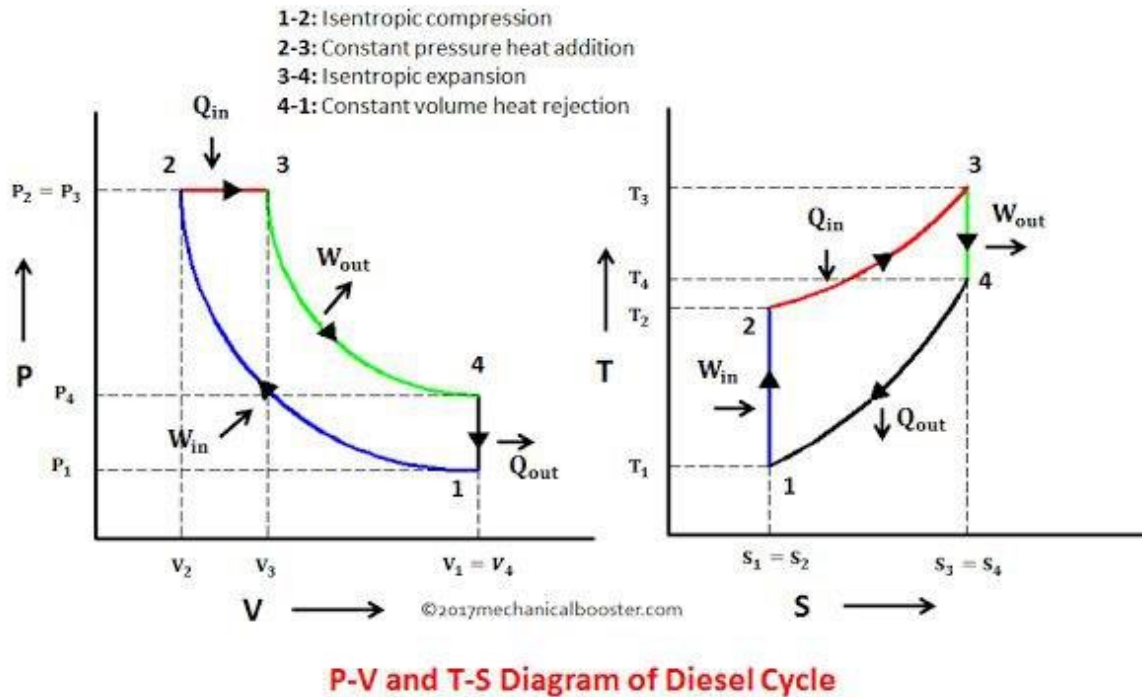


Figure1.1: P-V and T-S Diagram of Diesel Cycle

The thermal efficiency of the Otto cycle is primarily dependent on the compression ratio and specific heat ratio of working fluid. With larger compression ratios, the thermal efficiency is higher, but this is limited by engine knock on startup.

I.1.3.2. Diesel Cycle:

The Diesel cycle is the most suitable cycle for compression-ignition engines, which are more commonly used in diesel engines [4]. Unlike the Otto cycle, combustion is constant-pressure, which is the key difference. There are four processes of the Diesel cycle:

1. Isentropic compression
2. Isobaric heat addition (constant-pressure combustion)
3. Isentropic expansion
4. Isochoric heat rejection

CHAPTER I: Bibliographic Research

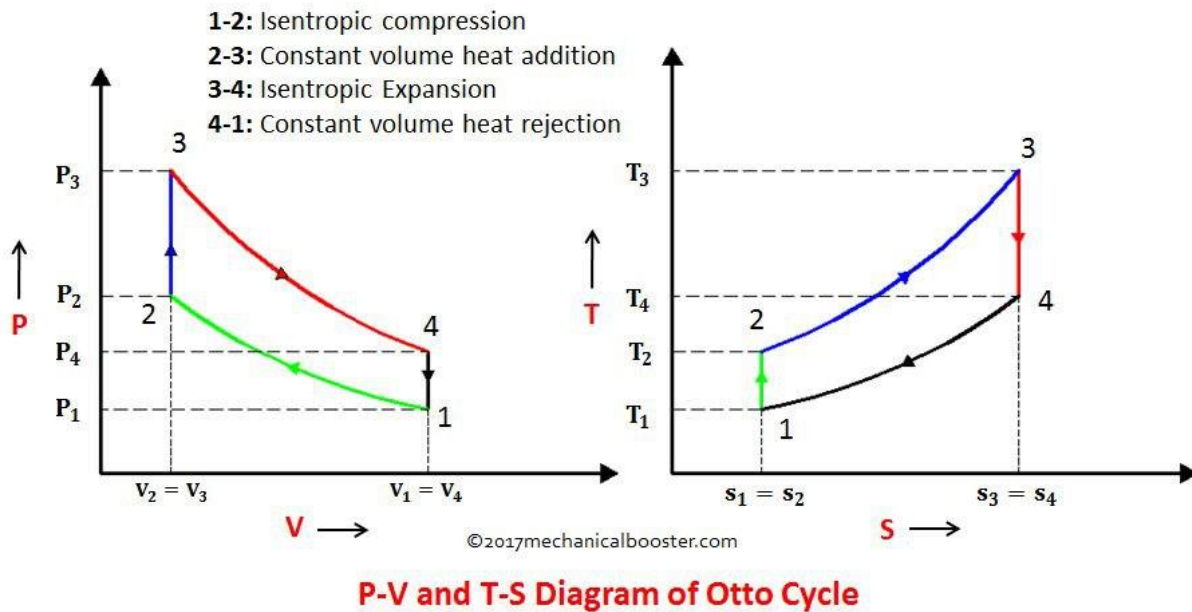


Figure1.2: P-V and T-S Diagram of Otto Cycle

In the Diesel cycle, the thermal efficiency increases with the compression ratio due to both, but as diesel engines employ higher compression ratios, they are more efficient compared to Otto engines. The cut-off ratio (end volume to start volume at the end of combustion) also has an influence on efficiency, though.

I.1.4 Energy Flow and Losses in ICes

In internal combustion (IC) engines, chemical energy from the fuel is considered to be 100%, but only 25–35 % and up to 42% in high-efficiency diesel engines is typically converted into brake power [4]. The majority of it is wasted in the form of heat or through other inefficiencies. The most significant energy loss is via the exhaust gases, which can lose up to 40% of the energy from the fuel as waste heat to the surroundings. Additionally, approximately 10% to 20% of the input energy is lost via the engine's cooling system, while 5% to 10% is lost due to mechanical friction, pumping losses, and other internal resistances. Another 2% to 5% is lost due to radiated heat and miscellaneous loss.

Although this energy breakdown is a comparatively low thermal efficiency compared to the fuel input, IC engines are still of tremendous value in modern applications due to their reliability, power density, and entrenched infrastructure. With the use of energy recovery systems—like turbochargers, organic Rankine cycles (ORCs), and a thermoelectric generator (TEGs)—there is scope to sharply enhance the overall efficiency. These technologies give internal combustion engines a path to remain relevant in an era more focused on energy efficiency and sustainability[5].

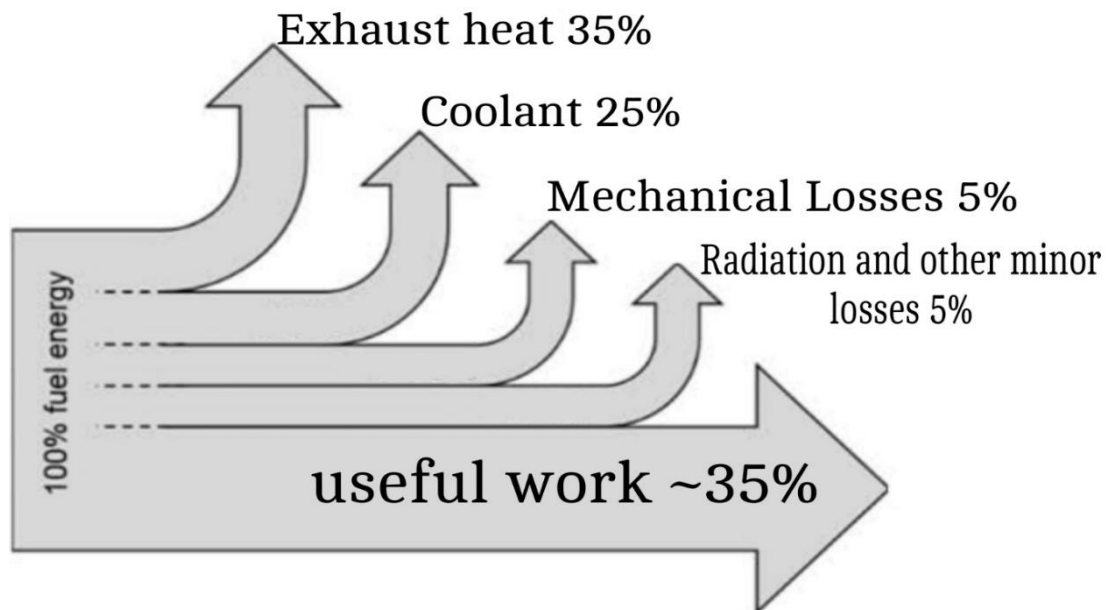


Figure 1.3: Energy flow and losses in ICEs

I.2 Engine Case Study: Cummins QSK19 -A Prime Candidate for Waste Heat Recovery Simulation

To model waste heat recovery using Organic Rankine Cycle (ORC) and Thermoelectric Generators (TEG) in a realistic and industry-relevant context, we selected the Cummins QSK19 engine as the reference heat source. The engine was selected due to its widespread industrial application, robust thermodynamic performance, and availability of credible public performance data.

I.2.1:General Description of the Cummins QSK19

The Cummins QSK19 is a 4-stroke, turbocharged, 6-cylinder diesel engine with a displacement of 18.9 liters. It is tailor-made for heavy-duty applications in oil & gas, mining, power generation, and off-grid industrial equipment, offering an attractive balance between thermal efficiency, longevity, and data transparency.

- Engine Type: Inline-6, 4-stroke Diesel
- Displacement: 18.9 L
- Bore x Stroke: 159 mm x 159 mm
- Compression Ratio: ~16.0:1
- Turbocharging: Yes (High-efficiency Holset turbocharger)
- Aspiration: Turbocharged and aftercooled
- Fuel System: Direct Injection, Common-Rail
- Cooling: Jacket water cooling
- Emissions Systems (optional): Diesel Particulate Filter (DPF), Selective Catalytic Reduction (SCR)



Figure 1.4: The Cummins QSK 19 -1-

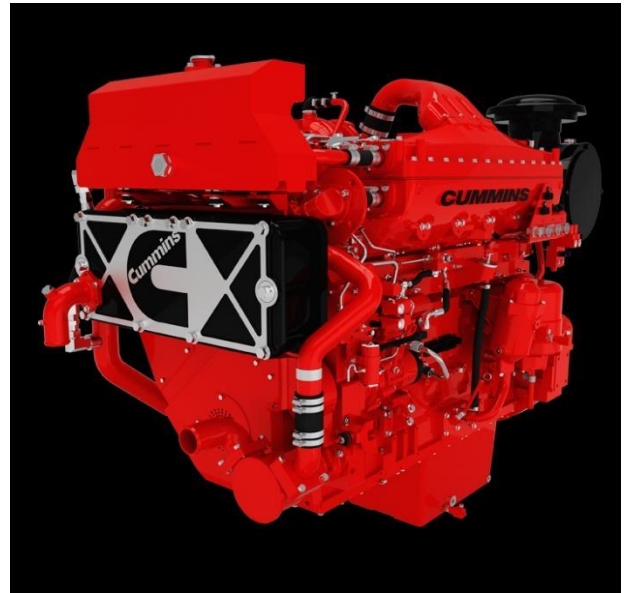


Figure 1.5: The Cummins QSK 19 -2-

I.2.2.Power and Performance Parameters

These parameters are of utmost importance to decide engine input-output energy balance and to determine the amount of recoverable thermal energy.

- Rated Power Output: 580 kW (dependent on configuration)
- Brake Thermal Efficiency (BTE): Approximately 35% – 42%
- Fuel Consumption: ~117.6 L/h at 100% load for 1500 RPM
- Engine Speed: Typically 1500 RPM
- Air-Fuel Ratio: ~23–30 (lean-burn diesel)
- Exhaust Back Pressure Limit: ~10–30 kPa (typical range)

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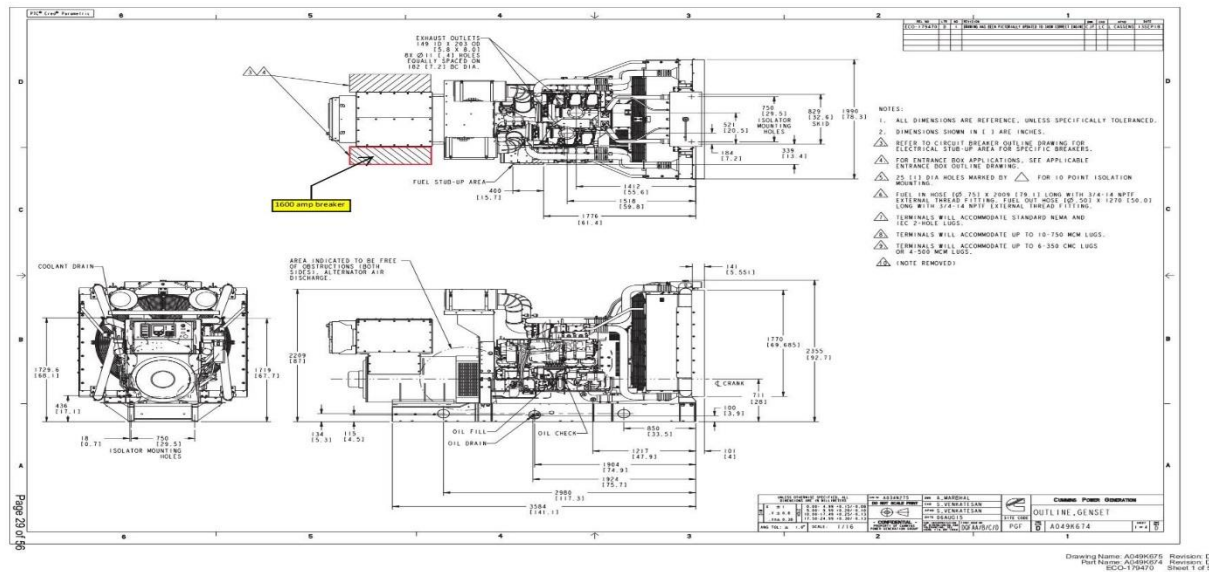


Figure 1.6: Schematic of Cummins QSK19 Describing the Engine

1.2.3. Exhaust Gas Properties

The exhaust gas is the primary source of heat for the ORC and secondarily for the TEG. The following values are important in establishing available heat energy and heat exchanger design for the ORC cycle.

- Exhaust Gas Temperature at Full Load:

450°C – 600°C, load and turbocharger configuration dependent

- Exhaust Mass Flow Rate

~0.8 – 1.2 kg/s at 100% load

- Specific Heat of Exhaust Gas (C_p):

Estimate around 1.1 kJ/kg·K (for diesel exhaust, estimated)

- Total Exhaust Thermal Power:

It may be up to 400 – 600 kW at full load with sufficient thermal potential for ORC systems

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I.2.4.Cooling Circuit Data (Optional for TEG Application)

The cooling circuit (especially jacket water) can be a secondary heat source for low-grade waste heat recovery, specifically for TEG systems.

- Jacket Water Outlet Temp: 90 – 105°C
- Coolant Flow Rate: ~300–450 L/min
- Engine Oil Temp: ~100–120°C loaded
- Total Heat Rejected to Coolant: ~150 – 250 kW (full load)

I.2.5.Engine Layout and Scalability

A second area of QSK19 strength is modularity. This enables multiple parallel engine system simulation for scalable industrial uses (e.g., 2–4 engines to power an off-grid mining camp).

- System Integration Potential
 - ♦ Exhaust Heat → ORC Heat Exchanger → Turbine
 - ♦ Residual Heat → TEG Modules on manifold or coolant circuit
 - ♦ Parallel Operation: Imitating 4× QSK19 engines = 3–5 MW power station

I.2.6.Data Availability & Modeling Benefits

Performance curves, thermal balance sheets, and parts diagrams made available to the public by Cummins simplify simulation. This data renders your model thermodynamically realistic and correct, especially with regard to academic integrity and industrial applicability.

- Available Data Includes:
 - Exhaust temperature vs. engine load
 - Brake power and fuel consumption curves
 - Engine schematics for heat exchanger integration
 - Cooling system performance

I.3 Waste Heat Sources in ICEs

Waste heat refers to the thermal energy generated during mechanical or industrial processes—such as fuel combustion or chemical reactions—that is not converted into useful work and is instead lost to the environment. Internal combustion engines (ICEs) and turbine-based power generation units are prime examples of systems that produce substantial amounts of waste heat during their operation. This thermal energy is

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dispersed across various engine subsystems, both major and minor. Recovering this otherwise lost energy can significantly enhance overall efficiency and is commonly achieved using dedicated waste heat recovery technologies.

I.3.1 Exhaust System

- Exhaust gases after combustion:

High-temperature gases ranging from 300°C to 700°C are expelled through the exhaust manifold and tailpipe, representing one of the largest losses of usable thermal energy.

- Turbocharger (if equipped):

Although designed to harness some of this exhaust energy to improve performance, turbochargers themselves emit residual heat into the surrounding environment.

I.3.2 Cooling System

- Engine coolant (radiator circuit):

The coolant absorbs heat from the engine block and cylinder head, transferring it to the air through the radiator—a significant channel of waste heat.

- Heater core (in automobiles):

Designed to utilize engine heat for cabin comfort, this component transfers some of the coolant's thermal energy into the vehicle interior, although the rest is still released externally.

I.3.3 Other Minor Waste Heat Sources

I.3.3.1 Engine Structure – Radiation Losses

- Cylinder walls, piston crowns, cylinder head, and valves:

These critical components conduct heat during combustion.

- Crankcase and oil pan:

These parts contribute to thermal losses by radiating absorbed heat into the surrounding air.

- External engine surfaces

I.3.3.2 Lubrication System

Lubricating oil circulates through the engine, absorbing heat from components like the pistons, crankshaft, camshaft, and bearings.

The heated oil releases energy through the oil cooler or sump, with oil temperatures typically ranging between 70°C and 120°C.

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I.3.3.3 Combustion Process Inefficiencies

- Incomplete combustion:

Not all fuel is completely burned; leftover hydrocarbons and carbon monoxide—forms of chemical energy—are exhausted in the exhaust or combusted subsequently in the catalytic converter.

- Frictional losses:

Internal friction between moving parts converts mechanical energy to low-grade heat, adding to the engine's thermal inefficiency.

I.3.3.4 Fuel and Intake Systems

- Fuel heating:

In systems such as direct-injection gasoline engines or engines using exhaust gas recirculation (EGR), the incoming air/fuel mixture can absorb heat from surrounding engine components, slightly raising its temperature before combustion.

- Intercoolers (in turbocharged engines):

These devices remove heat from compressed intake air to boost efficiency, but the extracted heat is typically rejected to the atmosphere.

I.3.3.5 Auxiliary Systems – Components

- Alternator:

Produces electricity from mechanical energy, but in the process suffers losses in efficiency that present as heat.

- Starting motor and electrical devices:

Smaller components like these generate resistance electrical heat, especially under load or from cycling.

- Air conditioning compressor:

Imposes a mechanical load on the engine and converts the heat energy to the ambient through the condenser.

- Power steering and hydraulic pumps:

Convert mechanical energy into fluid pressure. Heat is lost with hydraulic fluid as well as on component surfaces.

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I.4 Waste Heat Recovery Technologies

Waste heat recovery (WHR) in internal combustion engines has become a significant research area, particularly for heavy-duty and off-grid applications [5]

I.4.1 Classification of Waste Heat Recovery (WHR) System

A) By Heat Source

Exhaust Gas: Principal high-temperature source (300–700°C), ideal for ORC, TEGs, and turbo-compounding.

Coolant: Conveys medium-temperature heat (80–120°C); preheating fluid for ORC, cabin, or fuel/lubricant preheat is possible.

Lubricating Oil and Intercoolers: Secondary low to medium-grade sources, recoverable by means of compact exchangers.

B) Based on Temperature Range

High-Temperature (>400°C): Suited for exhaust-based ORC applications with toluene or steam.

Medium-Temperature (150–400°C): EGR recovery and oil, through use of ORC or Kalina cycle.

Low-Temperature (<150°C): Intercoolers and coolants; recovered via low-boiling-point ORCs or Stirling engines.

C) By Technology Type

Thermodynamic Cycles: ORC and Kalina machines recover heat to generate mechanical or electric power with the help of a working fluid.

Solid-State Devices: TEGs use the Seebeck effect to generate electricity directly from heat.

Mechanical Systems: Turbo-compounding returns exhaust energy back to the crankshaft.

Thermal Storage: Phase Change Materials (PCMs) store excess heat to be utilized in the future.

D) By Final Application

Electricity Generation: ORC and TEGs can provide auxiliaries or charge batteries.

Mechanical Work: Turbo systems can boost engine power.

Thermal Use: Preheat cabin, oil/fuel preheat, or battery thermal management.

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Coolant Heat in Hybrid Systems: Frequently used for preheating ORC working fluid or stabilizing TEG during start-up....[5],[6].

I.4.2 Most Important Performance Indicators of WHR Systems

Quantifying the thermal, mechanical and economic efficiency is required to evaluate the feasibility and effectiveness of waste recovery systems (WHR) and to do that you need certain performance metrics. These metrics allow engineers and scientists to compare different WHR technologies—e.g., the Organic Rankin Cycle (ORC) and thermoelectric generators (TEGs)—and measure their suitability for application in specific engine configurations or operating conditions. Significant measures are thermal efficiency, power density, specific power, cost-effectiveness, and system reliability.

The thermal performance of a WHR system, usually expressed as recovered work output over total recoverable waste heat input, is an important measure of system performance. In the case of ORC systems, it is a function of working fluid properties, temperature gradients, and component efficiencies (e.g., pump, turbine). For TEGs, material properties and hot-to-cold side temperature difference limit efficiency. In practice, this results in ORC systems with greater efficiencies (about 20%) than TEGs (typically less than 10%).

Power density in the form of power output per unit volume (W/m^3) or per unit mass (W/kg) is a very critical parameter, especially in mobile or space-constrained applications like automotive or off-highway engines. A high power density will allow the WHR system to deliver plenty of energy without significantly contributing to the system's weight or dimensions.

Specific power, or the power recovered per unit exhaust gas flow (kW per kg/s), is useful in determining the integration potential of WHR systems with internal combustion engines. It relates the engine's exhaust characteristics to the ability of the WHR system to make use of that flow as useful energy.

Economically, cost-effectiveness is measured in terms of parameters such as cost per kilowatt of recovered power ($\$/\text{kW}$) and the payback period, an approximation of the time it would take the system to recover its installation cost through savings in fuel. Both of these are crucial in commercial and industrial installations, where return on investment determines viability.

Lastly, system robustness, durability, and reliability are important factors to consider, especially for extreme working conditions. Simple systems with few moving parts (like TEGs) are generally favored for their ruggedness, even if they are less efficient. But ORC systems can be more efficient at the cost of increased system complexity, maintenance needs, and vulnerability to fouling or degradation of the working fluid.

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I.5 Organic Rankine Cycle

I.5.1 Organic Rankine Cycle Definition:

The Organic Rankine Cycle (ORC) is a thermodynamic cycle that converts low to medium temperature heat sources into mechanical work, which is usually converted to electricity.

Unlike the traditional Rankine Cycle that uses water and steam as a working fluid, the ORC uses organic fluids (refrigerants) with low boiling points, allowing it to operate efficiently with low-grade heat sources such as:

- Geothermal energy
- Biomass combustion
- Industrial waste heat
- Solar thermal
- Engine exhaust

I.5.2 Rankine Cycle Principles:

The Rankine Cycle is based on four main thermodynamic processes:

1. Isentropic Compression (Pump):

The working fluid (in liquid state) is pumped to a high pressure. Since the fluid is nearly incompressible, the work input is low.

2. Isobaric Heat Addition (Evaporator/Boiler):

The high-pressure liquid is heated at constant pressure until it evaporates into vapor.

3. Isentropic Expansion (Turbine):

The vapor expands in a turbine, producing mechanical work. The temperature and pressure drop.

4. Isobaric Heat Rejection (Condenser):

The low-pressure vapor releases its heat to the environment and condenses back to a liquid, completing the cycle.

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In the ORC, these steps are identical in principle, but adapted to organic working fluids.

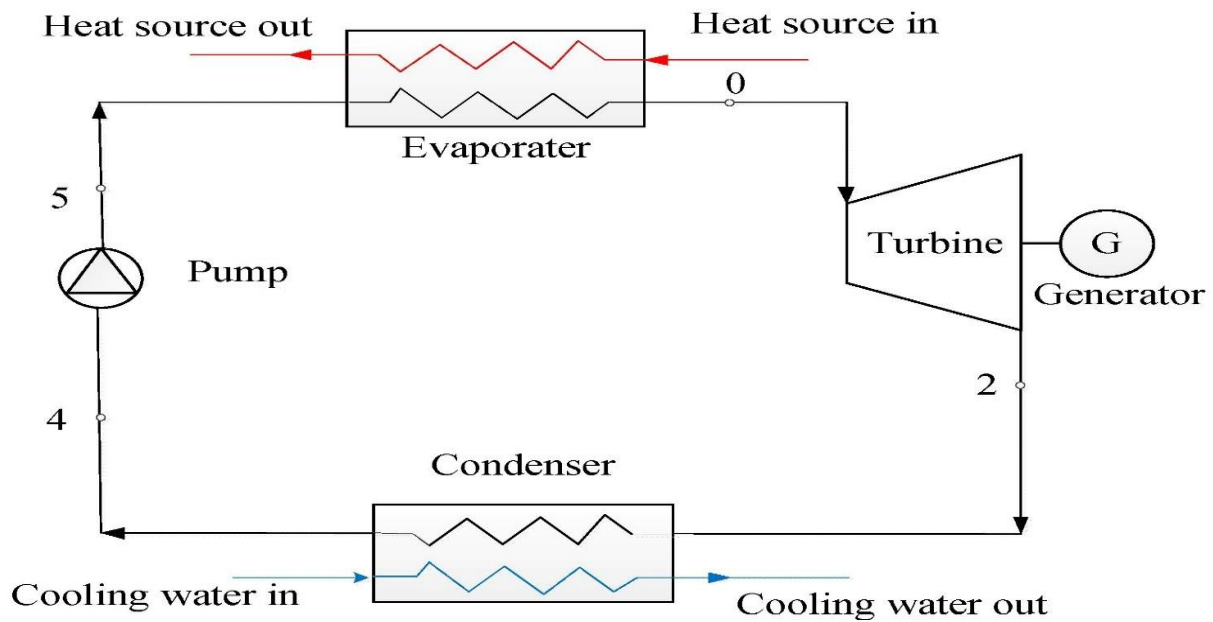


Figure 1.7: Organic Rankine Cycle

I.5.3 Working Fluids and Thermophysical Properties

Organic fluids are commonly used in Organic Rankine Cycle (ORC) systems due to the following advantages:

Advantages:

- Lower boiling points than water
- Higher efficiency when utilizing low-temperature heat sources
- Reduced need for high operating pressures

Common Working Fluids:

- R245fa
- R123
- Toluene
- Isopentane
- Cyclopentane
- Silicone oils

Key Thermophysical Properties:

- Boiling Point: Should align with the temperature of the available heat source
- Thermal Stability: Must tolerate the system's maximum operating temperature without degradation

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- Viscosity: Lower viscosity is preferred to minimize pumping losses and improve circulation
- Specific Heat Capacity: Influences the fluid's ability to absorb and transfer heat
- Latent Heat of Vaporization: Determines the energy required for phase change from liquid to vapor
- Environmental Impact: Fluids should have low ODP (Ozone Depletion Potential) and low GWP (Global Warming Potential)

Classification of Working Fluids:

- Dry Fluids: Do not condense immediately after expansion (e.g., R245fa)
- Wet Fluids: Partially condense during expansion (e.g., water)
- Isentropic Fluids: Exhibit nearly constant entropy during expansion—ideal for turbine performance

I.5.4 ORC System Components:

1. Pump (Isentropic Compression):

Increases the pressure of the working fluid (liquid phase) .
Requires low power input due to the incompressibility of liquids.

2. Evaporator (Heat Exchanger):

Transfers heat from the source (solar, geothermal, waste heat) to the working fluid .
Causes fluid to vaporize at high pressure.

3. Turbine (Isentropic Expansion):

High-pressure vapor expands and drives the turbine blades .
Converts thermal energy into mechanical work (then electrical energy via a generator)

4. Condenser (Heat Rejection):

The low-pressure vapor releases heat to a cooling medium (air or water) .
Vapor condenses back to liquid, ready to be pumped again.

I.6 Thermoelectric Generators (TEGs)

I.6.1 Seebeck Effect and Device Physics

The fundamental physical principle of thermoelectric generators (TEGs) is the Seebeck effect, which was first discovered by Thomas Johann Seebeck in 1821. The Seebeck effect is defined as the direct conversion of heat energy into electrical energy because of a temperature difference between two different conductors or semiconductors. When one end of these materials is heated and another end is cooled, charge carriers (electrons or holes) in the material moves from hot end to cold end creating an electric potential difference, known as the Seebeck voltage.

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Mathematically, the voltage output of a thermoelectric element can be represented as:

$$V = \alpha * \Delta T \dots [7]$$

A TEG module is composed of numerous pairs of n-type and p-type semiconductor legs in electrical series and thermal parallel between two ceramic plates. The n-type legs have negative Seebeck coefficients and carry electrons as the majority carriers, while the p-type legs have positive coefficients and carry holes. Such complementary design enhances the voltage output of the module. The legs are embedded in insulating ceramic substrates, which provide structural support and electrical insulation.

The electrical output and efficiency of a TEG system are not only a function of the temperature difference but also on the material figure of merit defined as:

$$\frac{ZT = S^2 \times \sigma \times T_{avg}}{\kappa} \dots [8]$$

In actual systems, the performance of a TEG module also depends on thermal contact resistances, electrical load matching, and the ability to maintain a stable temperature gradient. Effective heat sink design is crucial in keeping the cold side at a low enough temperature, especially in hybrid WHR systems where coolant heat or ambient air can be used for passive or active cooling.

Thus, the Seebeck effect provides a low-maintenance, solid-state means of recovering waste heat as electricity, and TEGs are particularly well-suited for incorporation into maintenance-free, compact internal combustion engine waste heat recovery systems.

I.6.2 Module and Material Design

The efficiency of thermoelectric generators (TEGs) relies mostly on structural module design and materials selection. Since heat to electricity conversion makes use of the Seebeck effect, the ideal material for the ideal application should exhibit high Seebeck coefficient, high electrical conductivity, and low thermal conductivity so that they can produce a high figure of merit (ZT). Such contradicting specifications render it a tough task since the materials with good conductivity to electricity possess good thermal conductivity as well, and in the application of thermoelectric devices, that is undesirable.

Some of the most commonly used thermoelectric materials are bismuth telluride (Bi₂Te₃), lead telluride (PbTe), and silicon-germanium (SiGe) alloys. Bismuth telluride is particularly well-suited for low to moderate temperature applications (up to 250°C) and is used in most automotive and commercial modules. For applications involving elevated temperatures, i.e., internal combustion engine exhaust systems (300–600°C), PbTe and SiGe materials are used on account of their enhanced thermal stability and high ZT within this range. Newer materials like skutterudites, half-Heusler alloys, and nanostructured composites have also emerged in recent years with enhanced thermoelectric figure of merit and thermal stability at various temperature ranges.

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A standard thermoelectric module consists of several thermocouples, each being a pair of n-type and p-type semiconductor legs. The legs are electrically connected in series for increased voltage output and thermally connected in parallel for convenient heat flow through the device. The legs are typically sandwiched between ceramic substrates, such as alumina (Al₂O₃), which provide structural rigidity, thermal insulation, and electrical isolation. Its size, geometry, and number are important factors to affect the module's thermal resistance, output power, and internal resistance. Wider, shorter legs reduce thermal resistance and carry more current, while longer legs have improved ability for high voltage output since there is more temperature gradient available.

Design optimization of modules has several trade-offs between power output, efficiency, temperature tolerance, and mechanical reliability. Leg cross-sectional area, height, spacing, contact resistance, and number of thermocouples are significant design parameters. Thermal interface materials (TIMs) are also critical in eliminating heat loss at contact areas between hot and cold sides and maintaining stable thermal conductivity under operation.

Increased-performance TEG modules may involve segmented leg configurations, where several layers of different thermoelectric materials are used to more effectively treat the temperature difference across the leg. This allows for greater module efficiency overall, especially in high-temperature-range applications such as engine exhaust waste heat recovery.

To aid heat flow and maintain the necessary temperature differential, modules are often combined with purposeful heat exchangers or heat sinks, which may apply forced air, coolant flow, or phase change material. Proper thermal and electrical load matching is essential in order to provide the module with a condition of operating at or close to its maximum power point, which varies with temperature and load resistance.

I.6.3 Representative Performance and Uses

Thermoelectric generators (TEGs) are increasingly recognized for their potential in waste heat recovery (WHR) applications due to their solid-state construction, compactness, and low maintenance requirements. Although TEGs are generally less efficient than conventional thermodynamic cycles, their reliability, scalability, and absence of moving parts make them well-suited to particular uses—especially those in which space is limited or mechanical simplicity is beneficial.

Practically, the efficiency of TEG modules is usually between 3% and 8%, based on the temperature difference, materials, and module design. In the ideal case in the lab using advanced materials and big temperature differences (e.g., 600°C on the hot side and 50°C on the cold side), one can reach efficiencies up to 10–12%. Such conditions are not typical in practical applications, though. In most internal combustion engine (ICE) uses, the exhaust temperature ranges from 300–600°C, and the available cold sink (i.e., ambient air or engine coolant) is near 60–100°C, which limits the achievable ΔT and, consequently, the TEG efficiency.

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Power output is a function of both the temperature gradient and the number of thermoelectric couples in the module. For automotive applications, TEG systems tend to be in the 100 W to 1 kW range, depending on engine size and heat recovery design. Larger industrial engines can provide higher outputs, particularly when integrated into hybrid ORC–TEG systems where exhaust and coolant heat are merged for utilization.

TEGs have been used in a wide range of applications. For passenger cars, trucks, and off-highway vehicles exhaust heat recovery, they are used in the automotive industry to improve fuel efficiency and reduce CO₂ emissions. The major automobile manufacturers have developed prototype TEG systems that provide power back to the electrical system, which reduces alternator load and improves overall engine efficiency. In aerospace and defense, TEGs are used in spacecraft and remote sensors, exploiting their ability to provide long-term, maintenance-free electric power. In stationary and industrial applications, TEGs can be used for heat recovery from chemical reactors, furnaces, or boilers, resulting in plant efficiency.

Furthermore, TEGs are interesting for off-grid or remote power systems, particularly where electrical infrastructure access is low. They are also being designed for battery-powered or hybrid systems, where they can scavenge heat from auxiliary components to extend battery life or support onboard electronics.

In combined WHR architectures, such as hybrid ORC–TEG systems, TEGs are typically placed in the high-temperature zone, immediately downstream of the exhaust manifold, where they recover residual heat that may not be efficiently harvested by ORC evaporators. TEGs can also be used as a second recovery device in lower temperature zones, i.e., after ORC stages or on the EGR loop, as a layered energy harvesting approach.

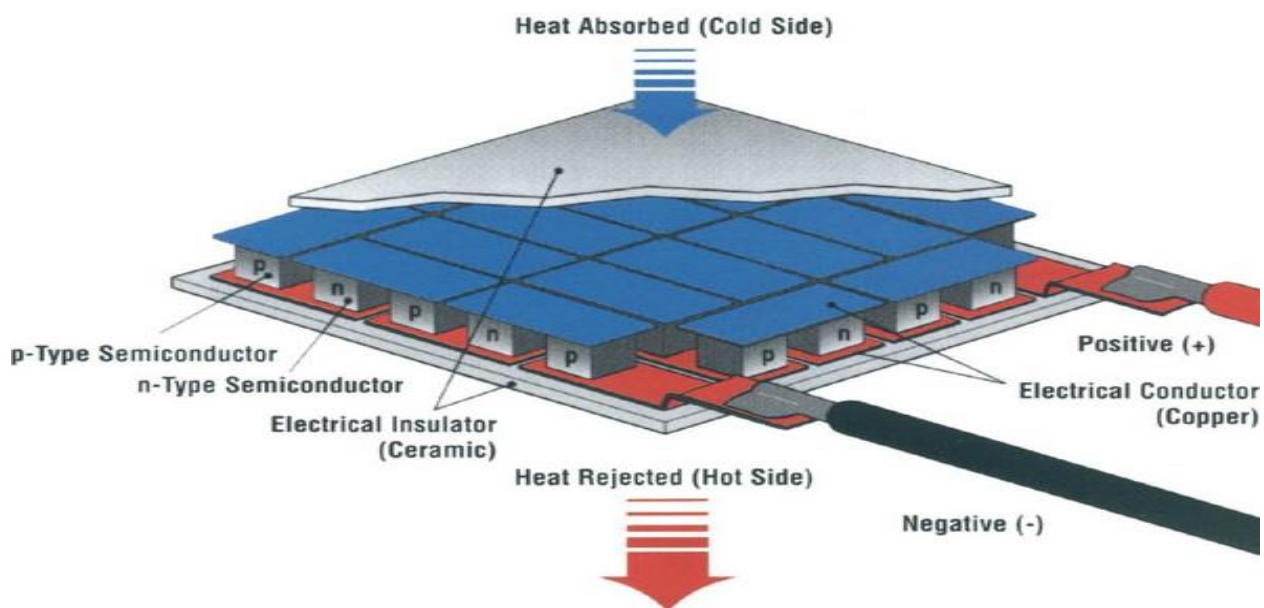


Figure 1.8: Schematic of a thermoelectric generator

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I.7 Absorption Refrigeration Systems: Background and Literature

Absorption refrigeration systems (ARS) refer to low-grade heat driven cooling technologies, rather than utilizing mechanical work as in conventional vapor compression cycles. The mechanism is based on a refrigerant–absorbent working couple, where the most common includes water–lithium bromide (H_2O – LiBr) for air conditioning or ammonia water (NH_3 – H_2O) when the temperature needs to be lower. These systems are suitably adaptable to be combined with waste heat recovery systems, as they can operate satisfactorily under low temperatures of approximately 80–100 °C.

Reliability, silence, and minimal maintenance are linked to absorption chillers, as they do not have any moving parts. They work optimally when used in cascaded or hybrid power systems, where waste heat from other subsystems (e.g., ORC condensers) is available. Most recent studies (e.g., Zhang et al., 2019; Li et al., 2021) have explored using them in combination with internal combustion engines and organic Rankine cycles, with findings indicating improved exergy efficiency and system-level COPs of 0.6–0.75 for single-effect LiBr -water systems[9],[10].

So, therefore, absorption chillers provide an attractive option for low-grade heat recovery from ICE-ORC cascades, not only promoting energy efficiency but also other sustainable goals.

I.8 Summary and Research Gap

This work investigates the potential of waste heat recovery from internal combustion engines (ICE) through two complementary technologies: the Organic Rankine Cycle (ORC) and the Thermoelectric Generator (TEG). The study begins with a detailed review of the ICE thermal profile, emphasizing the considerable amount of energy lost through exhaust gases — an opportunity for recovery that can significantly enhance system efficiency.

In the existing literature, ORC systems are well-known for recovering medium-grade thermal energy and converting it into mechanical or electrical power, particularly effective in the 150 °C to 350 °C range (depending on the working fluid). On the other hand, TEG systems offer a solid-state solution to capturing high-temperature gradients (typically above 500 K) by directly converting thermal energy into electricity using the Seebeck effect. Depending on the thermoelectric material selected (e.g., Bi_2Te_3 , PbTe , or SiGe), TEGs can recover high-, medium-, or low-grade heat, allowing them to be adapted for a wide variety of thermal sources.

Despite the extensive body of work evaluating these two systems independently, comparative analyses between TEG and ORC under the same engine conditions remain limited. Moreover, there is a noticeable gap in the exploration of combined hybrid systems where both technologies are used in a thermally cascaded configuration to maximize energy recovery from different temperature segments of the exhaust stream.

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This study addresses these gaps by:

- A comparative simulation of ORC and TEG systems under the same conditions of ICE, which show their respective energy recovery capabilities, efficiencies, and limitation of applications.
- Proposing and modeling a hybrid waste heat recovery process (ICE → TEG → ORC) where TEG captures the high-grade thermal energy (711–611 K) and ORC captures the mid-grade interval (611–373 K) to achieve maximum utilization of exhaust heat in stages.
- As an extension further, the hybrid design also explores the use of absorption chillers to utilize the low-grade heat of the ORC condenser (~373 K) — with possibilities for combined cooling use and added functionality of the system.

By doing this, the thesis not only compares the stand-alone performance of ORC and TEG but also quantifies the enhancement of the overall energy recovery by hybridization. Absorption cooling is not a final target but positioned to demonstrate the universality and completeness of the suggested cascade strategy.

CHAPTER II:

Modeling and Simulation of ICE-ORC Integration

II.1. System Description and Assumptions

II.1.1 ICE Exhaust Conditions and Mass Flow

For this study, the internal combustion engine selected is the Cummins QSK19-G4 — a powerful, 6-cylinder turbocharged diesel engine built for dependable power generation.

When it comes to recovering waste heat, especially through the use of an Organic Rankine Cycle (ORC), it's crucial to have a clear and accurate understanding of the engine's exhaust flow.

Fuel Energy Input (Q_{fuel})

- Fuel Consumption: **147 L/h**
- Diesel Density: **0.85 kg/L**
- Lower Heating Value (LHV) of Diesel: **42.5 MJ/kg**

Fuel mass flow rate:

$$\dot{m}_{\text{fuel}} = (147 \times 0.85) / 3600 = 0.03471 \text{ kg/s}$$

Fuel energy input:

$$Q_{\text{fuel}} = \dot{m}_{\text{fuel}} \times \text{LHV} = 0.03471 \times 42,500 = 1475 \text{ kW}$$

Mechanical and Electrical Energy Output

- Mechanical Output (from datasheet): **574 kW**
- Generator Efficiency: **~90.6%**
- Electrical Output = $574 \times 0.906 = 520 \text{ kW}$

Exhaust Heat Loss

Conventional diesel engine wastes ~36% of fuel energy through exhaust:

$$Q_{\text{exhaust}} = 0.36 \times 1475 = 531 \text{ kW}$$

Coolant (Jacket Water) Heat Loss

Average coolant heat loss ~22.5% of fuel energy:

$$Q_{\text{coolant}} = 0.225 \times 1475 = 331.875 \text{ kW}$$

Other Losses (Lubrication + Radiation)

Estimated as ~8% of fuel input:

$$Q_{\text{misc}} = 0.08 \times 1475 = 118 \text{ kW}$$

CHAPTER II: Modeling and Simulation of ICE-ORC Integration

Overall Efficiency

$$\eta_{\text{overall}} = (\text{Electrical Output} / \text{Fuel Input}) \times 100$$

$$\eta_{\text{overall}} = (520 / 1475) \times 100 = 35.25\%$$

Table II.1 – Summary Table of The Energy Flow and Losses

Parameter	Value	Unit
Fuel Input (Q _{fuel})	1475	kW
Electrical Output	520	kW
Mechanical Output	574	kW
Exhaust Heat Loss	531	kW
Coolant Heat Loss	331.875	kW
Other Losses (Oil, Radiation)	118	kW
Overall Efficiency	35.25	%

This detailed information isn't just important for estimating how much thermal energy is available in the exhaust gases, but also plays a key role in shaping the design and improving the efficiency of the ORC system.

To support this analysis, Table 2.1 outlines the main exhaust gas characteristics—such as temperature, flow rate, and composition—which are essential for the thermodynamic calculations and performance simulation of the recovery process.

To meet the best ORC operating performance when integrated with the internal combustion engine (ICE), the heat exchanger is positioned between the engine exhaust outlet and the ORC evaporator. The heat exchanger's purpose is to regulate the exhaust gas temperature, exiting the engine at approximately 438 °C, and lower it to 380 °C, the best value for the selected ORC working fluid (toluene). This is done to avoid the thermal stressing of the system components and maintain the fluid below its thermodynamic stable range, yet further below the critical point. By this thermal regulation step, the ORC is given stable and controlled heat input to deliver maximum efficiency, maintain material integrity, and maintain the system to safe and feasible thermal levels. The key exhaust characteristics used to simulation are summarized below.

CHAPTER II: Modeling and Simulation of ICE-ORC Integration

Table II.2 – Exhaust Gas Conditions of the Cummins QSK19-G4

Parameter	Value	Unit
Engine Mechanical Power Output	574	kW
Engine Electrical Power Output	520	kW
Exhaust Gas Flow Rate	2.214	kg/s
Exhaust Temperature (Inlet)	438	°C
Exhaust Temperature (after heat exchanger)	380	°C
Exhaust Cooling Limit	150	°C
Specific Heat of Exhaust Gas	1.1	kJ/kg·K

The thermal energy potentially recoverable by the ORC system is calculated using:

$$\dot{Q}_{\text{exhaust}} = \dot{m}_{\text{exh}} \times C_p \times (T_{\text{in}} - T_{\text{out}})$$

Substituting values:

$$\dot{Q}_{\text{exhaust}} = 2.214 \times 1.1 \times (653.15 - 423.15) = 559 \text{ kW}$$

The exhaust outlet temperature (T_{out}) is not arbitrarily chosen. In this model, it is set to 150°C (423 K) to reflect the practical lower limit at which the ORC evaporator can still operate efficiently. This assumption ensures maximum thermal extraction while staying within the thermal design limits of the ORC's working fluid (Toluene), which begins to lose effectiveness below this temperature range. Thus, the model assumes that the ORC system is designed to absorb all thermal energy down to 150°C, beyond which further heat recovery would not contribute meaningfully to cycle performance.

CHAPTER II: Modeling and Simulation of ICE-ORC Integration

II.1.2. ORC Boundary Conditions

The organic Rankine Cycle (ORC) stands out as an effective thermodynamic process particularly adapted for capturing and utilizing heat from low to medium temperature sources, such as the exhaust gases from internal combustion engines. Instead of allowing this valuable thermal energy to dissipate unused, the ORC enables its conversion into mechanical or electrical power.

For accurate modeling and dependable evaluation of the system's performance, defining the right boundary conditions is essential, as these parameters directly influence the behavior and efficiency of the cycle.

In this work, toluene was selected as the working fluid because of its excellent thermal stability and well-suited boiling characteristics, which align well with the demands of high-temperature waste heat recovery—especially in automotive and industrial applications where such conditions are frequently encountered.

Table II.3 – ORC System Boundary Conditions

Cycle Point	Temp (°C)	Pressure (bar)	h (kJ/kg)	Isentropic h (h _s) [kJ/kg]	State Description
1 -Condenser Outlet	40	0.079	-132.35	-	Saturated Liquid
2 - Pump Outlet (Real & Isentropic)	41	20	-129.2	-130	Subcooled Liquid
3 - Evaporator Outlet	279.25	20	610.8	-	Superheated Vapor
4-Turbine Outlet (Real & Isentropic)	148.65	0.079	423.5	390.5	Expanded Vapor

In this study, the key thermodynamic properties at each point in the Organic Rankine Cycle (ORC)—namely temperature, pressure, specific enthalpy (h), and specific entropy (s)—were carefully determined based on established data relevant to subcritical ORC systems using toluene as the working fluid.

Most of these values were sourced from the NIST Chemistry WebBook, while additional data from scientific publications were consulted to ensure both precision and consistency across the analysis. In the specific cycle evaluated, the working fluid exits the evaporator as superheated vapor at a high temperature of 280°C and a pressure of 20 bars.

CHAPTER II: Modeling and Simulation of ICE-ORC Integration

This vapor then passes through the turbine, where it undergoes a pressure drop to 1.5 bar, producing mechanical work during expansion.

After this step, the fluid enters the condenser, where it gives off heat and condenses into a saturated or slightly sub-cooled liquid. From there, it moves into the pump, which increases its pressure back to the initial level, completing the loop before re-entering the evaporator.

This repeating cycle allows the system to harness waste heat and convert it into useful energy.

The selected operating conditions reflect common practice in high-temperature waste heat recovery applications and were aligned with the thermo-physical behavior of toluene to ensure both efficient energy conversion and reliable system performance.

II.2. Thermodynamic Modeling of ORC

II.2.1. Energy and Mass Balance Equations

In this section, the thermodynamic modeling for the Organic Rankine Cycle (ORC) begins with the application of the first law of thermodynamics to all parts of the cycle. The four fundamental components included are: the pump, where working fluid is pressurized; the evaporator, where the exhaust heat from the engine is transferred to the fluid, converting it into pure vapor; the turbine, where the fluid is expanded and generates work; and the condenser, where vapor is converted to liquid in order to complete the cycle. Energy and mass balance equations are applied for every component to study the performance of the cycle and determine the net power output.

Evaporator – Heat Input

The heat absorbed by the working fluid in the evaporator is given by:

$$\dot{Q}_{\text{exhaust}} = \dot{Q}_{\text{in}} \cdot 0.9 = \dot{m}_f \times (h_3 - h_2)$$

$$h_3 = h_2 + \dot{Q}_{\text{in}} / \dot{m}_f$$

Turbine Efficiency – Real vs. Isentropic Enthalpy

Isentropic efficiency for the turbine is defined as:

$$\eta_{\text{turbine}} = (h_3 - h_{4\text{real}}) / (h_3 - h_{4s})$$

Solving for real enthalpy at turbine exit:

$$h_{4\text{real}} = h_3 - \eta_{\text{turbine}} \times (h_3 - h_{4s})$$

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Pump Efficiency – Real vs. Isentropic Enthalpy

Isentropic efficiency for the pump is defined as:

$$\eta_{\text{pump}} = (h_{2s} - h_1) / (h_{2_real} - h_1)$$

Solving for real enthalpy at pump outlet:

$$h_{2_real} = h_1 + (h_{2s} - h_1) / \eta_{\text{pump}}$$

Turbine – Work Output

The turbine work output is calculated using:

$$\dot{W}_{\text{turbine}} = \dot{m}_f \times (h_3 - h_4)$$

Condenser – Heat Rejection

The heat rejected to the environment through the condenser is:

$$\dot{Q}_{\text{out}} = \dot{m}_f \times (h_4 - h_1)$$

Pump – Work Input

The work required by the pump to pressurize the liquid is:

$$\dot{W}_{\text{pump}} = \dot{m}_f \times (h_2 - h_1)$$

All enthalpy values used in these equations correspond to the boundary conditions previously listed in Section 2.1.2. These relationships enable the performance of the ORC system to be analyzed and optimized based on varying operational conditions.

II.2.2. Cycle Efficiency and Work Output Formulas

The efficiency of an Organic Rankine Cycle (**ORC**) system measures how effectively it converts recovered thermal energy into useful work and it depends on the fluid properties:

- Operating Temperatures
- Pressure
- Performance of key Components in the cycle

Net work Output determined by subtracting the work consumed by the feed pump from the work produced by the turbine.

The following section explains the approach used to calculate the efficiency and power output of the cycle, using Toluene as the working fluid.

Net Work Output

The net useful work produced by the cycle is the turbine output minus the pump input:

$$\dot{W}_{\text{net}} = \dot{W}_{\text{turbine}} - \dot{W}_{\text{pump}}$$

Thermal Efficiency of ORC

The thermal efficiency of the cycle is defined as:

$$\eta_{\text{ORC}} = \dot{W}_{\text{net}} / \dot{Q}_{\text{in}}$$

II.2.3 Working Fluid Selection

To select a working fluid for an **ORC** system is a critical step that should be taken carefully, based on the thermodynamic properties of the fluid and its ability to handle high thermal contact and maintain thermostability. For this study, Toluene was selected after a thorough comparison with other working fluids such as **R245fa**, **R123**, and **n-Pentane**, mainly because it is used in direct contact with high-temperature exhaust gas.

Toluene is an aromatic hydrocarbon with high thermal stability and favorable thermodynamic properties in the temperature range of **250–400°C**. Its high critical temperature (**591.8 K**) and moderate molecular weight (92.14 g/mol) make it ideal for recovering heat from internal combustion engine exhaust gases operating above 400°C.

Table II.4 – Comparison of Selected Working Fluids

Working Fluid	Boiling Point (°C)	Critical Temperature (°C)	Global Warming Potential (GWP)	Suitability for High Temp
Toluene	110.6	318.6	Low	Excellent
R245fa	15.3	154	950	Poor
R123	27.8	183.7	77	Moderate
n-Pentane	36.1	196.6	Low	Moderate

Toluene also offers relatively low environmental impact compared to fluorinated refrigerants like R245fa. Its flammability is manageable under controlled industrial

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settings, and it provides higher thermal efficiency due to its ability to operate at elevated temperatures. For these reasons, Toluene is selected as the working fluid for the ORC system in this study.

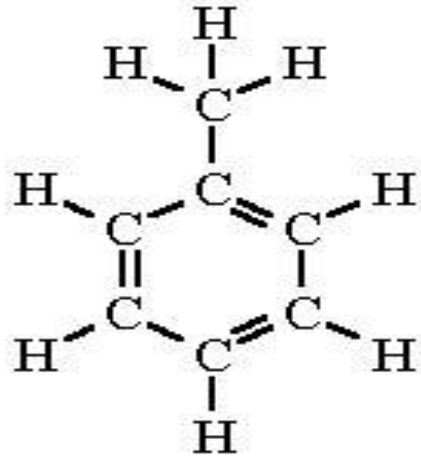


Figure 2.1: Toluene structure



Figure 2.2: Toluene Liquid form

II.3 Integration of Absorption Cooling System

II.3.1 Overview of Absorption Cooling Technology (LiBr–Water System):

The Lithium Bromide Water (LiBr–H₂O) absorption cooling system is a thermally activated refrigeration technology that utilizes waste heat such as that emitted by the exhaust gases of internal combustion engines (ICE) to produce cooling without mechanical work. This system is especially attractive for waste heat recovery applications, as it provides a means of generating chilled water or conditioned air without relying on conventional vapor-compression systems. In this cycle, water functions as the refrigerant, while lithium bromide (LiBr) acts as the chemical absorbent. The process operates under reduced pressure and proceeds through four main components:

1. Generator: High temperature waste heat is used to heat a strong (LiBr water) solution. This causes the water component (the refrigerant) to evaporate, separating from the absorbent.

2. Condenser: The water vapor produced in the generator is then condensed into a liquid, releasing latent heat to the surroundings. This step typically takes place at ambient or slightly elevated temperatures

3. Evaporator: The condensed water refrigerant is expanded into the evaporator, where it evaporates again under low-pressure conditions, typically providing cooling at temperatures ranging from 5°C to 10°C—ideal for air conditioning or process cooling.

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This evaporation process absorbs thermal energy from the cooling load.

4. Absorber: The resulting water vapor is absorbed by a weak LiBr solution in the absorber, releasing heat in the process and reforming a concentrated solution, which is then pumped back to the generator to close the cycle.

This system operates in a vacuum environment, enabling evaporation and condensation at relatively low temperatures. The absence of mechanical compression components significantly reduces electrical energy consumption and maintenance requirements.

From a performance perspective, single effect absorption systems based on LiBr-H₂O typically achieve a Coefficient of Performance (COP) in the range of 0.6 to 0.7, whereas double effect systems, which use a higher level of heat recovery, can reach COP values up to 1.2. These characteristics make LiBr-based systems particularly well-suited for applications involving medium-grade waste heat sources such as engine exhaust gases.

II.3.2 Working Principle of the LiBr–Water System

In this study, the LiBr–Water absorption pair is adopted as a thermally driven refrigeration system due to its proven efficiency, safety, and compatibility with waste heat sources, particularly in applications such as air conditioning and chilled water production. The LiBr–H₂O system is widely implemented in commercial and industrial settings for its reliability, non-toxicity, and ability to operate efficiently under moderate to high-temperature heat inputs, making it ideal for integration with internal combustion engine (ICE) exhaust recovery systems.

The working cycle of the LiBr–Water absorption system consists of four primary stages:

1. Generator: The cycle begins in the generator, where high-temperature exhaust gases from the ICE are used to heat a strong solution of lithium bromide and water. As the temperature rises, the water component evaporates and separates from the LiBr, leaving behind a more concentrated absorbent solution.

2. Condenser: The water vapor produced in the generator is then directed to the condenser, where it is cooled and condensed into a liquid by releasing its latent heat to a cooling medium typically ambient air or water.

3. Evaporator: The liquid water, now under low pressure, enters the evaporator, where it absorbs heat from the cooling load and evaporates. This phase change results in a cooling effect, enabling the system to deliver chilled water or air.

4. Absorber: The resulting water vapor is then absorbed back into the concentrated LiBr solution in the absorber. This absorption process is exothermic and releases heat, while regenerating the strong solution. The regenerated solution is subsequently

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pumped back to the generator to continue the cycle.

A key characteristic of this cycle is the absence of a mechanical compressor, which significantly reduces electrical energy consumption and mechanical noise, enhancing the system's operational efficiency and sustainability. Operating under vacuum conditions, the system allows water to evaporate and condense at relatively low temperatures, making it highly suitable for low-grade thermal energy recovery.

II.3.3 Thermal Integration with ICE Exhaust:

To maximize the recovery of waste heat from an internal combustion engine (ICE), the LiBr–Water absorption cooling system must be strategically integrated with the engine's exhaust stream. The primary objective of this integration is to harness a significant portion of the thermal energy typically lost to the environment and utilize it to drive the absorption refrigeration cycle efficiently.

At the core of this integration lies a dedicated heat exchanger, positioned within the exhaust flow path of the ICE. This exchanger captures the high temperature exhaust gases often exceeding 400 °C and transfers their thermal energy to an intermediate heat transfer fluid, such as thermal oil or pressurized water. This fluid then transports the recovered heat in a controlled and regulated manner to the generator of the LiBr–Water absorption system.

This indirect heat transfer configuration serves multiple critical functions. Firstly, it isolates the absorption system from direct contact with corrosive and potentially harmful exhaust gases, thereby improving the longevity and reliability of the system. Secondly, it allows for precise thermal management, ensuring the generator receives consistent and appropriate heat input.

To maintain high thermal performance, it is essential to properly size the heat exchanger based on the engine's exhaust profile and cooling demand. Additionally, thermal insulation of all associated piping minimizes heat losses and helps preserve system stability during operation.

The integration of the absorption system in this manner significantly enhances the overall energy efficiency of the ICE. Beyond improving waste heat utilization, it offers additional functional benefits, such as pre cooling intake air for improved combustion efficiency, providing air conditioning for nearby spaces, or supporting industrial process cooling. This approach aligns with sustainable energy strategies by reducing fuel consumption, lowering emissions, and minimizing the system's total energy footprint.

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II.3.4 Operating Conditions and Performance Parameters:

The performance of the LiBr–Water absorption cooling system is highly dependent on the thermal conditions of both the internal combustion engine (ICE) and the absorption cycle. Several key parameters directly affect the system's cooling capacity, efficiency, and overall effectiveness when integrated with the engine's exhaust stream.

Exhaust Gas Temperature: The Cummins QSK19G4 engine generates exhaust gases at a temperature of approximately 438 °C, which is well within the required range to operate a single-effect absorption cooling cycle. This high-grade waste heat serves as the primary energy input to drive the desorption process in the generator.

Generator Operating Temperature: For optimal thermal separation of the LiBr–Water solution, the generator typically requires a temperature range between 80 °C and 180 °C. A higher generator temperature enhances the driving potential of the system and contributes to an improved Coefficient of Performance (COP), thereby increasing the cooling efficiency.

Evaporator Temperature: The system is generally designed to produce chilled water at temperatures between 5 °C and 10 °C, suitable for applications such as air conditioning or process cooling. While lower evaporator temperatures can increase the cooling load capacity per unit of flow, they often lead to a reduction in COP, necessitating careful optimization based on the target cooling application.

Coefficient of Performance (COP): The thermal efficiency of the system is measured by its COP, which typically ranges from 0.6 to 0.7 for single-effect systems. In more advanced double-effect configurations, the COP can be elevated to values between 1.0 and 1.2, provided the system receives sufficient thermal input and maintains appropriate operating conditions.

Cooling Capacity: Depending on system scale and application, the LiBr–Water cycle can deliver a cooling capacity ranging from 2.5 kW to 5.0 kW for small-scale systems. In industrial configurations, the capacity can be scaled significantly, subject to the available exhaust heat and thermal load requirements.

Control and Regulation Strategies: To ensure stable and efficient operation, several active control strategies are employed. These include regulating the heat exchanger flow rate, maintaining a consistent generator temperature, and utilizing auxiliary cooling systems such as cooling towers to support the absorber and condenser. These measures are essential to prevent crystallization, ensure proper heat exchange, and stabilize the overall cycle.

In summary, the performance of the LiBr–Water absorption cooling system is intricately linked to the thermal profile of the ICE and the surrounding environment. Precise thermal matching, optimized heat exchanger design, and advanced control systems are critical to achieving high efficiency, stability, and reliability in real world integrated energy recovery applications

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II.4 EES Simulation Setup

II.4.1 System Architecture and Simulation Setup

In this section, the setup and simulation environment of the Organic Rankine Cycle (ORC) system integrated with the Cummins QSK19-G4 internal combustion engine (ICE) is presented. The aim is to recuperate high-temperature waste heat from the exhaust gases of the engine and convert it into beneficial power using toluene as the working fluid.

The design is to add a heat exchanger between the ICE and the ORC to reduce the exhaust gas temperature from 438 °C (711.15 K) to 380 °C (653.15 K), which is more appropriate for the thermal stability of the ORC system. The system consists of four major components: pump, evaporator, turbine, and condenser, in a closed loop system.

Toluene is chosen because of its tolerance for high temperature and also its established potential for use in ORC cycles. The cycle starts with the saturated liquid from the condenser entering the pump. It is then pressurized and fed into the evaporator where it receives heat from the ICE exhaust through the heat exchanger. It enters as superheated vapor into the turbine where it expands and does work. Then the fluid leaves the turbine and goes back to the condenser to complete the cycle.

Key assumptions in the model:

- Steady-state, one-dimensional flow
- Negligible pressure losses in pipelines
- Evaporator input at 380 °C after heat exchanger
- Pump and turbine have specified isentropic efficiencies

II.4.2 Thermodynamic State Points and Property Table

In the simulation of the ORC with the Cummins QSK19 ICE, there are six different thermodynamic states through which the working fluid goes. The system is provided with a simple evaporator only, but two points (states 3 and 4) are assigned in the evaporator for the purpose of illustrating the phase change and the process of superheat in the T-s diagram.

These six states are defined as follows:

1. Pump inlet (condenser outlet).
2. Evaporator inlet (after pump).
3. Saturated liquid inside evaporator.
4. Saturated vapor inside evaporator.
5. Turbine inlet (superheated vapor).
6. Turbine outlet / condenser inlet.

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Table II.6 Thermodynamic Property (ORC Cycle – Toluene):

State	Pressure (bar)	Temperature (°C)	Enthalpy h (kJ/kg)	Entropy s (kJ/kg·K)	Description
1	0.079	40	-132.4	-0.380	Pump inlet (saturated liquid)
2	20	41	-129.2	-0.3775	Evaporator inlet (after pump)
3	20	263	356.0	0.7687	Saturated liquid inside evaporator
4	20	263	571.1	1.170	Saturated vapor inside evaporator
5	20	271	590.9	1.207	Turbine inlet (superheated vapor)
6	0.079	139	408.4	1.287	Turbine outlet / condenser inlet

Note: States 3 and 4 are intermediate states within the evaporator used to visualize phase changes. Values obtained from EES simulation.

II.4.3 Efficiency and Performance Calculations

The thermodynamic analysis of the Organic Rankine Cycle (ORC) is presented in this chapter with the simulation results through EES. The aim is to analyze the net work from the cycle, the thermal input, and the respective cycle efficiency under steady-state operation.

a) Work and Heat Transfer Calculations

The primary performance metrics are calculated using the enthalpy differences between state points:

- **Pump Work (W_p):**

$$W_{\text{pump}} = h_2 - h_1$$

- **Turbine Work (W_t):**

$$W_{\text{turbine}} = h_3 - h_4$$

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- **Net Work Output (W_{net}):**

$$W_{net} = W_{turbine} - W_{pump}$$

- **Heat Input (Q_{in}):**

$$Q_{in} = h_3 - h_2$$

b) Thermal Efficiency of the ORC

The thermal efficiency of the cycle is given by:

$$\eta_{ORC} = (W_{net} / Q_{in}) \times 100$$

Where:

- h_1 to h_4 are enthalpies at respective state points from EES
- Efficiency is expressed as a percentage (%)

This efficiency refers to the degree to which the ORC can convert absorbed heat into mechanical work. The result depends heavily on accurate fluid properties, component response, and boundary conditions specified in the previous sections.

II.4.4 Isentropic Efficiency

This part confirms the actual performance of the turbine and pump by comparing actual and isentropic processes through efficiency equations.

Turbine Isentropic Efficiency

The isentropic efficiency of the turbine indicates how closely the real expansion process approaches the ideal (isentropic) expansion:

$$\eta_{turbine} = (h_3 - h_4) / (h_3 - h_{4s})$$

Where:

- h_3 : Enthalpy at turbine inlet
- h_4 : Enthalpy at turbine outlet
- h_{4s} : Enthalpy at turbine outlet (isentropic)

Pump Isentropic Efficiency

Similarly, the isentropic efficiency of the pump quantifies how effectively the pump compresses the working fluid compared to the ideal case:

$$\eta_{pump} = (h_{2s} - h_1) / (h_2 - h_1)$$

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Where:

- h_1 : Enthalpy at pump inlet
- h_2 : Enthalpy at pump outlet
- h_{2s} : Enthalpy at pump outlet (isentropic)

These efficiencies are used to calculate the internal losses in the compression and expansion processes. The isentropic enthalpies h_{4s} and h_{2s} values are calculated in EES by maintaining the constant entropy through the turbine and pump, respectively.

II.4.5 EES Cycle Diagram

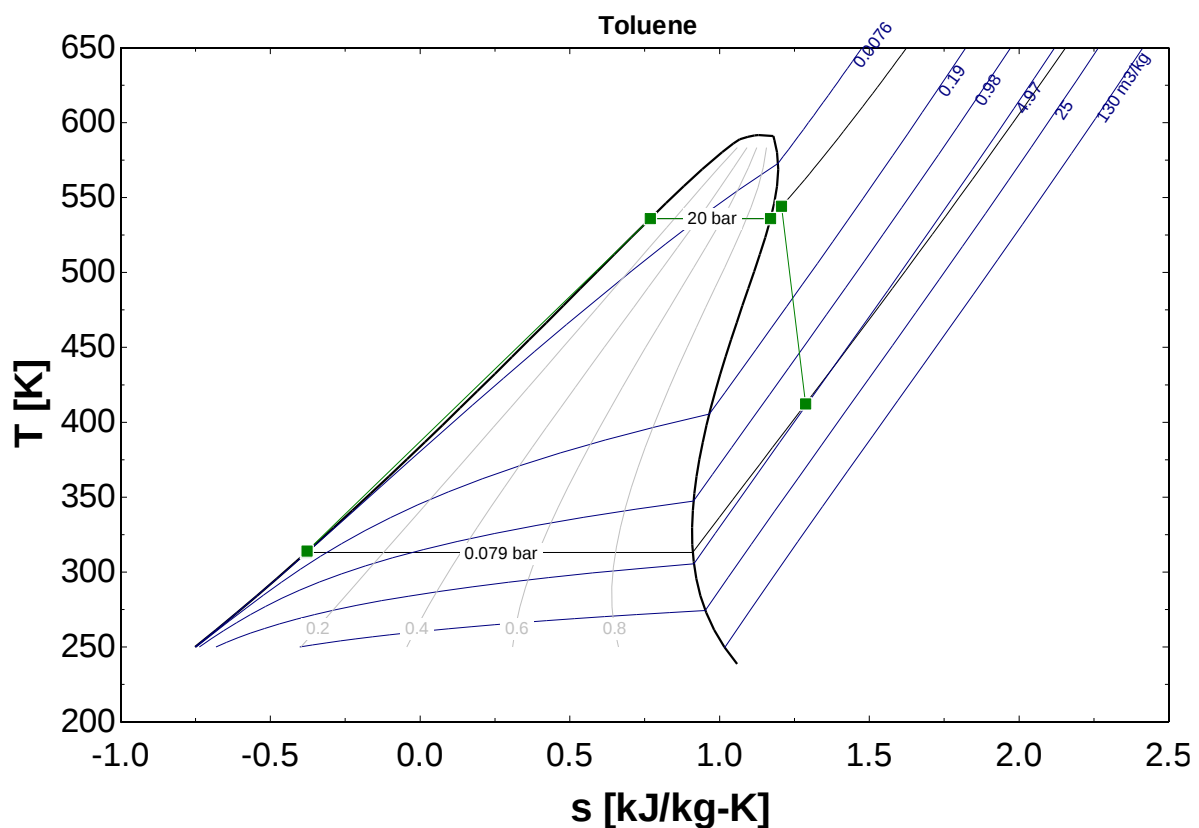


Figure 2.3: Simulation Based T-S Diagram

The Temperature-Entropy (T-s) diagram was generated using Engineering Equation Solver (EES) to draw the thermodynamic cycle with very high clarity and accuracy. The diagram has an important role to play in describing the four major states in the cycle that the working fluid experiences. By isentropic compression in the pump stage, from the evaporator taking the isobaric increment of heat and isentropic expansion on the turbine stage and ending the cycle with an isobaric rejection of heat in the condenser stage. The T-s diagram is not merely a visual tool for determining the nature of each process (e.g., reversible or irreversible, phase change or superheating) but also permits qualitative and quantitative examination of system performance.

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The area and shape of the cycle on the diagram permit an appreciation of the magnitude of net work output, as well as the relative quantity of heat input and rejection. Deviation from idealized horizontal or vertical lines on the graph reflects entropy generated due to irreversibility, which directly affect cycle efficiency as well as indicate potential areas of optimization. Furthermore, the diagram emphasizes the thermodynamic correspondence of temperature differences to entropy change and thus enables clearer understanding of energy conversion. For this reason, it proves a precious analysis aid in both assessing the efficiency as well as the thermodynamic restrictions of the specified system.

II.5 Parametric Studies

Parametric studies play a crucial role in analyzing how different operating conditions impact the performance of absorption cooling systems. By carefully adjusting key variables such as temperatures of the { evaporator, generator, absorber, and condenser } it becomes possible to identify operating points that maximize both efficiency and cooling capacity.

II.5.1 Effect of Evaporator Temperature:

The evaporator temperature is a key factor influencing the performance of absorption cooling systems. It significantly affects the coefficient of performance (COP), the exergetic coefficient of performance (ECOP), and the overall cooling capacity, especially in systems operating with LiBr-water or ammonia-water working pairs.

Impact on COP and Cooling Capacity:

Raising the evaporator temperature generally results in a higher coefficient of performance (COP) and increased cooling capacity. As the evaporator temperature rises, the system requires less input energy to deliver the same cooling effect, leading to improved overall efficiency.

Impact on Exergetic Performance:

While increasing the evaporator temperature improves the system's energetic performance, it generally leads to a decrease in exergetic efficiency (ECOP). This decline occurs because the exergy associated with the cooling effect diminishes at higher evaporator temperatures, even though the system requires less energy input overall.

Typically, the evaporator temperature that maximizes ECOP is lower than the temperature that maximizes COP. Several studies have reported that the highest ECOP is achieved at evaporator temperatures between 1°C and 1.5°C.

System Design Considerations:

Selecting the appropriate evaporator temperature requires balancing the desired cooling output, system efficiency, and the characteristics of the available heat source (such as internal combustion engine (ICE) exhaust).

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Lower evaporator temperatures are necessary for applications that require chilled water or sub-zero refrigeration; however, they typically result in a lower COP. On the other hand, operating at higher evaporator temperatures improves the COP but may not deliver sufficiently low cooling temperatures for certain applications.

II.5.2 Impact of Turbine Efficiency:

Turbine efficiency plays a crucial role in determining the overall performance of waste heat recovery systems, especially those based on the Organic Rankine Cycle (ORC). This section explores how changes in turbine isentropic efficiency impact the power output, thermal efficiency, and economic feasibility of ORC systems that recover exhaust heat from the Cummins QSK19-G4 engine.

Theoretical Background:

The isentropic efficiency of a turbine (η_{turbine}) is defined as the ratio of the actual work output to the ideal work output under isentropic (reversible and adiabatic) conditions:

$$\eta_{\text{turbine}} = W_{\text{actual}} / W_{\text{isentropic}}$$

where:

- **W_{actual}** is the actual work produced by the turbine.
- **$W_{\text{isentropic}}$** is the work produced during an ideal isentropic expansion process.

Impact on System Performance

Power Output: Turbine efficiency has a direct and proportional impact on the net power output of the ORC system. Studies indicate that for every 10% increase in turbine efficiency, the net power output can increase by approximately 8–12%.

Thermal Efficiency: Higher turbine efficiencies lead to significant improvements in the overall thermal efficiency of the ORC system. For instance, under the exhaust conditions of the Cummins QSK19-G4 engine (inlet temperature of 438°C and 701.4 kW of available heat), the system's thermal efficiency can rise from around 8% at 60% turbine efficiency to over 15% at 90% turbine efficiency.

Exergy Destruction: A decrease in turbine efficiency results in greater exergy destruction within the system, thereby lowering the exergetic efficiency. Since the turbine is one of the primary sites of exergy loss, improving its efficiency is key to optimizing the overall system performance.

CHAPTER III :

Modeling and Simulation of ICE-TEG Integration

CHAPTER III : Modeling and Simulation of ICE-TEG Integration

III.1 System Description and Assumptions

III.1.1 ICE Exhaust Temperature Profile

The internal combustion engine (ICE) used in this study is the Cummins QSK19-G4, a 6-cylinder turbocharged diesel engine designed for power generation. To determine the potential for waste heat recovery using systems like Thermoelectric Generators (TEGs), a proper characterization of the exhaust stream is essential.

According to Cummins Power Generation (DQFAD Generator Set Submittal Sheet), the key exhaust gas parameters are:

Table III.1 – Exhaust Gas Conditions of the Cummins QSK19-G4

Parameter	Value	Unit
Engine Mechanical Power Output	574	kW
Engine Electrical Power Output	520	kW
Exhaust Gas Flow Rate	2.214	kg/s
Exhaust Temperature (Inlet)	438	°C
Exhaust Cooling Limit (Assumed)	150	°C
Specific Heat of Exhaust Gas	1.1	kJ/(kg·K)

The thermal energy potentially recoverable from the exhaust is calculated using the formula:

$$Q_{\text{exhaust}} = m_{\text{exh}} \times C_p \times (T_{\text{in}} - T_{\text{out}})$$

Substituting the values:

$$Q_{\text{exhaust}} = 2.214 \times 1.1 \times (711 - 423) = 701.4 \text{ kW}$$

Thus, approximately 701.4 kW of thermal energy is available for recovery. The exhaust outlet temperature (T_{out}) is set at 150°C (423 K) to ensure practical operation of the waste heat recovery system.

III.1.2 TEG Configuration (PbTe Material)

The configuration of the Thermoelectric Generator (TEG) system plays a critical role in its performance, especially when integrated with waste heat recovery applications like the Cummins QSK19-G4 engine. In this section, the design considerations, material selection, and operational configuration of the TEG system are described.

Based on thorough research and conclusions drawn from recent doctoral theses and

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scientific literature, PbTe (Lead Telluride) has been selected as the thermoelectric material due to its excellent performance at intermediate to high temperatures (400–600°C).

Material Selection: PbTe

Lead Telluride (PbTe) is a well-established thermoelectric material known for its:

- High Seebeck coefficient ($\sim 250\text{--}400\ \mu\text{V/K}$),
- Moderate thermal conductivity,
- Excellent thermoelectric figure of merit ($ZT \approx 1.0$ to 1.5 at around 500°C).

This makes PbTe particularly suitable for applications utilizing high-temperature exhaust gases.



Figure 3.1: Lead telluride (pbte) Thermoelectric generator



Figure 3.2: Row form of Lead telluride (pbte)

The material exhibits the following properties:

- Seebeck coefficient (α): **250** $\mu\text{V/K}$ at **400–500°C**
- ZT value: **1.0** to **1.5** (depending on doping and nanostructure optimization)
- Working temperature range: **400°C** to **600°C**
- Electrical conductivity: **High** (low internal resistance)
- Thermal stability: Excellent up to **600°C** with optimized doping (e.g., sodium (Na), antimony (Sb))

TEG Module Design and Configuration

The TEG system is designed with modular arrays composed of PbTe-based modules. Each module maintains a high-temperature gradient across its legs by:

- Hot side connected to the exhaust gas (**438°C**),
- Cold side connected to a cooling system ($\sim 100^\circ\text{C}$).

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Configuration details:

- Hot side temperature : **438°C**
- Cold side temperature : **100°C**
- ΔT across module : **~338 K**
- Number of modules: **~1150 module** installed over the heat exchanger surface.
- Expected power per module : **~14–15 W**
- Total electrical output : **~17.1 kW**

Modules are connected electrically in series to build up voltage and thermally in parallel to keep a strong temperature gradient.

Module Mechanical Assembly

Modules are clamped between high-thermal-conductivity plates (typically aluminum or copper), with thermal interface materials (TIMs) used to reduce contact resistance. A mechanical frame is used to absorb thermal expansion stresses without damaging the thermoelectric legs.

Good assembly ensures:

- Maximum heat transfer,
- Mechanical protection,
- Electrical stability.

III.2 Thermoelectric Modeling

III.2.1 Heat Transfer Analysis (Fourier's Law)

In thermoelectric generator (TEG) systems integrated with internal combustion engines, the effective utilization of waste heat is fundamentally dependent on the accurate analysis of heat transfer mechanisms. At the core of this analysis lies Fourier's Law of heat conduction, which governs the transfer of thermal energy through solid materials. The equation is mathematically represented as:

$$Q = (k * A * \Delta T) / L$$

Where:

- **Q** is the rate of heat transfer (**W**).
- **k** is the thermal conductivity of the thermoelectric material (**W/m·K**).
- **A** is the cross-sectional area perpendicular to the direction of heat flow (**m²**).
- **ΔT** is the temperature difference across the material (**K**).
- **L** is the length or thickness of the conductive path (**m**).

In this context, the TEG modules are strategically placed downstream of the Organic Rankine Cycle (ORC) evaporator, where exhaust gas temperatures remain sufficiently high to drive meaningful thermoelectric conversion. The temperature gradient (ΔT) is

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established between the hot exhaust gases and a cold sink—typically engine coolant or ambient air.

Thermal conductivity (k) is material-specific and plays a critical role in determining the efficiency of heat conduction. For high-performance TEGs, materials such as Bismuth Telluride (Bi_2Te_3) or Lead Telluride (PbTe) are often selected due to their favorable thermoelectric properties at medium to high temperature ranges. The dimensions (A and L) are predefined by the TEG module geometry and packaging constraints around the exhaust manifold.

In the EES simulation model, the thermal input (Q) into each TEG module is calculated dynamically based on the actual temperature differential observed between the hot and cold interfaces. This dynamic modeling allows for accurate representation of the spatial and temporal variations in engine load and exhaust temperature.

Moreover, multi-module configurations are also considered, where the cumulative heat transfer is a summation of the contributions from individual modules arranged either in series or parallel configurations. This modular approach enhances both redundancy and scalability of the thermoelectric array.

A proper estimation of heat flow is not only essential for assessing the electrical potential of the TEG system but also crucial for thermal management. Excessive heat accumulation without efficient dissipation can reduce performance or even lead to material degradation.

Thus, the Fourier-based thermal analysis in EES acts as a cornerstone for the complete thermoelectric simulation, setting the stage for calculating the electrical output in the subsequent sections, especially in relation to the Seebeck effect and temperature gradient characteristics.

III.2.2 Electrical Output Calculation (Seebeck Coefficient, ΔT , ZT)

The TEG's electrical output is estimated using a performance model that integrates theory of Seebeck effect with the dimensionless material figure of merit (ZT). This is more realistic and accurate in projecting how effectively the TEG will be in converting thermal energy into electric power. By taking into account the temperature gradient across the module and the properties of the thermoelectric material itself, the model simulates actual operating conditions typically encountered within diesel engine exhaust systems. This ensures that the predicted electrical output closely and very accurately replicates the expected performance under varying thermal loads and operational temperatures.

The electrical power generated by a TEG is directly influenced by:

- The temperature difference between the hot and cold sides,
- The Seebeck coefficient of the thermoelectric material,
- The electrical and thermal conductivity of the material, and
- The thermal energy absorbed from the exhaust gas.

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Key Operating Parameters:

- Hot-side temperature (T_{hot}) = 711.15 K
- Cold-side temperature (T_{cold}) = 373.15 K
- Temperature difference $\Delta T = T_{hot} - T_{cold} = 338$ K
- Seebeck coefficient (α) for PbTe $\approx 250 \mu\text{V/K} = 0.00025$ V/K
- Electrical conductivity (σ) $\approx 1.0 \times 10^5$ S/m
- Thermal conductivity (κ) ≈ 2.0 W/m·K
- Average temperature (T_{avg}) = $(T_{hot} + T_{cold}) / 2 = 542.15$ K

- **Seebeck Voltage (Open Circuit):**

The voltage generated by a single thermoelectric couple under open-circuit conditions are given by:

$$V = \alpha \times \Delta T$$

- **Heat Absorbed by TEG (Q_{TEG}):**

TEG is designed to absorb exactly **100 K** of temperature difference from the exhaust flow, corresponding to a heat fraction of **100/288 = 0.347**.
Total exhaust heat **$Q_{exhaust} = 701.4$ kW**

$$Q_{TEG} = 0.347 \times Q_{exhaust}$$

- **Figure of Merit (ZT) Calculation:**

$$ZT = \frac{S^2 \times \sigma \times T_{avg}}{\kappa}$$

III.2.3 Module Efficiency (Maximum and Realistic)

The overall efficiency of a thermoelectric module is not only a function of the intrinsic material properties, including the figure of merit (ZT), but also of actual design factors. These include module geometry, electrical and thermal contact resistances, and quality of thermal interfaces. Even with high ZT, poor design or suboptimal connections can affect performance significantly.

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The efficiency of a TEG module is theoretically derived from its ZT value and the temperature boundaries using the following classical expression:

$$\eta_{\max} = \frac{\Delta T}{T_{\text{hot}}} * \frac{\sqrt{1 + ZT} - 1}{\sqrt{1 + ZT} * \frac{T_{\text{cold}}}{T_{\text{hot}}}}$$

Realistic Efficiency:

Assuming 60% of max efficiency:

$$\eta_{\text{real}} = 0.6 \times \eta_{\text{max}}$$

Electrical Output Power:

$$P_{\text{electrical}} = \eta_{\text{real}} \times Q_{\text{TEG}}$$

Per Module Performance (1150 modules):

$$P_{\text{module}} = (P_{\text{electrical}} \times 1000) / 1150$$

One critical contributor to real-world efficiency is thermal resistance both within the module and in external system interfaces. These can induce temperature drops that decrease the effective gradient across the thermoelectric elements and restrict output.

In this case it doesn't have an effect because the material (PbTe) have low thermal resistance .

III.3 EES Implementation

III.3.1 Thermal Boundary Conditions and Heat Recovery Scope

In this simulation, the Thermoelectric Generator (TEG) is positioned after the Internal Combustion Engine (ICE) to recover a portion of the high- temperature waste heat emitted the engine through the exhaust gases. The exhaust gas leaves the engine at a temperature of 711.15 K (438 °C) and passes over the hot side of the TEG module. The cold side is maintained at 353.15 K (80 °C) using an active or passive cooling mechanism, resulting in a temperature difference (ΔT) across the TEG of :

$$\Delta T = T_{\text{hot}} - T_{\text{cold}} = 711.15 - 353.15 = 358 \text{ K}$$

This temperature difference is responsible for the thermoelectric effect. The larger the ΔT , the larger the output voltage and more effective the system, provided the thermoelectric material (in this case, PbTe) is within its operating range of temperatures.

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However, it does not deliver all the exhaust energy to the TEG. The simulation also assumes that only a fraction of the entire exhaust heat is accessible to the TEG — specifically, the top 100 K of the exhaust temperature drop, from 438 °C (711.15 K) to 338 °C (611.15 K). It is due to:

- TEG modules operate best within a limited high-temperature window (PbTe performs well between 500 K and 800 K).
- The remaining heat may be reserved for an ORC system or cannot be practically extracted due to heat exchanger limitations.
- Avoiding full exhaust recovery prevents overestimating the energy that can be realistically transferred to the modules.

Not all of the exhaust energy is utilized by the TEG, however. The simulation predicts that only a fraction of the exhaust heat is accessible to the TEG — i.e., the highest 100 K of the range of exhaust temperatures, between 438 °C (711.15 K) and 338 °C (611.15 K). This is due to the following factors.

This fraction is applied to the total exhaust energy ($Q_{\text{exhaust_total}} = 701.4 \text{ kW}$) to determine the available heat input to the TEG:

$$Q_{\text{TEG}} = 0.347 \times Q_{\text{exhaust_total}}$$

III.3.2 Material Efficiency and ZT Significance

The performance of a thermoelectric generator (TEG) is highly dependent on the material properties of the thermoelectric material in its modules. In this arrangement, lead telluride (PbTe) is chosen as the thermoelectric material due to its excellent performance in high-temperature ranges of 500 K to 800 K. The performance of the material is largely evaluated by its dimensionless figure of merit (ZT), which indicates how efficiently it can convert heat into electricity.

The ZT value is calculated using the following relation:

$$ZT = \frac{S^2 \times \sigma \times T_{\text{avg}}}{\kappa}$$

Where:

- S is the Seebeck coefficient (**250 $\mu\text{V/K}$**)
- σ is the electrical conductivity (**$1.0 \times 10^5 \text{ S/m}$**)
- T_{avg} is the average operating temperature, calculated as the mean of the hot and cold sides (**532.15 K** in this case)
- κ is the thermal conductivity (**2.0 $\text{W/m}\cdot\text{K}$**)

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Substituting the values into the equation, the ZT of PbTe under the current boundary conditions is approximately 1.507, indicating high potential for thermoelectric conversion. The larger the ZT, the higher the performance of the material in a compromise between electrical conductivity, thermopower, and low thermal conductivity.

Nevertheless, ZT alone does not dictate the overall efficiency of a real-world TEG system. It must be multiplied by the operating temperature difference (ΔT) to derive the theoretical maximum efficiency ($\eta_{\max}$), and then reduced to account for real-world inefficiencies (η_{real}). Even with an ideal ZT, overall system performance is constrained by how effectively heat is transferred into the module and by the internal resistance of the material.

Thus, while PbTe is a good thermoelectric material at the chosen temperatures, its ZT value and temperature compatibility must always be considered simultaneously in order to realistically optimize and predict system output.

III.3.3 Electrical Output and Module Performance

The electrical output of a Thermoelectric Generator (TEG) system is effected by both the thermal conditions and the performance of the thermoelectric material. After defining the heat input and evaluating the material's figure of merit (ZT), the next critical step is to calculate the actual power generation and examine the behavior of individual modules.

The available thermal input to the TEG represents the portion of exhaust heat falling within the 100 K temperature window between 711.15 K and 611.15 K. And even after that it's effected by the efficiency of the heat exchange that goes from the exhaust to the TEG hot side which is usually around 90 to 95% dropping the actual heat absorbed to:

$$Q_{\text{TEG_actual}} = 0.9 * Q_{\text{TEG}}$$

The ideal efficiency of the thermoelectric generator is based on 2 big factors, the merit figure (ZT) and the heat difference between the cold and hot side (ΔT) and it's determined by this equation:

$$\eta_{\max} = \frac{\Delta T}{T_{\text{hot}}} * \frac{\sqrt{1 + ZT} - 1}{\sqrt{1 + ZT} * \frac{T_{\text{cold}}}{T_{\text{hot}}}}$$

The realistic efficiency usually is 60 to 70% of the ideal one due to the thermal and electric losses through the system and by that the total electrical power output can be expressed as:

$$P_{\text{TEG}} = \eta_{\text{real}} \times Q_{\text{TEG}}$$

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This value represents the net electric power generated by the entire **TEG** assembly under steady-state conditions.

Module-Level Performance

For practical applications, the TEG system is composed of multiple thermoelectric modules electrically connected in series or parallel, depending on system voltage and current requirements. Based on design assumptions, the system uses 1150 individual modules.

The output of each module can therefore be estimated by:

$$P_{\text{module}} = (P_{\text{TEG}} \times 1000) / N_{\text{modules}}$$

This value aligns with the expected output of high-performance PbTe modules operating at a ΔT of **100 K**, and confirms the consistency of the thermodynamic and electrical modeling.

It is important to note that module-level performance is sensitive to:

- Contact resistances
- Temperature uniformity across surfaces
- Matching of load resistance with internal resistance (for maximum power point)

Ensuring proper thermal design and electrical configuration is therefore essential to reach the predicted system performance in a real-world implementation.

III.3.4 Losses and Design Limitations

While the **TEG** system offers efficient energy recovery, a number of losses must be accounted for to close the gap between simulation and reality.

At first, the thermoelectric modules do not effectively convert all the exhaust thermal energy. Non-efficiencies in the heat exchanger, heat distribution non-uniformity, and thermal contact resistance at interfaces can result in significant losses of real thermal input. The losses are typically measured by a heat exchanger efficiency factor, generally set between **85%** and **95%** in practical applications.

Second, in the TEG module itself, there are losses inside from finite thermal and electrical conductivity. The Seebeck coefficient also varies by temperature and material composition, so actual performance does vary from ideal.

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Third, part of the generated electrical power is lost in resistive heating in cabling and module wiring. Additional parasitic loads such as power conditioning units (e.g., MPPT systems) can reduce net output.

The other important limitation is the rigid working window of the thermoelectric material. **PbTe**, for instance, performs between **500 K** and **800 K**. Working beyond these boundaries performs poorer or destroys the material, while lower ΔT reduces efficiency drastically.

In summary, total system losses arise from:

- * Heat exchanger losses
- * Thermal resistance at module interfaces
- * Internal electrical resistance and contact losses
- * Auxiliary systems (inverters, MPPT, etc.)

By incorporating realistic values for each of these losses, the net power output of the **TEG** system drops below the ideal value. Thus, while theoretical calculations (based on **ZT** and ΔT) suggest **17.05 kW**, real-world installations may yield outputs closer to **12–14 kW** depending on design quality and operational control.

III.4 Parametric Studies:

To optimize the performance of the Thermoelectric Generator (TEG) system integrated with the Internal Combustion Engine (ICE), a series of parametric analyses were conducted. The TEG is based on PbTe (Lead Telluride), chosen for its reasonable performance within the medium-to-high-temperature range of 300–600°C, which closely matches the temperature profile of the ICE exhaust. This study focuses on how critical parameters affect the output power, efficiency, and viability of the TEG system when coupled with the ICE.

III.4.1 Effect of Temperature Difference

The temperature difference (ΔT) between the hot and cold sides of the TEG is one of the most critical parameters influencing its performance.

Power Output: The power output increases significantly as ΔT rises, particularly between the cold side (100°C) and the hot side (438°C). This is due to the enhanced Seebeck voltage, which is directly proportional to the temperature differential.

Material Degradation Risks: However, when ΔT exceeds 350°C for PbTe modules, material degradation risks increase due to higher heat, leading to faster diffusion and a deterioration of electrical properties.

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Optimal ΔT for PbTe: At an ICE exhaust temperature of 438°C and maintaining a cold-side temperature of 100°C, an average ΔT of 338°C is achievable and is optimal for PbTe modules, balancing power generation and material longevity.

III.4.2 Impact of Module Size and Configuration

The TEG modules can be arranged either in series or parallel configurations, depending on the desired output current and voltage. The choice of configuration impacts performance significantly.

Large Modules: Larger modules can capture more heat but are more susceptible to non-uniform heating if the exhaust flow is not evenly distributed. This can lead to thermal stress and delamination if the substrate does not expand uniformly.

Small Modules in Array: Smaller modules provide better surface conformity and thermal matching. They facilitate modular scalability, easy replacement, and maintenance, making them ideal for long-term use.

Series Configuration: In series, the modules enhance voltage output. However, uniform thermal conditions are critical across all modules to prevent mismatch and reverse current, which can degrade system performance.

Parallel Configuration: A parallel configuration increases current output. It is more tolerant of module mismatch, but results in lower system voltage compared to a series setup.

In conclusion, The optimal configuration is a hybrid modular system combining both small modules in series-parallel arrangements. This approach provides a balance of high efficiency, good thermal stability, and system design flexibility.

III.4.3 Heat Sink Design Impact

The cold-side heat rejection of the TEG is a critical factor limiting its performance.

Key Considerations:

Heat Sink Material: Materials such as aluminum or copper are commonly used for heat sinks due to their thermal conductivity.

Geometry and Surface Area: The effectiveness of a heat sink depends on its design, including features such as fins, channels, and phase-change materials.

Cooling Method: Heat sinks can be passive (e.g., natural air cooling) or active (e.g., forced air or liquid-cooled systems).

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Heat Sink Performance: A poorly designed heat sink reduces ΔT , which in turn reduces the output power of the TEG. For sustained operation, particularly in high-performance systems, liquid cooling or phase-change materials may be necessary to maintain the cold-side temperature below 100°C.

Trade-offs: High-end heat sinks are more effective but come at a higher cost and complexity. Passive cooling systems, while less efficient, are cheaper and suitable for small engine enclosures with lower thermal output.

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System Modeling

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IV.1.1 Series Configuration: ICE → TEG → ORC → Absorption Machines

The conceptual Waste Heat Recovery (WHR) system has been conceptualized in a thermally cascaded configuration, where the Internal Combustion Engine's (ICE) exhaust energy is recovered by cascaded systems in stages: a Thermoelectric Generator (TEG), an Organic Rankine Cycle (ORC), and finally a series of Absorption Refrigeration Machines. All the subsystems have been conceptualized to be thermodynamically compatible to a specific temperature range so that staged recovery of high-, medium-, and low-grade thermal energy would be feasible for optimal efficiency.

IV.1.1.1 System Energy Flow Description

1. ICE Exhaust → TEG (PbTe):

The ICE releases hot exhaust gases at a temperature of approximately 438 °C. These exhaust gases are directed first through a TEG unit on PbTe (lead telluride) modules, which operate based on the Seebeck effect principle. There is a temperature gradient maintained across the TEG—utilizing an 80–100 °C cold side temperature—to generate direct electrical power. The used PbTe material is suitable for this 100 K differential and also thermally stable in the operating window.

2. TEG → ORC:

After partial heat recovery by the TEG, the exhaust temperature drops to 338 °C and is then fed into the ORC heat exchanger. The ORC is then employed to utilize this medium-grade heat in vaporizing an organic working fluid (Toluene) in a closed-loop system. The ORC consists of a couple of big components:

- **Pump (P1):** First, the working fluid is pumped up by a feed pump.
- **Preheaters (PH1 & PH2):**

Preheater 1: Raising the fluid temperature from 314 K to 334 K.

Preheater 2: Further heating from 334 K to 374 K.

The two-stage preheaters improve thermal efficiency through the recovery of sensible heat from internal hot streams (such as turbine exit).

- **Evaporator:** The preheated fluid absorbs latent heat and fully vaporizes at 536 K, prepared for expansion.

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- **Turbine:** A turbine (or scroll expander) is powered by high-enthalpy vapor, which converts thermal energy to mechanical or electrical energy. The vapor is discharged at the turbine at approximately 402 K.
- **Precooler:** The heat exchange causes the temperature of the turbine outlet to be reduced from 402 K to 362.5 K before flowing to the condenser.
- **Condenser:** The vapor is liquefied at low pressure, typically around 105 °C (378–383 K), which is the cycle termination.

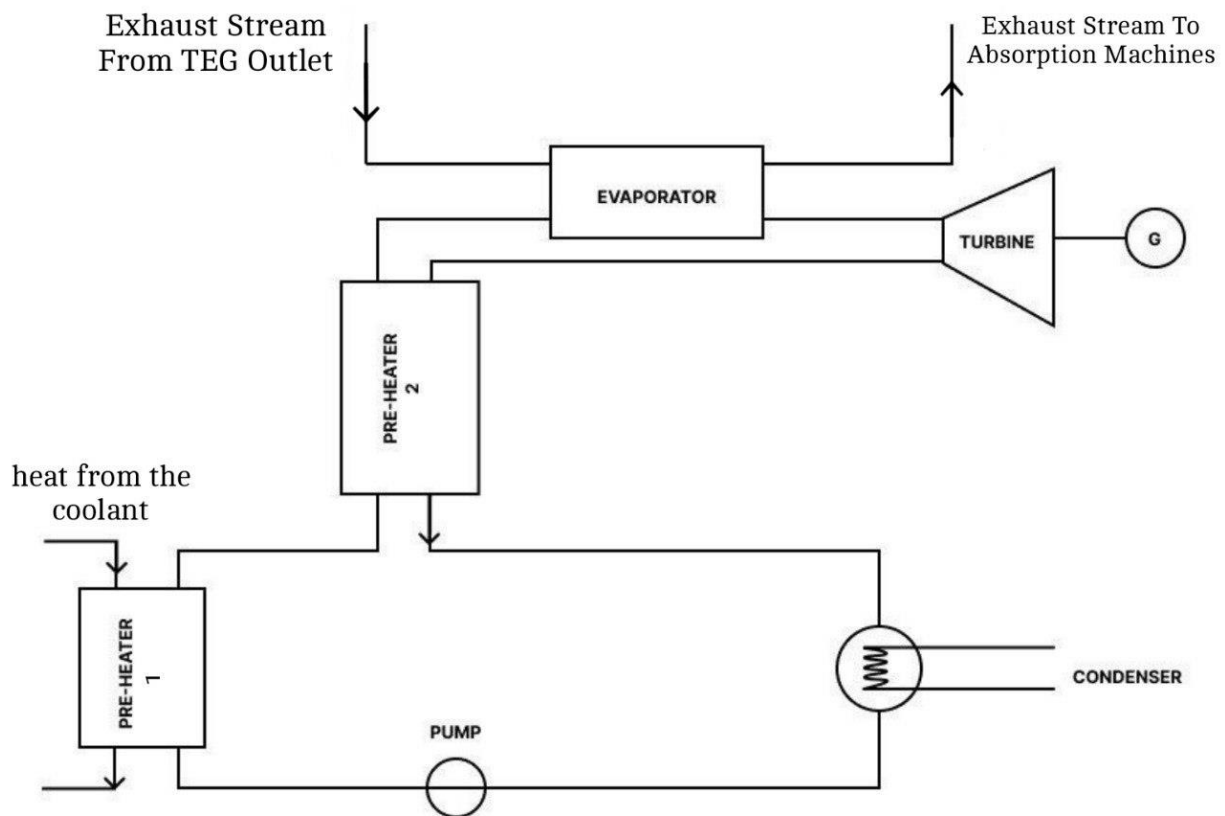


Figure 4.1: ORC System With Pre-Heating

3. ORC Outlet → Absorption Machines

Low-grade residual heat with an outlet condenser temperature of 105 °C is provided. The heat is then utilized for providing four units of absorption refrigeration, each having an ability to utilize thermal energy of 90–105 °C. Overall cooling impact is provided by the four units from endothermic phase change drives in the absorption working pair cooling down the exhaust to a final temperature level of approximately 86 °C before exhausting to the surroundings.

IV.1.1.2 Justification for Cascade Design

Temperature Matching

The TEG unit is placed in the hottest temperature segment of the exhaust stream for maximum thermoelectric efficiency. The next ORC operates in an optimum range for toluene, and finally, the absorption machines utilize the remaining low-grade heat. The staged design does this by ensuring that each component operates within its thermodynamic comfort level.

Exergy Optimization

Through spreading the exhaust heat across a spectrum of suitable technologies, the system experiences minimum exergy destruction and maximum recoverable work.

Better Energy Utilization:

The cascade arrangement enables comprehensive utilization of the exhaust heat across three various functional outputs: power from TEG and ORC, and refrigeration from absorption machines.

IV.1.1.3 Advantages of Having Two Preheaters in ORC

- Enhanced Thermal Efficiency

Capture beneficial heat from inner components such as turbine exhaust allows for less external use of energy in the evaporator, improving overall cycle efficiency.

- Constant Heating for Component Survival

Preheating working fluid through staging minimizes thermal shock and stress upon sensitive components such as the evaporator, leading to higher operating reliability.

- Use of Low-Grade Heat

Preheaters enable the use of energy that is insufficient to cause full vaporization but still useful to heat the working fluid.

- Reduced Irreversibilities:

Staged and controlled heat transfer reduces entropy generation, resulting in a better reversible and efficient process.

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- System Flexibility:

Multiple preheaters provide for greater control of thermal gradients, improving flexibility with varying engine loads or climatic conditions.

IV.1.2 Thermal Coupling Strategies

Thermal coupling plays an essential role in ensuring efficient energy cascade and utilization within the hybrid Waste Heat Recovery (WHR) system comprising an Internal Combustion Engine (ICE), a Thermoelectric Generator (TEG), an Organic Rankine Cycle (ORC), and Absorption Machines. The heat integration is a sequential program: ICE → TEG → ORC → Absorption Machines, with each of the subsystems being at a lower thermal grade than the previous one, and staged recovery of high-, medium-, and low-grade heat. Thermal coupling is very efficient to ensure optimal system efficiency, temperature compatibility, lesser pressure and thermal losses, and lesser system complexity and cost.

IV.1.2.1 Coupling Between ICE and TEG

The TEG is mounted on the exhaust stream of the ICE, and direct heat is transferred from the exhaust hot gases. The exhaust gas leaves the engine at approximately 711 K (438 °C), and the cold side of the TEG is at 373 K with the hot side maintained at 611 K. This is within the ideal working range of PbTe thermoelectric modules that work well between 500–750 K. The direct coupling eliminates intermediate losses, enhances compact system integration, and provides instant thermal response. However, it is not without some challenges as well. The variable operating conditions of the ICE can create fluctuating exhaust temperatures that can cause mechanical and thermal stress to the TEG modules, which can have an impact on long-term performance and stability.

IV.1.2.2 Coupling Between TEG and ORC

The heat excreted out of the TEG system is not wasted but is directly input into the ORC evaporator to be used as the energy source for toluene organic working fluid boiling. The ORC is supplied with the exhaust heat at around 338 °C (611 K), which is very close to the boiling point of toluene, the working fluid utilized in this setup. This thermal match can efficiently change phase and transform energy without overburdening the thermal capacity of the fluid. Among its benefits are:

- Enhanced temperature compatibility between subsystems.
- Protection to the ORC system from overbearing thermal loads from the upstream TEG.
- Improved stability in turbine operation due to lower heat input pulsation.

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However, the coupling significantly depends on the effectiveness of the heat exchangers. If the temperature exchange between the ORC and TEG is not highly effective, or where there are high losses incurred by the heat exchangers, the overall recovery efficiency can decline very considerably. Thermal mismatches in outlet and inlet conditions could also vitiate the likely energy benefits, necessitating precise tuning and control of operating conditions.

IV.2 Thermodynamic Model Development

IV.2.1 Energy Flow Through The WHR Cascade (ICE → TEG → ORC → Absorption Machines)

This section describes the thermal energy distribution and recovery strategy in the proposed Waste Heat Recovery (WHR) cascade system, which integrates a high-power Internal Combustion Engine (ICE) with a Thermoelectric Generator (TEG), an Organic Rankine Cycle (ORC), and a set of four absorption cooling machines.

The engine exhaust exits at 711.15 K (438 °C) and carries substantial thermal energy. The recovery is divided into three sequential thermal levels, each matched with a suitable conversion technology to extract the maximum possible energy before the exhaust is released to the environment.

The energy flow is divided based on the temperature span available in the exhaust gases:

- Initial exhaust temperature ($T_{\text{exhaust_in}}$): **711.15 K (438 °C)**
- TEG outlet (and ORC inlet) temperature ($T_{\text{transition}}$): **611.15 K (338 °C)**
- ORC outlet temperature ($T_{\text{exhaust_out}}$): **378.15 K (105 °C)**

Energy Captured by TEG

The TEG system captures heat from the first 100 K segment of the engine exhaust stream, from 711.15 K (438 °C) down to 611.15 K (338 °C). This band is carefully chosen to match the optimal operating window of PbTe modules.

Instead of using a heat fraction, the actual heat absorbed is calculated directly from the exhaust gas flow properties:

$$Q_{\text{TEG}} = Q_{\text{exh}} = \dot{m}_{\text{exh}} \times C_p \times (T_{\text{in}} - T_{\text{out}})$$

$$Q_{\text{TEG_actual}} = 0.9 \times Q_{\text{TEG}}$$

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The electrical output of the TEG is then calculated based on a realistic thermoelectric efficiency (η_{real}) of around 6%:

$$P_{\text{electrical}} = \eta_{\text{real}} \times Q_{\text{TEG_actaul}}$$

Energy Supplied to ORC

The ORC absorbs the remaining portion of the exhaust heat from 611.15 K down to 378.15 K:

$$Q_{\text{exh}} = \dot{m}_{\text{exh}} \times C_p \times (T_{\text{in}} - T_{\text{out}})$$

$$Q_{\text{ORC}} = 0.9 \times Q_{\text{exh}}$$

The net electrical power is given by :

$$P_{\text{electrical}} = \eta_{\text{real}} \times Q_{\text{ORC}}$$

This cascade setup allows for stepwise energy harvesting across the exhaust gas temperature spectrum. By matching each segment with the appropriate technology, the system extracts more usable work and boosts total efficiency.

IV.2.2 Combined Efficiency Formulation

In a cascaded Waste Heat Recovery (WHR) system utilizing both a Thermoelectric Generator (TEG) and an Organic Rankine Cycle (ORC), evaluating the overall system efficiency requires accounting for both subsystems and the way thermal energy is divided between them. This section formulates the combined thermal-to-electrical efficiency and defines the relationship between individual component efficiencies and total energy utilization.

The electrical system efficiency (η_{electric}) is defined as the ratio of the total net electrical power recovered from the exhaust gas (via both TEG and ORC) including the ICE power generation to the total fuel energy from the combustion :

$$\eta_{\text{electric}} = \frac{P_{\text{ICE}} + P_{\text{TEG}} + P_{\text{ORC}}}{Q_{\text{sc}}}$$

Where:

- P_{ICE} is the net electrical power produced by the internal combustion engine .
- P_{TEG} is the net electrical power produced by the TEG system.
- P_{ORC} is the net electrical power produced by the ORC system.
- Q_{sc} is the total heat energy available from the fuel combustion.

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The total system efficiency (η_{total}) is defined as the ratio of the total net electrical power recovered from the exhaust gas (via both TEG and ORC) and the heat energy recovered in the absorption units and including the ICE power generation to the total fuel energy from the combustion

$$\eta_{total} = \frac{P_{ICE} + P_{TEG} + P_{ORC} + 4 * Q_{AM}}{Q_{sc}}$$

- $4*Q_{AM}$ is the net cold energy produced by the 4 absorption machine (AM) .

For a cascaded Waste Heat Recovery (WHR) system utilizing both a Thermoelectric Generator (TEG) and an Organic Rankine Cycle (ORC), the determination of the overall system efficiency needs to address both subsystems as well as the division of thermal energy between them. In this work, the hybrid thermal-to-electrical efficiency is developed and the relationship between component-level efficiency and overall energy utilization is determined.

This combined efficiency demonstrates the merit of hybrid systems. By tackling the range of temperatures in the exhaust stream, the system can recover more useful work than with either cycle alone. Additionally, the cascade integration enables heat rejection from one subsystem (TEG) to become input to the next (ORC), minimizing energy wastage.

Additional Integration: Heat Redistribution following ORC

Following the energy harvesting through the TEG and ORC systems, the residual thermal energy of the exhaust stream (below ~ 378.15 K or 105°C) is not discarded. Instead, it is recuperated by a final heat exchanger (HX) placed at the outlet of the ORC subsystem. The exchanger recuperates low-grade heat and redirects it for absorption refrigeration.

For distributed application, the exhaust gas mass flow is split into four parallel flows, one to each absorption machine. These are low driving temperature ($\sim 80\text{--}90^\circ\text{C}$) and thus particularly suitable for this residual heat. This final step not only increases overall energy efficiency but also facilitates tri-generation — the provision of power, cooling, and potentially heating from the same waste heat source.

The configuration supports:

- Better thermal matching for the absorption systems,
- Modular operation with parallel units,
- Further reduction in exhaust temperature before environmental release.

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This three-tier cascade — TEG → ORC → Absorption Cooling — demonstrates a holistic approach to energy recovery, maximizing utility at each temperature level and significantly reducing thermal waste.

IV.3 EES Simulation Of The Hybrid Recovery System

IV.3.1 TEG Modeling and High-Temperature Heat Recovery

This sub-section addresses simulation of the Thermoelectric Generator (TEG) subsystem using the Engineering Equation Solver (EES) software. The TEG is situated at a strategic location just after the internal combustion engine (ICE), where it harnesses the high-grade thermal energy from the engine's exhaust gases. The exhaust gases exit the engine at a temperature of about 438 °C (711.15 K), and this provides a large opportunity for direct thermal-to-electric conversion.

In this configuration, the TEG is designed to recover energy specifically from the upper 100 K of the exhaust temperature range. The hot side of the TEG module is in direct contact with the 711 K exhaust, while the cold side is maintained at 373K (100 °C), creating a steep and effective thermal gradient. PbTe is known for its high thermoelectric performance in the 500–800 K range, making it well-suited for this application.

Unlike traditional modeling approaches that rely on estimating the heat fraction, this simulation directly assigns the entire 100 K segment of thermal energy to the TEG. This removes the need for approximation and allows for a more accurate and focused analysis of TEG performance under real operating conditions. The heat input is further adjusted for heat exchanger losses, with an assumed 90% efficiency, reflecting practical implementation scenarios.

The material properties of PbTe — including its Seebeck coefficient, electrical conductivity, and thermal conductivity — are used to calculate the thermoelectric figure of merit (ZT). This value serves as the basis for estimating the maximum theoretical efficiency of the TEG.

Thus, the TEG system is found to generate a good amount of electrical power from this relatively small window of temperature, and the output is distributed across 1150 modules. There is a consistent electrical output from each module, and therefore the system is modular, scalable, and reliable. The simulation confirms the engineering feasibility of utilizing a TEG at the high-temperature side of the exhaust stream and discloses its important place in a cascade waste heat recovery system, ahead of the mid- and low-temperature ORC and absorption facilities.

IV.3.2 ORC Modeling and Mid-Temperature Energy Conversion

Following the TEG unit, the remaining thermal energy is routed to an Organic Rankine Cycle (ORC) system designed to operate in the medium temperature range. In the

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simulation environment developed using **EES**, the **ORC** model is carefully placed to extract heat from exhaust gases cooled down to approximately 611 K (338 °C) and further reduce their temperature to 378 K (105 °C), making use of the heat available before the gases are eventually released or directed to other recovery systems.

The working fluid selected for this system is toluene, which has demonstrated stable thermodynamic behavior and a strong performance profile in medium-to-high temperature ORC applications. The same ORC system in chapter 2 been used with with a slit modifications.

One of the key features integrated into the system is a pre-heating heat exchanger, where the cooling water from the engine — typically discarded or underutilized — is repurposed to raise the temperature of the fluid leaving the pump. This brings the working fluid from a temperature around 313 K (40 °C) up to 334 K (61 °C) before it enters the main evaporator

A second level of internal heat recovery is achieved using a recuperative heat exchanger. In this stage, thermal energy from the fluid exiting the turbine is transferred back to the fluid entering the evaporator. This helps elevate the fluid temperature even further, up to approximately 374 K, significantly reducing the thermal load on the main evaporator and improving the overall thermal efficiency of the cycle.

The evaporator then utilizes the remaining exhaust gas energy to fully evaporate and slightly superheat the working fluid, which is expanded in the turbine to generate mechanical work. The exhaust gases themselves also reduce in temperature as they transfer energy to the ORC fluid, ultimately exiting the system at a low enough temperature to be suitable for low-grade heat recovery applications, e.g., absorption cooling.

Actual equipment efficiencies for the turbine and pump are included in this simulation model so that the cycle performance predictions are more reflective of actual industrial conditions. Net power output is determined after accounting for internal losses, and system behavior is illustrated with state-point tables and T-s diagrams graphed in EES.

This section of the simulation demonstrates how the ORC bridges the energy conversion gap between the high-temperature TEG system and the low-grade absorption chillers, achieving maximum utilization of the exhaust gas energy across a wide temperature spectrum. By integrating pre-heating stages and internal recovery, cycle performance is enhanced without external heat sources, contributing to the overall efficiency and sustainability of the waste heat recovery system.

IV.3.3 Final Heat Distribution and Absorption Chillers

After the exhaust gases have passed through both the TEG and ORC subsystems, they still retain a significant amount of low-grade thermal energy. In this configuration, the remaining heat—exiting the ORC at approximately 378 K (105 °C)—is directed into a final heat recovery stage. This stage is designed to supply thermal energy to four single-effect

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absorption chillers, which operate effectively within the low-temperature range of 105 °C to 85 °C.

To achieve this, the exhaust flow is passed through a final heat exchanger, where it is split into four separate streams, each tailored to deliver a enough amount thermal input to one chiller unit. This parallel configuration ensures balanced distribution of heat, enhances reliability, and provides modularity to the cooling system.

The absorption chillers utilize this thermal energy to drive a refrigeration cycle based on the principles of sorption, using pairs such as LiBr–H₂O or NH₃–H₂O, depending on the design. In this case the selected pair is lithium bromide and water (LiBr–H₂O). Since these systems do not require mechanical compressors, they are ideal for integrating with waste heat sources and add minimal parasitic energy consumption to the system.

Although the exhaust gas temperature has been significantly reduced to this extent, the energy remains available to support cold energy generation, making use of what would otherwise be completely wasted heat. This methodology is still further enhancing the thermal recovery of the internal combustion engine, so that nearly the entire thermal range of the exhaust—from 711 K to approximately 363 K—is put to use and reused with the aid of three different technologies (TEG, ORC, and chillers).

By integrating absorption cooling into the tail section of the waste heat recovery cascade, the system not only gains efficiency overall but also becomes valuable through provision of auxiliary processes such as air conditioning, refrigeration, or process cooling without burn-up of additional fuel or electricity.

IV.4 Parametric Analysis of Thermal Cascade Strategy

Efficiency of a cascade waste heat recovery (WHR) process, incorporating Thermoelectric Generators (TEG), Organic Rankine Cycle (ORC), and absorption chillers, is extremely sensitive to the most important thermal parameters. In this chapter, a comprehensive parametric analysis is carried out in order to analyze how temperature grades and thermal interface design affect the overall system efficiency, energy flow, and functional distribution of recovered energy.

This cascade system correspond to the following thermal flow:

ICE → TEG → ORC → Absorption Machines

The objective is to investigate the influence of thermal boundaries—i.e., the TEG exit temperature and ORC inlet and outlet temperatures—on the subsystem efficiencies and to determine the scope of heat recovery and distribution across the configuration.

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IV.4.1 Temperature Cascade and Heat Allocation

The cascade arrangement is based on coupling each recovery system with the respective part of the exhaust gas temperature range. The exhaust gas from the ICE is led to exit at 711.15 K (438 °C). From this high-grade source, the thermal energy is divided between three recovery stages:

A. TEG Stage (High-Temperature Segment)

- Inlet Temperature: 711 K
- Outlet Temperature: 611 K
- ΔT : 100 K

Estimated Efficiency: 6.83 % (PbTe material)

This stage extracts the highest-temperature heat. A ΔT of 100 K keeps the PbTe modules in their most favorable thermal range (500–750 K) without impairment. It is assumed that the TEG heat exchanger is 90% efficient and delivers around 219 kW of viable thermal input.

B. ORC Stage (Mid-Temperature Segment)

- Inlet Temperature: 611 K
- Outlet Temperature: 378 K
- ΔT : 233 K
- Working Fluid: Toluene

Thermal Efficiency: ~23.94 %

The ORC is driven by the residual heat following the TEG section. Toluene's thermal stability makes it a perfect candidate for the mid-segment, with the leftover 238 K used to recover approximately ~122 kW of electrical energy.

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C. Absorption Chillers (Low-Temperature Segment)

- Inlet Temperature: ~ 378 K (105 °C)
- Chillers Used: 4 parallel units
- Input Heat Requirement: ~ 14.3 kW each

Total Cooling Output: ~ 40.04 kW (COP ~ 0.7)

The condenser heat of the ORC is diverted to absorption chillers, which utilize low-grade residual heat to generate chilled air or water. The final stage optimizes system utility by providing thermal comfort or industrial cooling.

IV.4.2 Rationale of Temperature Choice

The chosen temperature ranges for each subsystem are based on material limitations, efficiency curves, and standards of industry:

Table IV.1: Temperature Choice Justification

Stage	Range Temperature (K)	Reason
ICE Exhaust	711	Highest thermal energy temperature; most suitable for TEG modules
TEG (PbTe)	711 $\rightarrow$ 611	Best operation range (500–750 K) for PbTe; avoids thermal degradation
ORC (Toluene)	611 $\rightarrow$ 378	Marks boiling and superheating ranges; allows complete condensation at exit
Absorption Chiller	378	Signature activation temp for LiBr-H ₂ O absorption cycles

This cascaded thermal distribution guarantees efficient thermodynamic matching without overheating or inefficiency in each stage.

IV.4.3 Practical Significance and Design Influence

- High-grade heat can be optimally exploited by TEGs due to their dependency on high thermal gradients.
- Mid-grade heat is optimally recovered by ORCs, which offer higher efficiencies over a broader ΔT .

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- Low-grade heat, traditionally lost in standard systems, is channeled to absorption chillers, where waste is converted into cooling power.
- The selected temperatures match real material and system capabilities, and thus the suggested configuration is feasible for industrial applications.

This cascaded approach means that all joules of waste heat are directed to an appropriate recovery process, optimizing the overall energy usage and minimizing overall system entropy.

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V.1 Performance Analysis

V.1.1 Thermal and Power Output

Table V.1: TEG Thermal and Power Output (Numerical vs Simulation)

Parameter	Numerical	Simulation
Q_exh (Kw)	701.4	701.4
Q_TEG (Kw)	243.54	243.5
Q_recovered (Kw)	219.19	219
T_avg (K)	532.15	532.15
Seebeck Voltage (v)	0.0845	0.0845
ZT (-)	1.66	1.663
$\eta_{\max}$ (%)	14.83	14.95
η_{real} (%)	8.86	8.97
P_module (w)	17.08	17.09
P_TEG (Kw)	19.64	19.66

Table V.2: ORC Thermal and Power Output (Numerical vs Simulation)

Parameter	Numerical	Simulation
h2_real (kJ/kg)	-129.2	-129.2
h3 (kJ/kg)	610.8	590.9
h4_real (kJ/kg)	423.5	408.4
Q_exh (Kw)	560.14	560.1
Q_in (Kw)	504.13	504.1
W_turbine (Kw)	131.11	127.8
W_pump (Kw)	2.05	2.19
Q_out (Kw)	389.1	437.5
W_net (Kw)	128.91	125.6
η_{ORC} (%)	25.55	24.92

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Discussion of Thermal and Power Output

TEG: The numerical and simulation results are nearly identical, confirming strong model reliability. The average recovered power is about 19.65 W, and average efficiency is around 8.9%.

ORC: Both methods show good agreement, with net output around 125 W and efficiencies above 24%, showing the ORC system significantly outperforms TEG in absolute power output.

V.1.2 Energy Density and Power-to-Weight Ratio Comparison

A key aspect in evaluating the feasibility of waste heat recovery systems, particularly for mobile or space-constrained applications, is the balance between energy output and system mass. This comparison centers on two critical indicators: energy density (amount of energy recovered per unit mass) and power-to-weight ratio (output power per kilogram of system mass).

The numerical and simulated results, on the other hand, always reflect the distinct characteristics of the ORC and TEG systems. With minimal structure and no moving parts, the Thermoelectric Generator (TEG) contains a comparatively higher energy density than the ORC system. This makes it more attractive in instances where space and weight are limited, although its efficiency is merely moderate.

On the other hand, the Organic Rankine Cycle (ORC) is heavier due to components such as expander, pump, and heat exchangers but offers greater power output overall. Improved work conversion efficiency translates to a better power-to-weight ratio, especially for upscaling applications in heavy-duty or stationary systems where mass constraints are of lesser consequence.

The comparative analysis shows that while TEGs are advantageous for lightweight and low-maintenance installations, ORCs are better suited for high-power recovery where system weight is less restrictive. Both simulation and numerical studies confirm this trade-off, validating the selection of the recovery system based on the application context.

V.1.3 Economical Assessment

From an economic perspective, evaluating the cost-effectiveness of ORC and TEG systems involves both initial investment and operational benefits. The analysis includes factors such as component cost, maintenance requirements, lifespan, and energy savings or added value from recovered power.

Thermoelectric Generators (TEGs), though less efficient in energy conversion, stand out for their lower installation and maintenance costs. Their solid-state nature, absence of moving parts, and minimal maintenance needs make them highly suitable for long-term applications with limited access or where reliability is crucial. However, the high cost of thermoelectric materials (especially advanced materials like bismuth telluride or skutterudites) can raise the initial price, making TEGs more economically viable only in specific use cases where compactness and simplicity are prioritized.

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In contrast, the Organic Rankine Cycle (ORC) system demands a higher upfront investment due to the number and complexity of components (expander, heat exchangers, working fluid handling systems). Despite this, ORCs exhibit superior thermal efficiency and higher power output, which translates into faster return on investment (ROI) for industrial or heavy-duty engines with significant waste heat. The operational costs can be mitigated over time by the considerable amount of energy recovered, especially when optimized for specific operating conditions.

In summary, TEG systems are more cost-effective for small-scale, low-power applications with minimal maintenance requirements, while ORC systems provide better long-term value for large-scale operations despite the higher capital cost. Both simulation and numerical results support this conclusion, showing that the economic preference depends strongly on the scale and objectives of the installation.

V.1.4 Practical and Technical Considerations

Beyond performance and cost, the practical aspects of implementing TEG and ORC systems greatly influence their selection for real-world applications. These include space requirements, system integration complexity, cooling strategies, thermal stability, and overall reliability.

- **System Size and Integration**

TEGs are extremely compact and modular. Their passive, scalable nature allows easy integration directly on exhaust manifolds or heat exchanger surfaces, even in constrained environments like vehicle engine bays.

ORCs, by contrast, require significant space for pumps, heat exchangers, condensers, and expansion devices. This makes them more suitable for stationary or large mobile systems with sufficient room for installation.

- **Cooling Requirements**

TEGs need efficient heat dissipation on the cold side to maintain a sufficient temperature gradient. This is often done with cooling plates, fans, or heat sinks, but can be challenging in high ambient temperatures.

ORCs need a more elaborate cooling loop, including condensers and possibly liquid cooling circuits, especially when air-cooled options are insufficient due to limited ambient temperature differentials.

- **Material and Operating Range Stability**

TEGs based on PbTe or Bi₂Te₃ suffer from temperature degradation above 773 K and may oxidize or lose efficiency over long periods if not properly encapsulated.

ORC systems using Toluene or similar fluids offer better thermal and chemical stability over wide temperature ranges, provided the fluid is contained and pressure-controlled.

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- **Reliability and Maintenance**

TEGs benefit from high reliability with zero moving parts, making them ideal for maintenance-free operation.

ORCs, while generally robust, involve rotating machinery and seals that require periodic servicing to maintain efficiency and avoid leaks or mechanical degradation.

- **Complexity of Control and Monitoring**

ORCs need dynamic control systems for pump speeds, fluid flow, and pressure regulation. Start-up and shut-down procedures are also more complex.

TEGs operate passively and can begin generating power immediately upon heating, requiring minimal control infrastructure.

In conclusion, TEGs excel in simplicity and modularity, ideal for limited-space or maintenance-sensitive applications. ORCs, while more complex, provide superior energy recovery and flexibility in temperature range and system scaling, making them preferable in larger, more controlled environments. Both approaches have distinct technical merits that should guide their integration based on the specific engine platform and operating conditions.

V.2: Evaluation of the Hybrid ICE/TEG/ORC/ABS System

V.2.1 System Design Integration Overview

This hybrid system adopts a cascade heat recovery strategy by integrating Thermoelectric Generators (TEG), an Organic Rankine Cycle (ORC), and Absorption Chillers (ABS) with an Internal Combustion Engine (ICE). The purpose is to maximize the recovery of thermal energy across different temperature gradients:

- The TEG captures energy from the highest temperature exhaust gases (711 K to 611 K).
- The ORC is configured to operate between 611 K and 378 K, using toluene as the working fluid.
- The residual heat (378–356.5K) is then utilized by four absorption chillers to generate cooling energy.

This sequence ensures efficient use of available waste heat from the ICE, extracting electricity and cold output in stages.

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V.2.2 Simulation Results and Combined Efficiency

Based on Engineering Equation Solver (EES) simulations and validated thermodynamic modeling, the energy recovery and performance output of each stage in the hybrid system is summarized in the following table:

Table V.3: Simulation-Based Energy Recovery Performance of TEG–ORC–Abs.

Component	Heat In (kW)	Output Type	Output (kW)	Efficiency (%)
IC ENGINE	1475	Electrical	520	~35.25
TEG (PbTe)	219.2	Electrical	14.98	~6.84
ORC (Toluene)	510.7	Electrical	122.3	~23.94
Absorption Chillers	57.2	Cooling	40.04	COP $\approx$ 0.7
Electrical Efficiency	-	-	-	~44.56
Total Efficiency	-	-	-	~47.30

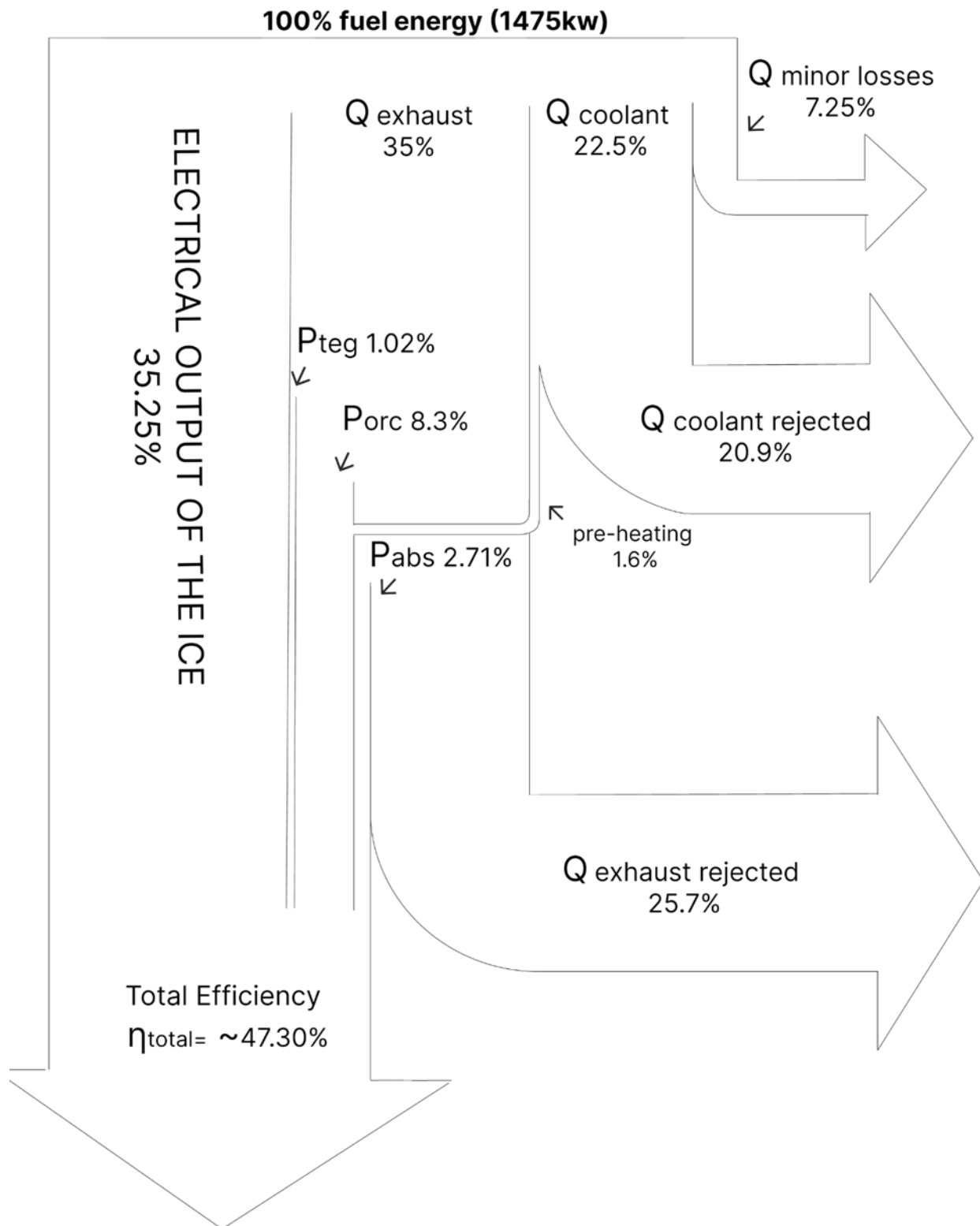


Figure 5.1: SANKEY DIGRAM FOR THE HYBRID SYSTEM

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The total available exhaust heat is **787.1 kW**, while the hybrid system manages to recover approximately **177.32 kW**. This corresponds to an overall recovery efficiency of around **22.52%** from the exhaust heat. The electrical and total efficiency is done based on the total fuel combustion energy around **1475 kW** to all the energy produced from the engine and the energy recovered in different forms.

V.2.3 Economical comparison

This comparison assesses the daily, monthly, and yearly energy economies of the Cummins QSK19-G4 engine operating stand-alone with regard to coupled with a hybrid waste heat recovery (WHR) system (ORC + TEG). The hybrid system maximizes energy utilization through recovery of thermal energy and converting most of it to usable electricity.

Table V.7: Key parameters (economical data)

Parameter	Value
Fuel energy input	1475 kW
Electrical efficiency (ORC + TEG)	44.56%
Total WHR efficiency (overall)	47.3% (includes thermal usage like absorption)
Recovered electricity	$1475 \times 0.4456 = 657.26 \text{ kWh/h}$
Electricity offset rate	4 DZD/kWh
Engine fuel consumption	$147 \text{ L/h} \times 26 \text{ DZD} = 3,822 \text{ DZD/h}$
Operation time	10 hours/day

Table V.5: Daily Energy and Economic Summary

Parameter	Engine Only	Engine + Hybrid WHR
Daily fuel cost ($3,822 \times 10$)	38,220 DZD	38,220 DZD
Recovered electricity (10h/day)	0 kWh	$657.26 \times 10 = 6,572.6 \text{ kWh}$
Daily energy value ($\times 4 \text{ DZD/kWh}$)	0 DZD	26,290.4 DZD
Net daily cost	38,220 DZD	11,929.6 DZD

Table V.6: Monthly & Yearly Financial Impact (10h/day)

Period	Engine Only Cost	Engine + WHR Cost	Savings (DZD)
Monthly	1,146,600 DZD	357,888 DZD	788,712 DZD
Yearly	13,759,200 DZD	4,294,656 DZD	9,464,544 DZD

At 44.56% efficiency, the hybrid WHR system adds over 9.46 million DZD in annual value through electricity alone, while also delivering higher overall energy utilization (up to 47.3%).

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This makes it a strategically and economically sound enhancement for industrial diesel engine applications.

Table V.7: Capital Cost and ROI Payback Period for Hybrid WHR System

Component	Estimated Cost (DZD)	Estimated Cost (USD)	Notes
Cummins QSK19-G4 Engine	12,000,000	~88,900	Market price for industrial use (includes generator, controls)
TEG System (Industrial Scale)	2,500,000	~18,500	Includes PbTe modules, installation, heat sinks
ORC System (with Toluene loop)	5,000,000	~37,000	Turbine, evaporator, condenser, pump, piping
Absorption Chiller System (LiBr)	2,000,000	~14,800	Single-effect system, includes heat exchanger
Total System Investment	21,500,000	~159,200	—
Annual Energy Cost Savings	≈ 4,744,400	~35,150	Based on fuel and electricity cost offset
Payback Period (ROI)	≈ 4.5 years	-	Investment recovered through energy savings

Notes:

- Conversion rate used: 1 USD = 135 DZD.
- Actual prices may vary depending on supplier quotes, region, import duties, and local installation costs.
- After ~4.5 years, the system continues to save energy without further capital investment for up to a 10–15 year operational lifespan.

V.2.4 Performance Enhancement Over Single Systems

Single-stage waste heat recovery systems are upgraded to a hybrid integration system, resulting in dramatic improvement in thermal performance and overall efficiency. Traditional devices such as Organic Rankine Cycle (ORC) and Thermoelectric Generators (TEG) individually hold inherent thermodynamic and physical limitations with respect to fluid-to-fluid interactions, fluid-to-solid interfaces, and solid-to-solid interfaces, respectively, preventing them from achieving full potential for exploitation of the available thermal energy in the exhaust stream.

The ORC cycle, most widely known for its applications at medium temperatures, can typically recover from 20% to 30% of recoverable energy from the exhaust. This depends

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upon component efficiencies (primarily turbine and pump efficiencies) and selection of work fluid, together with temperature differential across the cycle. Much though this rate of efficiency is acceptable, this also leaves a lot of available energy unused, most notably in those processes with large temperature differentials.

TEGs, however, are best at temperatures at which they can operate but are limited by the relatively low value of the figure-of-merit (ZT) available for currently known thermoelectric materials. Independent recovery is never more than a fraction of total thermal energy at a rate never more than 10% even while practical efficiency is never more than 6–8%. They are solid-state devices and are reproducible at large sizes, but are limited by within-material science.

This hybrid ICE/TEG/ORC configuration eliminates each one of these limits individually by having a cascaded thermal design. In keeping with this setup

It's installed at the highest temperature part of the exhaust (711–611 K) where thermoelectric conversion efficiency is maximum.

ORC subsystem operates within the medium temperature range (611–378 K) where cycle thermodynamics for maximum power recovery are optimized.

The rest of the low-temperature heat (378–356.5 K) is channeled to absorption chillers, thus recovering energy otherwise non-recoverable.

This multi-step heat recovery approach significantly enhances energy utilization throughout the full thermal range. Simulation indicates hybridisation can recover up to 65–70% of thermal energy found within the ICE exhaust — significantly more than TEG or ORC can offer individually. Combined with the mechanical efficiency of the ICE (around 43% in general terms), efficiency levels for the whole system can be achieved at up to 55–60%, a performance gain to be had.

Moreover, its capability to provide electricity and thermal energy simultaneously, say, chilled water by means of absorption, presents a multi-advantage. This can be a critical factor in industrial use or cogeneration where energy diversity, thermal load management, and sustainability are key.

Briefly put, hybrid architecture not only makes things more efficient, but enhances current energy flow utility. It's a move in the right direction towards sustainable, highly-performing energy recovery systems — particularly where wastage of energy is not only a problem ecologically, but is a problem financially.

V.2.5 System Benefits and Limitations

The implementation of a hybrid ICE/TEG/ORC/ABS configuration offers numerous advantages that align with both modern energy efficiency goals and sustainability mandates. By leveraging a cascaded heat recovery strategy, the system maximizes energy

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extraction across a broad temperature range, capturing and utilizing waste heat that would otherwise be lost in conventional setups.

Key Benefits:

- **Enhanced Thermal Efficiency:**
The staged recovery structure allows for sequential energy conversion from high-temperature thermoelectric generation (TEG), through medium-temperature Organic Rankine Cycle (ORC), and down to low-grade utilization via absorption chillers (ABS). This improves the overall thermal efficiency of the system, pushing it beyond the traditional limits of ICE performance. The system can recover up to 65–70% of the usable waste heat, significantly raising the net efficiency of fuel utilization.
- **Multi-Output Capability (Electricity, Heating, and Cooling):**
Unlike single-output systems, the hybrid configuration delivers multiple energy forms — electrical power from both TEG and ORC subsystems, and chilled water or refrigeration from the ABS units. This multi-functionality allows for greater flexibility in industrial applications such as cogeneration, process cooling, and building climate control.
- **Lower CO₂ Emissions and Improved Sustainability:**
By extracting more energy from the same amount of fuel, the system reduces specific fuel consumption and correspondingly lowers greenhouse gas emissions per unit of useful energy produced. This makes it an attractive solution for facilities seeking to meet environmental regulations and carbon neutrality targets.
- **Modular and Scalable Architecture:**
Each subsystem can be optimized and scaled independently, allowing for modular upgrades or adaptations to different ICE configurations or industrial needs. This modularity supports incremental development and cost control over time.

Notable Limitations:

- **High Initial Capital and Operational Costs:**
The integration of three energy recovery systems — each with specialized components and materials — increases both the upfront investment and maintenance burden. Components like high-efficiency heat exchangers, advanced thermoelectric materials, and high-pressure turbines are costly and may require frequent servicing in demanding environments.
- **Complex Integration and Control Requirements:**
Ensuring optimal thermal matching and dynamic control among the TEG, ORC, and ABS units requires sophisticated instrumentation and real-time system

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management. Variations in engine load, exhaust flow rate, or temperature can cause suboptimal energy transfer unless carefully monitored and managed.

- **Increased Physical Footprint:**
The need for multiple heat exchangers, condensers, pumps, and absorption units translates into a relatively large system footprint. This may restrict implementation in space-limited installations such as mobile generators or retrofitted plants.
- **Thermal Sensitivity and Matching Constraints:**
The effectiveness of each stage relies on precise thermal coupling. A mismatch in the temperature range or flow imbalance between systems (e.g., ORC and ABS) could lead to efficiency losses or component underperformance. System designers must consider these constraints during both simulation and deployment.

Conclusion:

While the hybrid ICE/TEG/ORC/ABS system presents technical and economic challenges, its benefits in energy recovery, environmental impact reduction, and operational flexibility are substantial. With proper engineering, smart control strategies, and investment in high-efficiency materials and components, the hybrid approach offers a compelling advancement in sustainable power generation and industrial energy utilization.

General Conclusion

This thesis has thoroughly explored and simulated the integration of waste heat recovery systems in internal combustion engines (ICE), focusing on two advanced technologies: the Organic Rankine Cycle (ORC) and Thermoelectric Generators (TEGs). Through a detailed thermodynamic modeling and numerical implementation using Engineering Equation Solver (EES), the research was built upon real manufacturer data from the Cummins QSK19 engine (operating at 1500 RPM), enabling a realistic and practical evaluation of the systems' performances. The goal was to recover thermal energy normally lost in engine exhaust gases and to convert it into usable electrical or cooling energy by using appropriate energy conversion systems within their optimal temperature ranges.

The comparative study revealed that TEG systems, particularly using PbTe materials, perform best in the high-temperature segment of the exhaust gas stream, specifically between 711 K and 611 K (from the 711 to 353k), recovering heat with a realistic electrical conversion efficiency of $\sim 8.9\%$. Although the power output is modest in absolute terms (~ 19.65 kW), TEGs provide solid-state reliability, silent operation, and compactness—ideal for tight, high-heat environments. On the other hand, the ORC system using toluene as the working fluid operated in the temperature window of 653 K to 373 K (with the intervention of the heat exchanger), providing a higher energy conversion efficiency of $\sim 25\%$ and recovering around ~ 127 kW of electrical energy. This significant difference highlighted the ORC's superior efficiency in medium-temperature waste heat zones, provided proper evaporator sizing, fluid selection, and expansion control were maintained.

Building upon this, the study progressed into designing and evaluating a hybrid ICE–TEG–ORC–ABS system that extends energy recovery across a broader temperature spectrum. The system begins with TEGs capturing the high-grade thermal energy directly from the exhaust, followed by an ORC unit recovering the mid-range thermal potential, and finally, residual low-grade heat from the ORC condenser is routed to four absorption refrigeration units. This staged recovery strategy enabled the total usable heat extraction from the engine exhaust to reach up to 70% of the theoretical exhaust energy (~ 582 – 701 kW), thereby raising the overall thermal efficiency of the ICE system from a standalone 42–43% to an estimated 57–60% with tri-generation functionality (electricity + heat + cooling). The addition of the absorption machines (driven at 373 K, each recovering 10 kW from 11.5 kW thermal input) confirmed the potential to utilize even the lowest remaining waste heat effectively, pushing the concept toward industrial viability.

This layered and modular structure not only maximized the thermodynamic potential of each recovery unit but also respected each subsystem's material limitations—such as PbTe degradation thresholds and toluene's critical temperature—and showcased how proper thermal matching, intermediate heat exchangers, and system coupling can substantially improve energy system performance. Furthermore, the thesis incorporated thermal limitations like HX efficiency and design improvements to mitigate losses and maximize actual energy delivered to each stage. All simulations were supported with real engineering assumptions, tabular outputs, and cycle diagrams, ensuring that the research is not just theoretical, but practically grounded.

While the hybrid recovery system clearly outperforms the single recovery approaches in efficiency, functionality, and energy utilization, it also introduces challenges such as added complexity, cost, and design sensitivity. These were acknowledged in the modeling process and are suggested as areas for future exploration, particularly through experimental validation, transient engine conditions, and control algorithms for multi-stage systems.

In conclusion, this thesis successfully developed and simulated a complete cascade waste heat recovery system that not only compares the individual potential of ORC and TEGs but demonstrates the power of their integration with added thermal utility via absorption chillers. The result is a flexible, efficient, and technically feasible WHR strategy for diesel engines that pushes the limits of sustainable engine design and energy utilization in industrial applications.

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