3. ULUSLARARASI

İYONYA

BİLİMSEL ARAŞTIRMALAR KONGRESİ

24-25 AĞUSTOS 2025

İZMİR

EDİTÖRLER:
Prof. Mohammed WAHEEB
Prof. Dr. Seyfi ŞEVİK
Doç. Dr. Dilek KONUK ŞENER
Dr. Ali Buğra KÜÇÜK
Dr. Murat ATA

www.isarconference.org

İKSAD Publishing House

KONGRE KİTABI

INDEX

ISBN: ' 978-625-378-301-3 '

UPGRADING THE MARIB GAS TURBINE POWER PLANT IN YEMEN WITH A BRAYTON–ORGANIC RANKINE CYCLE FOR HIGHER EFFICIENCY AND LOWER EMISSIONS

Abdulrazzak AKROOT
Karabük University, Faculty of Engineering, Department of Mechanical Engineering,78050, Karabük
ORCID: 0000-0000-1700-8480
abdulrazzakakroot@karabuk.edu.tr

ABSTRACT

The Marib gas turbine power plant in Yemen currently operates on a simple Brayton cycle, releasing high-temperature exhaust gases without recovery, resulting in substantial energy losses and elevated CO_2 emissions. This study proposes an integrated Brayton–Organic Rankine Cycle (BC–ORC) configured to capture and utilize this waste heat, improving performance and environmental sustainability. In the proposed system, the Brayton cycle serves as the topping cycle, while an organic Rankine cycle using toluene as the working fluid operates as the bottoming cycle, driven by the gas turbine exhaust gases. A steady-state thermodynamic model was developed using Engineering Equation Solver (EES) to evaluate the integrated system. Energy and exergy analyses were conducted for each component and the overall cycle. Parametric studies examined the effects of Brayton cycle pressure ratio (Pr), ORC turbine inlet temperature, and ORC turbine inlet pressure on net power output, efficiencies, and specific CO_2 emissions. Results show that integrating the ORC increases total net power output from 138.4 MW (BC only) to 195.9 MW, a 41.5% improvement. Thermal efficiency rises from 30.87% to 43.71%, and exergy efficiency from 29.81% to 42.21%, specific CO_2 emissions decrease by approximately 29%, from 639.1 to 451.3 kg/MWh. Parametric analysis indicates that moderate Pr values (6–10) provide the best balance between high net output and efficiency, higher ORC turbine inlet temperature enhances ORC contribution and slightly reduces emissions, while ORC turbine inlet pressure variation within 2000–3000 kPa has a negligible impact on performance. The findings demonstrate that implementing an integrated Brayton–ORC waste heat recovery system in the Marib power plant is a practical and cost-effective approach for enhancing Yemen's electricity generation efficiency and reducing its environmental footprint.

Keywords: Brayton Cycle, Organic Rankine Cycle, Waste Heat Recovery, CO_2 Emissions, Yemen, Marib Power Plant.

EMEN'DEKİ MARİB GAZ TÜRBİNİ SANTRALİNİN VERİMLİLİĞİNİ ARTIRMAK VE EMİSYONLARI AZALTMAK İÇİN BRAYTON–ORGANİK RANKİNE ÇEVRİMİ İLE YÜKSELTİLMESİ

ÖZET

Yemen'deki Marib gaz türbini santrali hâlihazırda basit bir Brayton çevrimiyle çalışmakta, yüksek sıcaklıktaki egzoz gazlarını geri kazanım yapmadan atmosfere bırakmakta ve bu durum önemli enerji kayıplarına ve yüksek CO_2 emisyonlarına yol açmaktadır. Bu çalışma, bu atık ısının geri kazanılmasını sağlamak ve performans ile çevresel sürdürülebilirliği iyileştirmek amacıyla, Brayton–Organik Rankine Çevrimi (BC–ORC) entegre edilmiş bir sistem önermektedir. Önerilen sistemde Brayton çevrimi üst çevrim olarak görev yaparken, Organik Rankine Çevrimi alt çevrim olarak tolüen çalışma akışkanıyla çalışmakta ve gaz türbininin egzoz gazlarıyla tahrik edilmektedir. Entegre sistemi değerlendirmek amacıyla Engineering Equation Solver (EES) kullanılarak kararlı durum termodinamik modeli geliştirilmiştir. Her bir bileşen ve genel çevrim için enerji ve ekserji analizleri yapılmıştır. Parametrik çalışmalar, Brayton çevrimi basınç oranı, ORC türbini giriş sıcaklığı ve ORC türbini giriş basıncının net güç çıkışı, verimler ve özgül CO_2 emisyonları üzerindeki etkilerini incelemiştir. Sonuçlar, ORC entegrasyonunun toplam net güç çıkışını 138,4 MW'tan (yalnızca BC) 195,9 MW'a çıkardığını, bunun %41,5'lik bir artış anlamına geldiğini göstermektedir. Termal verim %30,87'den %43,71'e, ekserji verimi ise %29,81'den %42,21'e yükselmiştir. Özgül CO_2 emisyonları yaklaşık %29 oranında azalmış, 639,1'den 451,3 kg/MWh değerine düşmüştür. Parametrik analiz, orta düzeydeki Pr değerlerinin (6–10) net güç çıkışı ve verim arasında en iyi dengeyi sağladığını, ORC türbini giriş sıcaklığının artırılmasının ORC katkısını yükseltip emisyonları hafifçe azalttığını, 2000–3000 kPa aralığındaki ORC türbini giriş basıncı değişiminin ise performans üzerinde ihmal edilebilir bir etki yarattığını göstermektedir. Bulgular, entegre bir BC–ORC atık ısı geri kazanım sisteminin Marib santralinde uygulanmasının, Yemen'in elektrik üretim verimliliğini artırmak ve çevresel etkisini azaltmak için pratik ve maliyet etkin bir yaklaşım olduğunu ortaya koymaktadır.

Anahtar Kelimeler: Brayton Çevrimi, Organik Rankine Çevrimi, Atık Isı Geri Kazanımı, CO_2 Emisyonları, Yemen, Marib Enerji Santrali.

1. INTRODUCTION

As traditional power sources are increasingly used, energy security and environmental implications are vital concerns. Combined systems efficiently generate additional power from one fuel source (Islam et al., 2014; Alfaris et al., 2024). These systems use waste heat to produce additional power and reduce greenhouse gas emissions (Axelsson et al., 2003; Ahmed et al., 2022). This integration reduces operating carbon footprint and increases energy efficiency, meeting global sustainability targets (Baleta et al., 2019; Liu et al., 2015). Combined systems are more efficient than traditional power generation, which wastes heat (Alfaris et al., 2025). They create additional power from one fuel source (Akroot and Al Shammre, 2024). The heat loss of conventional methods is eliminated (Olabi et al., 2020). The heat from power generation, usually lost, drives the system. Combined system converts waste heat into power using an organic Rankine cycle (ORC) (Sun et al., 2017; Tchanche et al., 2011). This clever integration increases energy production efficiency and reduces environmental effects (Sun et al., 2017; Talal and Akroot, 2023). The combined system requires a gas turbine or engine to generate electricity. This process generates much heat, which would otherwise be lost to the atmosphere. Heat recovery devices recuperate this wasted thermal energy in the combined systems (Chen et al., 2022; Talal and Akroot, 2023).

In the 21st century, the pursuit of sustainable, low-carbon energy is crucial to addressing climate change, necessitating the adoption of cleaner and more efficient technologies to minimize fossil fuel use and environmental harm (Kabeyi and Olanrewaju, 2022; Chen et al., 2022). To meet this challenge, research has increasingly focused on developing multi-energy systems that integrate diverse energy carriers—such as natural gas, electricity, and heat. These systems offer a promising pathway to deliver sustainable, efficient, and environmentally friendly energy by combining various energy subsystems. (Talal and Akroot, 2024) Several studies in the literature have explored combined heat and power (CHP) systems utilizing gas turbine engines (Dobre et al., 2024; Balli et al., 2021; Pilavachi, 2000). Bagherzadeh et al. (Bagherzadeh et al., 2020) proposes enhancing Brayton cycle performance using compressed air and organic Rankine cycles, identifying optimal compression ratios and working fluids, with R123 yielding the highest efficiencies and isopentane causing the least exergy destruction. Zare and Hasanzadeh (Zare and Hasanzadeh, 2016) utilized the Brayton cycle as the foundation of the power generation system and found that it could enhance exergy efficiency by over 30% for the entire power plant. Pan et al. (Pan et al., 2020) introduced a GT-SCO_2/ORC cogeneration system using gas turbine exhaust heat for improved efficiency. The system achieves energy and exergy efficiencies of 56.47% and 45.46%. Optimizing parameters like air compressor pressure ratio, gas turbine isentropic efficiency, and inlet temperature enhances thermodynamic and economic performance. Ochoa et al. (Ochoa et al., 2020) optimized a supercritical CO_2 Brayton and SORC system using PSO, showing that reheating reduces exergy destruction by 92.28% and improves thermal efficiency to 56.95%. Bian et al. (Bian et al., 2025) proposed integrating ORC and Brayton cycles for hydrogen liquefaction, improving efficiency with a 3.7% SEC reduction, 47.62% exergy efficiency, and eliminating the need for a hydrogen converter—offering a cost-effective, energy-efficient solution for clean energy applications. Abrosimov et al. (Abrosimov et al., 2020) analyzed an inverted Brayton cycle combined with an organic Rankine cycle (IBC-ORC) for high-temperature waste heat recovery from engine exhaust gases. Using Aspen HYSYS software and a 1.4 MW gas-fueled engine case, the system's performance was optimized under various ambient temperatures. Kareem et al. (Kareem et al., 2023) analyzed the exergy–economic performance of integrating Brayton and Organic Rankine cycles at Taji station in Baghdad to recover waste heat and reduce emissions. Results show the GSO CC system generates 258.2 MW with higher efficiencies (44.37% energy, 42.84% exergy) compared to the Brayton cycle alone (28.74% and 27.75%). Ismael et al. (Ismael et al., 2022) analyzed an organic Rankine cycle (ORC) integrated with a Brayton cycle using intercooling, reheating, and regeneration (BCIRR). Results show that increasing turbine inlet temperature boosts net power output and thermal efficiency. The combined cycle's efficiency is 11.7% higher than the Brayton cycle alone, and the ORC contributes about 28,650 kW of net power.

While previous studies have examined the integration of Brayton and Organic Rankine Cycles (ORC) for waste heat recovery and efficiency improvement in power generation systems, there remains a lack of applied research focusing on real-world gas turbine plants in conflict-affected and resource-constrained regions. This study is the first to propose and thermodynamically analyze a hybrid Brayton–ORC system specifically designed for the Marib gas turbine power plant in Yemen. By using toluene as the ORC working fluid and applying a steady-state simulation in Engineering Equation Solver (EES), the research provides a tailored, practical solution that significantly enhances both energy and exergy efficiency while reducing CO_2 emissions by nearly 30%. Unlike previous general or theoretical models, this work offers a region-specific, implementable strategy to upgrade an existing power facility, demonstrating both technical feasibility and environmental benefit under the unique constraints of Yemen's energy infrastructure.

2. MATERIAL AND METHODS

This study develops and analyzes a hybrid Brayton Cycle–Organic Rankine Cycle (Brayton–ORC) system as an upgrade to the existing gas turbine power plant in Marib, Yemen. The current plant operates using a simple gas turbine cycle, which releases high-temperature exhaust gases directly to the atmosphere. Figure 1 illustrates the thermodynamic configuration of a hybrid Brayton–ORC system, designed to enhance energy recovery by integrating a Brayton cycle (top cycle) with a bottoming ORC. The proposed system consists of a simple Brayton cycle (BC) as the topping cycle, with an organic Rankine cycle (ORC) as the bottoming cycle for waste heat recovery. The BC generates primary power through gas turbine operation, while the ORC produces additional electricity by utilizing the high-temperature exhaust gases from the BC. This configuration maximizes energy utilization and improves overall thermal performance.

The integration of an ORC bottoming cycle ensures better utilization of waste heat from the Brayton cycle, increasing the overall thermal efficiency of the system. Using Toluene as the ORC working fluid provides a wide operational temperature range, improving heat recovery from the HRVG. The system configuration allows dual power generation (from both GT and ORT) with minimal fuel consumption. Ambient air is compressed to a high pressure (stream 2) in three parallel compressors, which improves combustion efficiency. Fuel is injected and combusted with the compressed air (stream 2), producing high-temperature flue gases (stream 3). The hot gases expand in three parallel gas turbines (stream 4 → stream 5), generating mechanical power that drives an electric generator (G). The exhaust gases from the Brayton cycle (stream 5) pass through the HRVG, transferring waste heat to the ORC working fluid (Toluene), which is circulated on the ORC side (stream 6). The vaporized working fluid expands in the ORC turbine (stream 7 → stream 8), producing additional power via another generator (G), thereby utilizing heat that would otherwise be lost. The partially cooled working fluid (stream 8 → stream 9) preheats the returning liquid (stream 11) before entering the condenser, improving cycle efficiency by reducing energy input requirements. The working fluid (stream 9 → stream 10) rejects heat to the cooling medium (stream 13 → stream 14), condensing it into a liquid state. The liquid working fluid (stream 10 → stream 11) is pumped back to the HRVG to close the cycle.

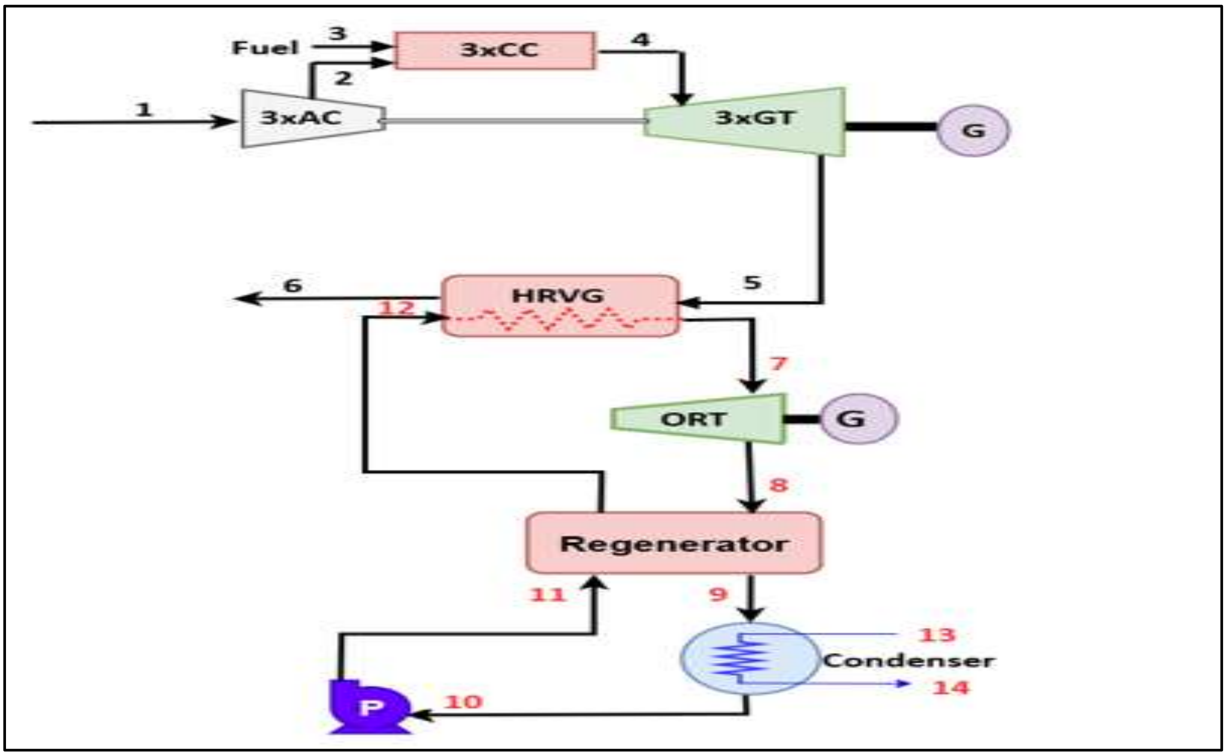


Fig. 1. Schematic diagram of the proposed hybrid Brayton–ORC power generation system implemented in Marib, Yemen.

The thermodynamic analysis of the combined cycle incorporates several assumptions, as outlined below (Akroot and Faraj, 2025; Akroot, 2025):

- The system operates under steady-state thermodynamic conditions.
- Air and combustion gases in the Brayton cycle are treated as ideal gases.
- The fuel entering the combustion chamber is natural gas, specifically 100% methane, with a lower heating value (LHV) of 50,056 kJ/kg.
- Pressure drops in heat exchangers (HRVG, regenerator, condenser, etc.) are considered negligible.
- The Brayton cycle uses air as the working fluid, and the ORC uses toluene.
- Saturated vapor is used as the working fluid entering the organic Rankine turbine.

3. RESULTS AND DISCUSSION

The results section presents a comprehensive evaluation of the integrated Brayton–ORC system, focusing on how key operating parameters influence power output, efficiency, and environmental performance. The analysis examines the effects of the Brayton Cycle (BC) pressure ratio, as well as the ORC turbine inlet temperature and pressure, on the thermodynamic behavior of both the standalone BC and the combined cycle. Table 1 presents the key operating parameters used for simulating the integrated Brayton–ORC system for the Marib gas turbine plant.

Table 1. Input Parameters for the Thermodynamic Simulation of the Brayton–ORC System in Marib Gas Turbine Power Plant

Parameter	**Value**
Compressor pressure ratio	10.5
Ambient temperature (°C)	26
Ambient pressure (°C)	101.3
Lower heating value of fuel(kJ/kg)	50056
Inlet air mass flow rate (kg/s)	501
Isentropic efficiency of the compressor (%)	85
Isentropic efficiency of gas turbine	89
Outlet temperature of gases from CC (K)	1350
The pressure of the ORF at the inlet of HRVG (kPa)	2800
Isentropic efficiency of the ORT	81
Outlet temperature of Condenser (°C)	35.8

Table 2 summarizes the key performance outcomes of the integrated Brayton–ORC system modeled for the Marib gas turbine plant. The results indicate that with a fuel mass flow rate of 9 kg/s and a toluene mass flow rate of 330.9 kg/s, the Brayton Cycle (BC) generates 138.4 MW, while the organic Rankine cycle (ORC) contributes an additional 57.56 MW, yielding a total net power output of 195.9 MW. Thermal efficiency improves from 30.87% in the standalone BC to 43.71% of the combined system. Similarly, exergy efficiency rises from 29.81% to 42.21%, reflecting the effective recovery of waste heat. The total exergy destruction is 253.1 MW, with significant reductions in CO_2 emissions: from 639.1 kg/MWh for the standalone BC to 451.3 kg/MWh in the integrated system, demonstrating the environmental advantage of waste heat recovery.

Table 2. Performance Results of the Integrated Brayton–ORC Waste Heat Recovery System for the Marib Gas Turbine Plant

Calculated Parameters	**Value**
Fuel mass flow rate. $\dot{m}_{fuel}$ (kg/s)	9
Toluene mass flow rate, $\dot{m}_{Toluene}$ (kg/s)	330.9
CO_2 mass flow rate, $\dot{m}_{Toluene}$ (kg/s)	24.57
Brayton cycle net power, $\dot{W}_{BC}$ (MW)	138.4
ORC net power, $\dot{W}_{ORC}$ (MW)	57.56

Brayton -ORC cycle net power, $\dot{W}_{net}$ (MW)	195.9
Thermal efficiency for Brayton -ORC cycle, $\eta_{th,cycle}$ (%)	43.71
Thermal efficiency for BC, $\eta_{th,BC}$ (%)	30.87
Exergy efficiency for Brayton -ORC cycle, $\eta_{ex,cycle}$ (%)	42.21
Exergy efficiency for BC, $\eta_{ex,BC}$ (%)	29.81
Exergy destruction, $\dot{E}_{D,Total}$ (MW)	253.1
CO_2 emission for Brayton -ORC cycle, $Emission_{cycle}$ (kg_{CO_2} /MWh)	451.3
CO_2 emission for Brayton cycle, $Emission_{BC}$ (kg_{CO_2} /MWh)	639.1

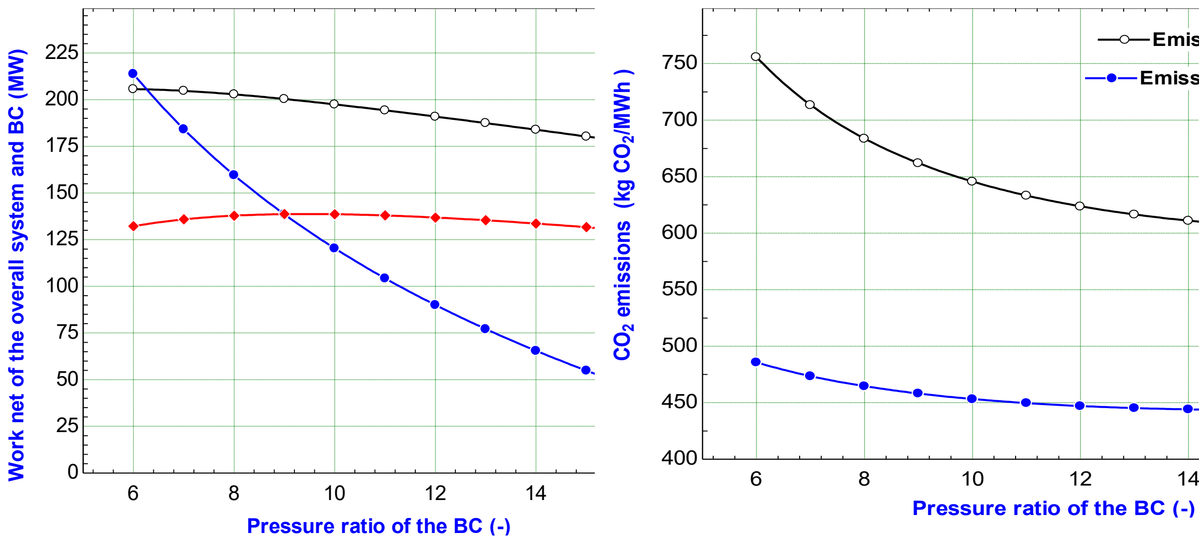
Table 3 represents the energy and exergy analysis for each major component of the integrated Brayton–ORC system in the developed model. The combustion chamber exhibits the highest energy input (448.23 MW) but also the largest exergy destruction (149.7 MW), accounting for the greatest irreversibility in the system due to chemical reaction losses. The heat recovery vapor generator (HRVG) is another major contributor to exergy destruction (42.61 MW) because of the large temperature difference between the exhaust gases and the ORC working fluid. The gas turbine shows a high exergy efficiency (95.5%), indicating effective energy conversion with minimal losses. Similarly, the air compressor achieves 91.17% exergy efficiency, reflecting efficient compression. The organic Rankine turbine also performs well with 84.97% efficiency. Conversely, the condenser has the lowest exergy efficiency (29.66%), as it rejects low-grade heat to the environment. The pump has the smallest exergy destruction (0.255 MW) and relatively high efficiency (82.36%).

Table 3. Energy and Exergy Distribution Across Components in the Brayton–ORC Waste Heat Recovery System

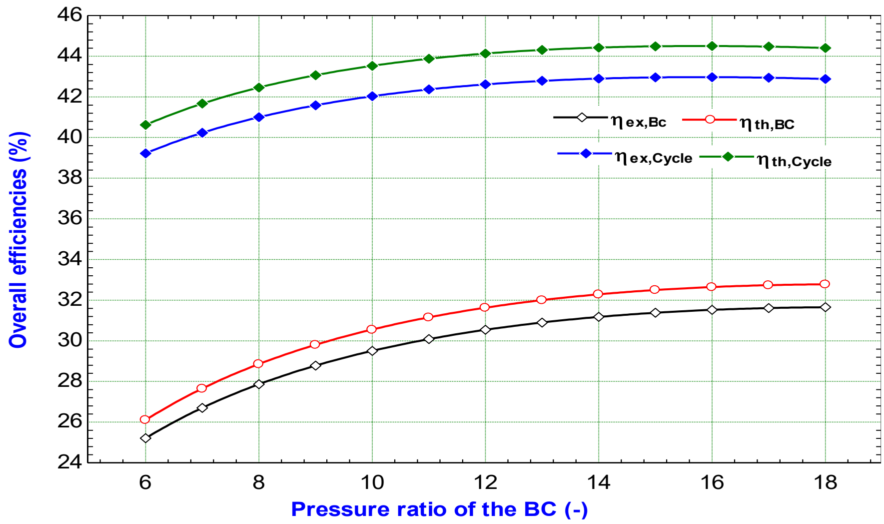
Component	**W OR Q (MW)**	**$\dot{E}_{dest}$ (MW)**	**Ψ (%)**
Air Compressor	172.1	13.48	91.17
Combustion chamber	448.23	149.7	75.97
Gas turbine	310.5	14.65	95.5
HRVG	229.05	42.61	65.19
Organic turbine	58.92	10.42	84.97
Regenerator	50.55	2.52	77.43
Condenser	137.14	6.37	29.66
Pump	1.37	0.255	82.36

Figures 2 illustrates the influence of the Brayton Cycle (BC) pressure ratio (Pr) on the performance of the integrated Brayton–ORC system, considering the net power output, CO_2

emissions, and thermal and exergy efficiencies. The results indicate that moderate Pr values (around 6–10) offer the best trade-off between maximizing total net power output and achieving substantial efficiency gains while maintaining low CO_2 emissions. Higher Pr improves standalone BC efficiency and reduces emissions, but comes at the expense of ORC performance and total output. Figure 2a illustrates the effect of the Brayton Cycle (BC) pressure ratio (Pr) on the net power outputs of the overall system ($\dot{W}_{net}$), the BC ($\dot{W}_{BC}$), and the ORC ($\dot{W}_{ORC}$) in the hybrid Brayton–ORC configuration. Overall system output ($\dot{W}_{net}$) starts at its highest value of 205.7 MW when Pr=6, then decreases almost linearly to 169.3 MW at Pr=18. The reduction is driven primarily by the decline in ORC power as Pr increases. BC output ($\dot{W}_{BC}$) initially increases from 132.2 MW at Pr=6 to a peak of 138.7 MW at Pr=9, due to improved compression and expansion efficiencies at moderate pressure ratios. Beyond this point, turbine power gains are offset by increased compressor work, leading to a gradual decline to 125 MW at Pr=18. ORC output ($\dot{W}_{ORC}$) shows a steady decrease from 73.49 MW at Pr=6 to 44.33 MW at Pr=18. This drop occurs because higher BC pressure ratios reduce the exhaust gas temperature and enthalpy available at the HRVG, limiting waste heat recovery potential. Even though BC work increases slightly at first, the reduction in ORC power dominates, Figure 2b shows the effect of the Brayton Cycle (BC) pressure ratio (Pr) on CO_2 emissions for the standalone BC ($\mathrm{Emission_{BC}}$) and the combined Brayton–ORC system ($\mathrm{Emission_{cycle}}$). This trend highlights that integrating the ORC not only boosts power output but also achieves substantial environmental benefits by lowering specific CO_2 emissions. The advantage is most significant at lower pressure ratios, making moderate Pr values (6–10) particularly attractive for balancing high efficiency with reduced emissions in the Marib gas turbine plant upgrade. For all pressure ratios, the combined Brayton–ORC system produces significantly lower CO_2 emissions compared to the standalone BC, due to improved fuel utilization and waste heat recovery. At Pr=6, CO_2 emissions are 755.8 kg CO_2/MWh for BC alone, but only 485.7 kg CO_2/MWh for the combined cycle, a 35.7% reduction. As Pr increases, CO_2 emissions from both systems gradually decline, reaching 601.9 kg CO_2/MWh for BC alone and 444.3 kg CO_2/MWh for the combined cycle at Pr=18. The rate of reduction is more pronounced at lower pressure ratios; beyond Pr≈14, the emission values for both configurations stabilize, indicating diminishing returns from further pressure ratio increases. resulting in an overall decline in $\dot{W}_{net}$ from 205.7 MW to 169.3 MW. Maximum total net power occurs at Pr = 6; beyond that, total efficiency drops due to reduced ORC recovery. Figure 2c shows the variation of thermal efficiency (η_{th}) and exergy efficiency (η_{ex}) for both the standalone BC and the combined Brayton–ORC system as a function of the Brayton cycle pressure ratio (Pr). The combined system achieves an absolute efficiency improvement of about 14–15 percentage points in thermal and exergy efficiencies over the BC alone at all pressure ratios. Efficiency gains are most pronounced at lower Pr values, where higher exhaust gas temperatures benefit the ORC. Although BC efficiency improves at higher Pr, the ORC gain is reduced due to lower exhaust heat availability. For the Marib power plant upgrade, operating in a moderate Pr range (around 10–14) strikes a good balance between maximizing BC efficiency and maintaining strong ORC performance, achieving high combined-cycle efficiency with reduced environmental impact. BC thermal efficiency ($\eta_{th,BC}$) increases from 26.1% at Pr=6 to 32.78% at Pr=18, reflecting improved cycle performance with higher pressure ratios, while BC exergy efficiency ($\eta_{ex,BC}$) follows a similar trend, rising from 25.21% to 31.65%. Thermal efficiency for the combined Brayton–ORC ($\eta_{th,cycle}$) starts at 40.62% when Pr=6 and peaks at 44.49% around Pr=15–16, showing a modest gain at higher pressure ratios but with diminishing returns beyond Pr≈14 , whereas the exergy efficiency ($\eta_{ex,cycle}$) improves from 39.22% to 42.98% over the same range, remaining consistently higher than the BC alone due to effective waste heat recovery in the ORC.



(a) (b)

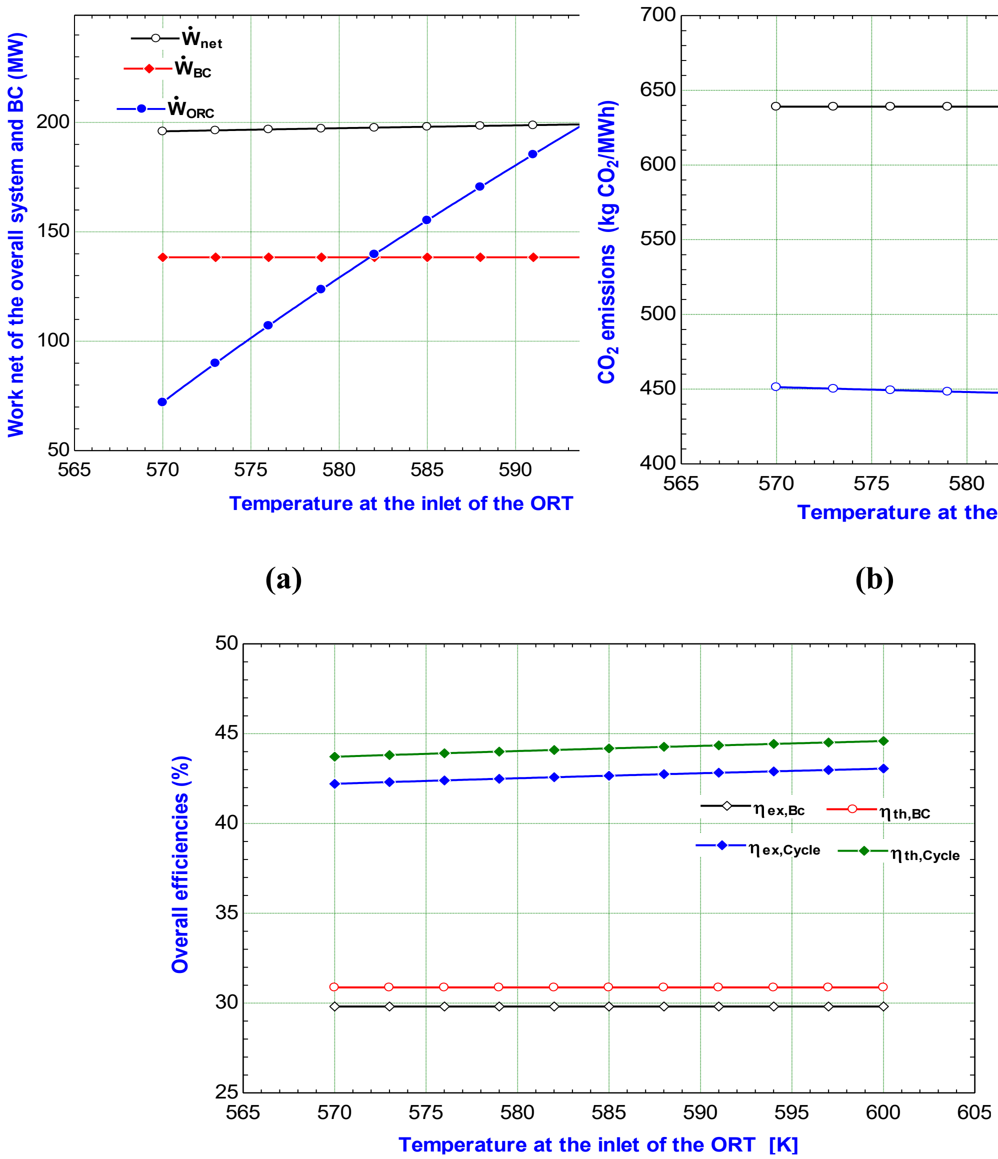


(c)

Fig. 2. Effects of the BC's pressure ratio in a combined Brayton–ORC System on (a) net power output (b) CO2 emission and (c) thermal and exergy efficiencies.

Figures 3 presents the effect of the ORC turbine inlet temperature (T_8) on the performance of the integrated Brayton–ORC system, considering the net power output, CO_2 emissions, and thermal and exergy efficiencies. The results present that raising T_8 improves ORC and total system performance, slightly boosts overall efficiencies, and reduces CO_2 emissions for the combined cycle, without impacting BC output. However, practical constraints such as the thermal stability limits of the working fluid (toluene) must be considered when selecting the optimal inlet temperature. Figure 3a shows the effect of ORC turbine inlet temperature (T_8) on the net power outputs of the Brayton Cycle (W˙BC), the ORC ($\dot{W}_{ORC}$), and the combined system ($\dot{W}_{net}$). Raising T8 significantly enhances ORC output and slightly boosts total system performance, without affecting BC power. As expected, BC power output ($\dot{W}_{BC}$) remains constant at 138.4 MW across the whole temperature range (570–600 K) because the BC operation is independent of the ORC inlet temperature. ORC power output ($\dot{W}_{BC}$) increases linearly from 57.56 MW at 570 K to 61.48 MW at 600 K. This is due to the greater specific enthalpy drop across the ORC turbine at higher inlet temperatures, which increases the available expansion work. Total net power output ($\dot{W}_{net}$) rises from 195.9 MW at 570 K to 199.9 MW at 600 K. The ~4 MW gain is directly attributed to the improved ORC performance, since BC output remains unchanged. Figure 3b presents the effect of ORC turbine inlet temperature (T_8) on CO_2 emissions for the standalone Brayton Cycle (BC ($\text{Emission}_{\text{BC}}$) and the combined Brayton–ORC system ($\text{Emission}_{\text{cycle}}$). While the improvement in CO_2 emissions with rising

T_8 is modest, it confirms that operating the ORC at higher turbine inlet temperatures enhances environmental performance by increasing waste heat utilization efficiency. Standalone BC emissions ($\text{Emission}_{\text{BC}}$) remain constant at 639.1 kg CO_2/MWh across the entire range of T_8 (570–600 K), since ORC inlet temperature does not influence BC fuel consumption or operation. Combined cycle emissions ($\text{Emission}_{\text{cycle}}$) decrease slightly from 451.3 kg CO_2/MWh at 570 K to 442.5 kg CO_2/MWh at 600 K. This ~2% reduction is directly linked to the increase in ORC power output at higher T_8, which increases the total electricity generated without increasing fuel input, thereby lowering the specific emissions per unit of electricity. Figure 3c shows the effect of the ORC turbine inlet temperature (T_8) on the thermal efficiency (η_{th}) and exergy efficiency (η_{th}) of both the standalone Brayton Cycle and the combined Brayton–ORC system. The results indicate that raising T_8 has a positive but limited effect on combined cycle efficiency, while it does not affect the BC alone. This suggests that while higher ORC inlet temperatures are thermodynamically beneficial, the magnitude of efficiency improvement is constrained by the finite temperature difference between the BC exhaust gases and the ORC working fluid, as well as the fixed performance of the BC. Both ($\eta_{\text{th,BC}}$) and ($\eta_{\text{ex,BC}}$) remain constant at 30.87% and 29.81%, respectively, for the entire T_8 range (570–600 K). This constancy is expected because BC efficiency is unaffected by ORC operating temperature, as there is no change in the BC's thermodynamic states or fuel consumption. Thermal efficiency of the combined cycle ($\eta_{\text{th,cycle}}$) increases slightly from 43.71% at 570 K to 44.59% at 600 K, and the exergy efficiency ($\eta_{\text{ex,cycle}}$) improves from 42.21% to 43.05% over the same range. The improvements, though modest (less than one percentage point), are consistent and result from higher ORC power generation at elevated inlet temperatures, which increases the proportion of waste heat converted into practical work.

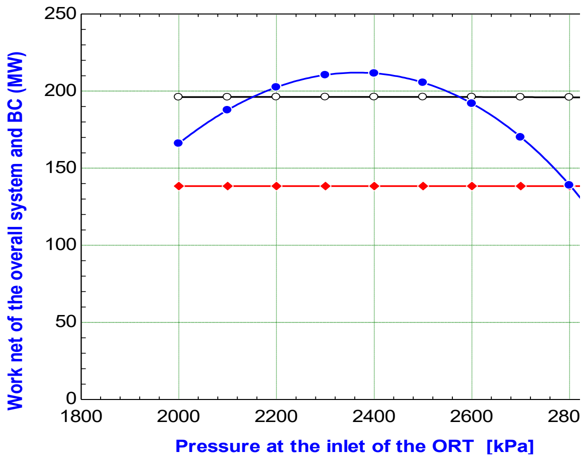


(a) **(b)**

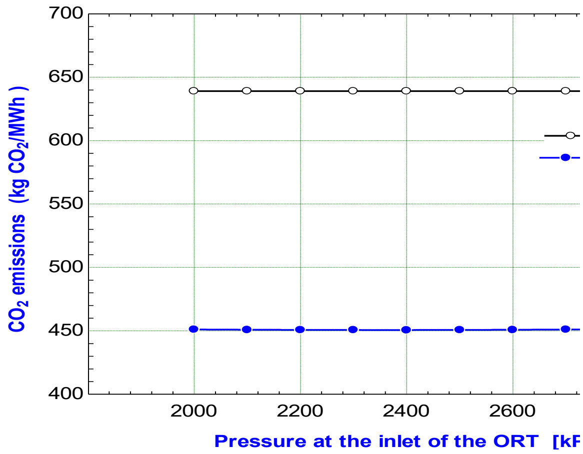
(c)

Fig. 3. Effects of the of ORC turbine inlet temperature in a combined Brayton–ORC system on (a) net power output (b) CO2 emission and (c) thermal and exergy efficiencies.

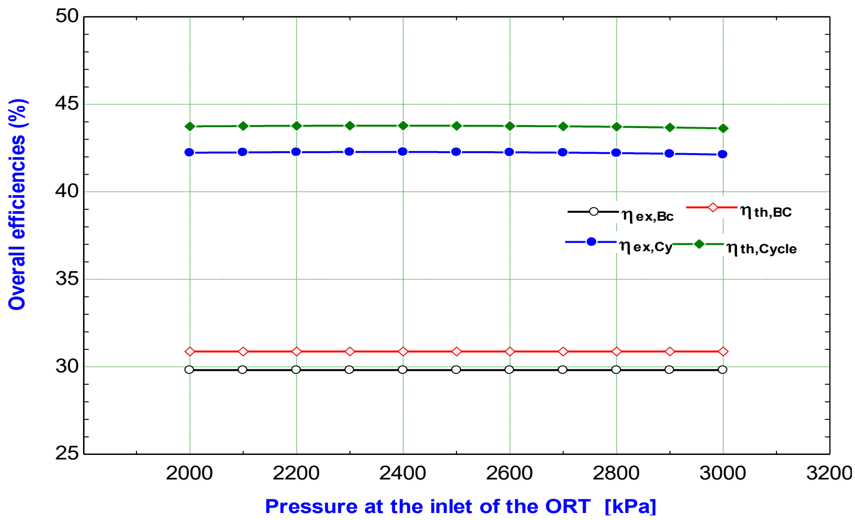
Figures 4 present the influence of the organic Rankine cycle (ORC) turbine inlet pressure (P_8) on the performance of the integrated Brayton–ORC system, focusing on power output, CO_2 emissions, and efficiency. The results demonstrate that, within the studied range of 2000–3000 kPa, ORC inlet pressure has negligible influence on the combined cycle's power output, specific CO_2 emissions, or efficiency. This indicates a broad operational flexibility in selecting P_8. Figure 4a shows the effect of ORC turbine inlet pressure (P_8) on the power outputs of the Brayton Cycle ($\dot{W}_{BC}$), ORC ($\dot{W}_{ORC}$), and the total combined system ($\dot{W}_{net}$). The results indicate that the system operates in a relatively stable zone for the studied range of ORC turbine inlet pressures, where neither BC nor ORC power is significantly impacted. This stability suggests operational flexibility in choosing P_8 without significant penalties in net output. However, slightly lower inlet pressures (around 2000–2400 kPa) produce marginally higher total power and may be preferable for maximizing energy recovery while potentially reducing mechanical stress on the ORC turbine. BC power output ($\dot{W}_{BC}$) remains constant at 138.4 MW across the entire inlet pressure range (2000–3000 kPa). This is expected because the BC operation is independent of the ORC inlet pressure. ORC power output ($\dot{W}_{ORC}$) is nearly constant, fluctuating slightly between 57.66 MW at 2000 kPa and 57.16 MW at 3000 kPa. This slight decrease (<0.9%) suggests that the ORC is relatively insensitive to inlet pressure changes within this range, likely because the temperature difference between the heat source (BC exhaust) and the working fluid saturation temperature remains adequate for heat transfer. Total net power ($\dot{W}_{net}$) changes minimally, from 196 MW at 2000 kPa to 195.5 MW at 3000 kPa, showing a negligible decline (<0.3%). Figure 4b presents the effect of ORC turbine inlet pressure (P_8) on CO_2 emissions for the standalone Brayton Cycle ($\mathrm{Emission_{BC}}$) and the combined Brayton–ORC system ($\mathrm{Emission_{cycle}}$). The results indicate that ORC turbine inlet pressure does not significantly impact CO_2 emissions for the standalone BC or the combined cycle within the tested range (2000–3000 kPa). Standalone BC emissions remain constant at 639.1 kg CO_2/MWh for all values of P_8. This is expected since ORC inlet pressure does not influence the BC's fuel consumption or power output. Combined cycle emissions are also nearly constant, varying minimally between 450.7 and 452.3 kg CO_2/MWh (a fluctuation of less than 0.35%). The slight variation is negligible and likely due to minor changes in ORC power output at different P8 values (as seen in the previous analysis). Figure 4c shows the effect of ORC turbine inlet pressure (P_8) on the thermal efficiency (η_{th}) and exergy efficiency (η_{ex}) for both the standalone Brayton Cycle and the combined Brayton–ORC system. Standalone BC efficiencies ($\eta_{\mathrm{th,BC}}$ and ($\eta_{\mathrm{ex,BC}}$) remain constant across all inlet pressures at 30.87% and 29.81%, respectively. This is expected since the BC performance is unaffected by ORC inlet pressure changes. Combined cycle efficiencies ($\eta_{\mathrm{th,cycle}}$ and $\eta_{\mathrm{ex,cycle}}$) also show minimal variation. Thermal efficiency ($\eta_{\mathrm{th,cycle}}$) stays between 43.62% and 43.77% and Exergy efficiency ($\eta_{\mathrm{ex,cycle}}$) varies slightly from 42.12% to 42.27%. These tiny fluctuations (<0.15 percentage points) indicate that ORC inlet pressure has an insignificant effect on the overall system efficiency within the tested range.



(a)



(b)



(c)

Fig. 4. Effects of the of ORC turbine inlet pressure in a combined Brayton–ORC system on (a) net power output (b) CO_2 emission and (c) thermal and exergy efficiencies.

CONCLUSIONS

This study evaluated the integration of an organic Rankine cycle (ORC) with the existing Brayton cycle (BC) at the Marib gas turbine power plant in Yemen to recover waste heat from high-temperature exhaust gases. A steady-state thermodynamic model was developed using Engineering Equation Solver (EES) to perform detailed energy and exergy analyses and investigate the influence of key operating parameters. The findings confirm that the proposed Brayton–ORC configuration significantly improves power generation efficiency and reduces environmental impact while requiring no significant structural changes to the existing system. The most important results obtained are:

- Net power output increased from 138.4 MW (BC only) to 195.9 MW (Brayton–ORC), a 41.5% gain.
- Thermal efficiency of the Brayton–ORC cycle improved from 30.87% to 43.71%.
- Exergy efficiency of the Brayton–ORC cycle increased from 29.81% to 42.21%.
- Specific CO_2 emissions of the Brayton–ORC cycle reduced by approximately 29%, from 639.1 kg/MWh to 451.3 kg/MWh.
- Optimal BC pressure ratio (Pr), in a moderate range of 6–10, achieves the best balance between total output and efficiency.
- Higher ORC turbine inlet temperature values increase ORC contribution and slightly reduce emissions.
- Variation of ORC turbine inlet pressure between 2000 and 3000 kPa shows a negligible impact on performance.

SYMBOLS AND ABBREVIATIONS INDEX

SYMBOLS		**Abbreviations**	
COP	coefficient of performance	AC	Air compressor
$\dot{E}$	exergy (kW)	CC	Combustion chamber
h	specific enthalpy (kJ/kg)	CHP	Combined heat and power
$\dot{m}$	mass flow rate (kg/s)	Comp	compressor
P	pressure (kPa)	Cond	condenser
$\dot{Q}$	heat transfer (kW)	GT	Gas turbine
s	specific entropy (kJ/kg. K)	HEVG	Heat recovery vapor generation
$\dot{W}$	Work done (kW)	ORC	organic Rankine cycle
Greek symbols		ORT	organic Rankine turbine
ŋ	thermal efficiency (%)	P	pump
ψ	exergy efficiency (%)		

REFERENCES

Abrosimov, Kirill, Andrea Baccioli, and Aldo Bischi. 2020. techno-economic assessment of combined inverted Brayton – Organic Rankine cycle for high-temperature waste heat recovery . Energy 211, 118406.

Ahmed, Ijaz, Muhammad Rehan, Abdul Basit, and Keum-Shik Hong. 2022. Greenhouse gases emission reduction for electric power generation sector by efficient dispatching of thermal plants integrated with renewable systems . Scientific Reports 12(1), 12380.

Akroot, Abdulrazzak. 2025. Thermodynamic and Environmental Performance Analysis of the Marib Integrated Power and Cooling Cycle (MIPCC) . Black Sea Journal of Engineering and Science 8(3), 814–23.

Akroot, Abdulrazzak, and Ayaa Faraj. 2025. Performance and exergoeconomic assessment of of integrated organic Rankine cycle with solar combined cycle system on sustainable power generation in Iraq . Engineering and Technology Journal 43(07), 561–76.

Akroot, Abdulrazzak, and Abdullah Sultan Al Shammre. 2024. Economic and Technical Assessing the Hybridization of Solar Combined Cycle System with Fossil Fuel and Rock Bed Thermal Energy Storage in Neom City . Processes 12(7), 1433.

Alfaris, Ali, Abdulrazzak Akroot, Saeed Alqaed, and Fahad Awjah Almehmadi. 2025. Performance analysis of integrated solar and natural gas combined cycle power plants in high solar potential regions . Scientific Reports 15(1), 9181.

Alfaris, Ali, Abdulrazzak Akroot, and Emrah Deniz. 2024. The Exergo-Economic and Environmental Evaluation of a Hybrid Solar–Natural Gas Power System in Kirkuk . Applied Sciences 14(22), 10113.

Axelsson, Helén, Simon Harvey, Anders Åsblad, and Thore Berntsson. 2003. Potential for greenhouse gas reduction in industry through increased heat recovery and/or integration of combined heat and power . Applied thermal engineering 23(1), 65–87.

Bagherzadeh, Seyed Amin, Behrooz Ruhani, Mohammad Mostafa Namar, Rezvan Alamian, and Sara Rostami. 2020. Compression ratio energy and exergy analysis of a developed Brayton-based power cycle employing CAES and ORC . Journal of Thermal Analysis and Calorimetry 139(4), 2781–90.

Baleta, Jakov, Hrvoje Mikulčić, Jiří Jaromír Klemeš, Krzysztof Urbaniec, and Neven Duić. 2019. Integration of energy, water and environmental systems for a sustainable development . Journal of cleaner production 215, 1424–36.

Balli, Ozgur, Selcuk Ekici, and Hikmet T Karakoc. 2021. Achieving a more efficient and greener combined heat and power system driven by a micro gas turbine engine: Issues, opportunities, and benefits in the presence of thermodynamic perspective . International Journal of Energy Research 45(6), 8620–38.

Bian, Jiang, Rui Zhang, Xuewen Cao, Jian Yang, Jingfa Li, and Bo Yu. 2025. Design and analysis of a novel integrated hydrogen liquefaction process using the organic Rankine cycle and dual-pressure Brayton cycle . Renewable Energy 248, 123112.

Chen, Weidong, Zhifeng Huang, and Kian Jon Chua. 2022. Sustainable energy recovery from thermal processes: a review . Energy, Sustainability and Society 12(1), 46.

Dobre, Cătălina, Mihnea Costin, and Mihaela Constantin. 2024. A review of available solutions for implementation of small–medium combined heat and power (CHP) systems . Inventions 9(4), 82.

Islam, MA, Md Hasanuzzaman, Nasrudin Abd Rahim, Afroza Nahar, and M Hosenuzzaman. 2014. Global renewable energy-based electricity generation and smart grid system for energy security . The Scientific World Journal 2014(1), 197136.

Ismael, Mays Alaa, Samir Gh Yahya, and Itimad DJ Azzawi. 2022. Experimental Investigation of Performance of Conventional Vapor Compression Refrigeration Cycle Using Geothermal Cooling in Extreme Hot Weather Conditions . International Journal of Heat and Technology 40(2), 449–56.

Kabeyi, Moses Jeremiah Barasa, and Oludolapo Akanni Olanrewaju. 2022. Sustainable Energy Transition for Renewable and Low Carbon Grid Electricity Generation and Supply . Frontiers in Energy Research. Frontiers Media S.A.

Kareem, Alaa Fadhil, Abdulrazzak Akroot, Hasanain A Abdul Wahhab, Wadah Talal, Rabeea M Ghazal, and Ali Alfaris. 2023. Exergo–Economic and Parametric Analysis of Waste Heat Recovery from Taji Gas Turbines Power Plant Using Rankine Cycle and Organic Rankine Cycle . Sustainability (Switzerland) 15(12).

Liu, Jianguo, Harold Mooney, Vanessa Hull, Steven J Davis, Joanne Gaskell, Thomas Hertel, Jane Lubchenco, Karen C Seto, Peter Gleick, and Claire Kremen. 2015. Systems integration for global sustainability . Science 347(6225), 1258832.

Ochoa, Guillermo Valencia, Jorge Duarte Forero, and Jhan Piero Rojas. 2020. A comparative energy and exergy optimization of a supercritical-CO2 Brayton cycle and Organic Rankine Cycle combined system using swarm intelligence algorithms . Heliyon 6(6).

Olabi, Abdul Ghani, Tabbi Wilberforce, Enas Taha Sayed, Khaled Elsaid, and Mohammad Ali Abdelkareem. 2020. Prospects of fuel cell combined heat and power systems . Energies 13(16), 4104.

Pan, Zhen, Mingyue Yan, Liyan Shang, Ping Li, Li Zhang, and Jiaqi Liu. 2020. Thermoeconomic Analysis of a Combined Natural Gas Cogeneration System With a Supercritical CO2 Brayton Cycle and an Organic Rankine Cycle . Journal of Energy Resources Technology 142(10), 102108.

Pilavachi, PA. 2000. Power generation with gas turbine systems and combined heat and power . Applied Thermal Engineering 20(15–16), 1421–29.

Sun, Wenqiang, Xiaoyu Yue, and Yanhui Wang. 2017. Exergy efficiency analysis of ORC (Organic Rankine Cycle) and ORC-based combined cycles driven by low-temperature waste heat . Energy Conversion and Management 135, 63–73.

Talal, Wadah, and Abdulrazzak Akroot. 2023. Exergoeconomic Analysis of an Integrated Solar Combined Cycle in the Al-Qayara Power Plant in Iraq . Processes 11(3).

------. 2024. An Exergoeconomic Evaluation of an Innovative Polygeneration System Using a Solar-Driven Rankine Cycle Integrated with the Al-Qayyara Gas Turbine Power Plant and the Absorption Refrigeration Cycle . Machines 12(2), 133.

Tchanche, Bertrand F, Gr Lambrinos, Antonios Frangoudakis, and George Papadakis. 2011. Low-grade heat conversion into power using organic Rankine cycles–A review of various applications . Renewable and sustainable energy reviews 15(8), 3963–79.

Zare, V, and MJEC Hasanzadeh. 2016. Energy and exergy analysis of a closed Brayton cycle-based combined cycle for solar power tower plants . Energy conversion and management 128, 227–37.