ASSESSING THE POTENTIAL FOR POWER GENERATION FROM LOW-GRADE WASTE HEAT: INTEGRATION OF AN ORGANIC RANKINE CYCLE WITH AN ABSORPTION HEAT TRANSFORMER

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ABSTRACT

Combining organic Rankine cycles (ORCs) with absorption heat transformers (AHT) shows promise in improving energy efficiency. Heat transformers utilizing lithium bromide (LiBr) are a distinct subtype of AHT, employing a liquid absorbent to absorb and release heat, providing an efficient approach to transfer waste heat streams and enhance the performance of the heat recovery systems. By integrating with ORCs, LiBr heat transformers offer a more effective means of harnessing low to medium-grade waste heat sources and transforming them into usable energy. This study proposes integrating an AHT with an ORC to harness low-grade waste heat from AHT and raise its temperature. Additionally, it aims to utilize high-grade heat released from the AHT absorber in an ORC cycle to generate electrical power. Simulation results show that the coefficient of performance (COP) of the AHT reached 0.435, while the exergy-based COP calculated at 0.651 indicates an effective AHT design. The coupled ORC cycle produced a net electrical power of 307.4 kW with an energy efficiency of 13.95%. The total energy efficiency and exergy efficiency of the integrated system were measured at 6.07% and 35.46%, respectively. Parametric analysis revealed that the temperature of the condenser in the AHT cycle and the pressure of the condenser in the ORC cycle have an inverse effect on the system's performance, whereas the high pressure of the ORC cycle exhibits a direct correlation with overall system performance indicators.

1 INTRODUCTION

A significant portion of the energy consumed by industries is lost in the form of heat, leading to notable environmental effects such as global warming, climate change, regional temperature increases, and greenhouse gas emissions (Xu and Wang, 2017). In response to this challenge, the European Union has introduced waste heat recovery from industries as a strategic solution to conserve energy and mitigate thermal pollution. Most of the waste heat generated in industries is below 120°C, presenting numerous challenges for its recovery (Yang *et al.*, 2017). The Absorption Heat Transformer (AHT) technology is recognized as one of the most promising methods for low-temperature heat recovery, attracting considerable attention from researchers and investors due to its flexibility and high reliability (Gao, Xu and Wang, 2021). The typical AHT system, employing the LiBr-H_2O working pair, recovers waste heat from low-temperature industries with a performance factor of 0.49 and elevates its temperature by 30-50°C (Cudok *et al.*, 2021).

The performance of AHT systems and methods for waste heat recovery have been extensively investigated across various industries, as documented in the literature. Ma et al. (Ma *et al.*, 2003) presented the results of utilizing an AHT system employing a LiBr-H_2O working pair with a capacity of 5000 kW to recover waste heat from a synthetic rubber plant. This system can elevate the temperature of waste heat with an average coefficient of performance (COP) of 0.47, increasing by nearly 25°C. The payback period for this system is approximately 2 years.

Sekar and Saravanan (Sekar and Saravanan, 2011) conducted experimental research on the performance of an AHT system integrated with a desalination system. Their results indicate that the proposed system achieves a maximum temperature increase of 30°C and a COP of 0.38. Under these conditions, the system produces fresh water at a flow rate of 4.10 kg/h. Aly et al. (Aly, Abrahamsson and Jernqvist, 1993) suggested the application of an AHT system for energy management in an industrial setting. The

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results demonstrate that this system can elevate the temperature of waste heat by 34°C. Furthermore, by generating steam at 3 bar pressure, 45% of the waste heat can be effectively reused within the industrial unit. Their economic evaluations indicate that the cost of steam is 14.25 $/GJ, the cost of installed equipment is 535 $/kW, and the payback period is less than 18 months. Ma et al. (Ma, Bao and Roskilly, 2016) explored various AHT configurations aimed at increasing waste heat temperatures within the range of 40–60°C. The results indicate that the single-stage AHT exhibits better performance, although the increase in temperature is moderate. Horuz and Kurt (Horuz and Kurt, 2009) demonstrated how various parameters affect the COP of AHT systems. According to their study, reducing the temperature of the condenser and increasing the temperature of the evaporator and generator increases the performance of the AHT system, and the thermal capacity of the absorber increases. Liu et al. (Liu *et al.*, 2024) designed an experimental AHT system to enhance low-grade heat from 85°C to generate steam at 100-120°C. For a temperature increase of 34.7°C, the system achieved a COP of 0.33. Mosaffa and Garousi (Mosaffa and Farshi, 2020) used an AHT cycle for CO_2 preheating in a supercritical power cycle. Based on the economic analysis, the payback period is calculated to be around 4.5 years.

The organic Rankine cycle (ORC) system is widely recognized as the fundamental method for generating electricity from low-temperature sources. Kaska (Kaşka, 2014) employed the ORC cycle with R245fa working fluid to recover waste heat from blast furnaces in the steel industry. The system's energy efficiency was 10.20%, whereas its exergy efficiency was 48.5%, for one configuration, and 8.8% and 42.2%, respectively, for the other one. The obtained results indicate that the evaporator pressure significantly influences the system performance. However, the low waste temperature imposes limitations, resulting in an inlet temperature to the turbine of approximately 90 °C. Nondy and Gogoi (Nondy and Gogoi, 2021) explored various configurations of the ORC cycle and demonstrated that the performance of the ORC cycle with an intermediate converter surpasses that of the basic ORC. Mohammed et al. (Mohammed *et al.*, 2020) utilized the ORC cycle to recover waste heat from a diesel engine and examined its performance using two fluids, R134a and R245fa. The results indicate that R134a exhibits better performance, saving special fuel, lubricating oil, and cooling water, and reducing waste heat by 18%. According to the literature, the performance of the ORC cycle is dependent on the temperature of the working fluid entering the turbine, and the cycle's performance improves with increasing temperature. On the other hand, a significant part of industrial waste heat typically falls below 120°C and recovering this heat directly with the ORC cycle will reduce its performance. In this regard, the combination of an ORC and AHT system appears to be an attractive option. The AHT system plays a crucial role in this synergy by increasing the temperature of the waste heat, thereby enhancing the overall performance of the ORC system.

This study proposes an integrated AHT-ORC cycle to utilize low-grade waste heat and elevate its temperature, making it possible for use in power generation cycles. This is particularly important due to limitations in power generation from low-grade waste heat. The system's performance was evaluated by a techno-economic analysis, and the impact of key parameters on the system's performance was investigated through a parametric analysis. The proposed system aims to recover waste heat effectively, boost its temperature, and convert it to electrical power with an acceptable cost rate. To this end, n-Pentane fluid has been selected as the operating fluid for the ORC cycle due to its complete environmental friendliness.

2 METHODS

This section describes the proposed system and presents the methodology used to evaluate the integrated AHT-ORC cycle proposal through energy and economic analysis.

2.1 AHT-ORC cycle

Figure 1 demonstrates the schematic of the introduced system in this study, which is the integration of the single-stage AHT and ORC cycle for power generation. Making use of low-grade waste heat at 90°C, the AHT cycle harnesses it as the primary heat source within its generator (stream 12) and evaporator (stream 14). This process initiates the evaporation of water within both components. In the generator, operating under AHT's low pressure, water evaporates from the LiBr-H_2O solution, leading to an increase in LiBr concentration. Subsequently, the resulting strong solution and evaporated water

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exit the generator separately. The evaporated water (stream 1) flows into the condenser, then after condensing it's pumped to the evaporator (stream 3) where it absorbs heat from the waste heat source, evaporates, and subsequently enters the absorber under high pressure within the AHT cycle (stream 4). Simultaneously, the strong solution (stream 8) undergoes pressurization and temperature elevation before entering the absorber after passing through the internal heat exchanger (stream 10). This absorption process, known for its exothermic nature, releases significant heat at high temperatures and pressures, making it valuable for power generation compared to the initial waste heat. The resulting weak solution (stream 5), generated post-absorption, undergoes further processing through the heat exchanger and expansion valve, ultimately re-entering the generator (stream 7) to sustain a continuous cycle. The n-pentane receives the released heat through the absorber, evaporates, and enters the turbine as saturated vapor (stream 19), initiating expansion within the turbine (OT) for power generation. The turbine outlet then passes through IHE_2 to raise the temperature of stream 18 before the evaporation process. Afterward, it undergoes condensation in $Cond_2$, resulting in the condensed n-pentane (stream 22), which is subsequently pumped to IHE_2 to elevate its temperature through heat transfer between stream 20. After passing through IHE_2, stream 18 can undergo the evaporation process, ensuring continuous operation of the power cycle loop. The design parameters and operational conditions of the AHT-ORC cycle are presented in Table 1.

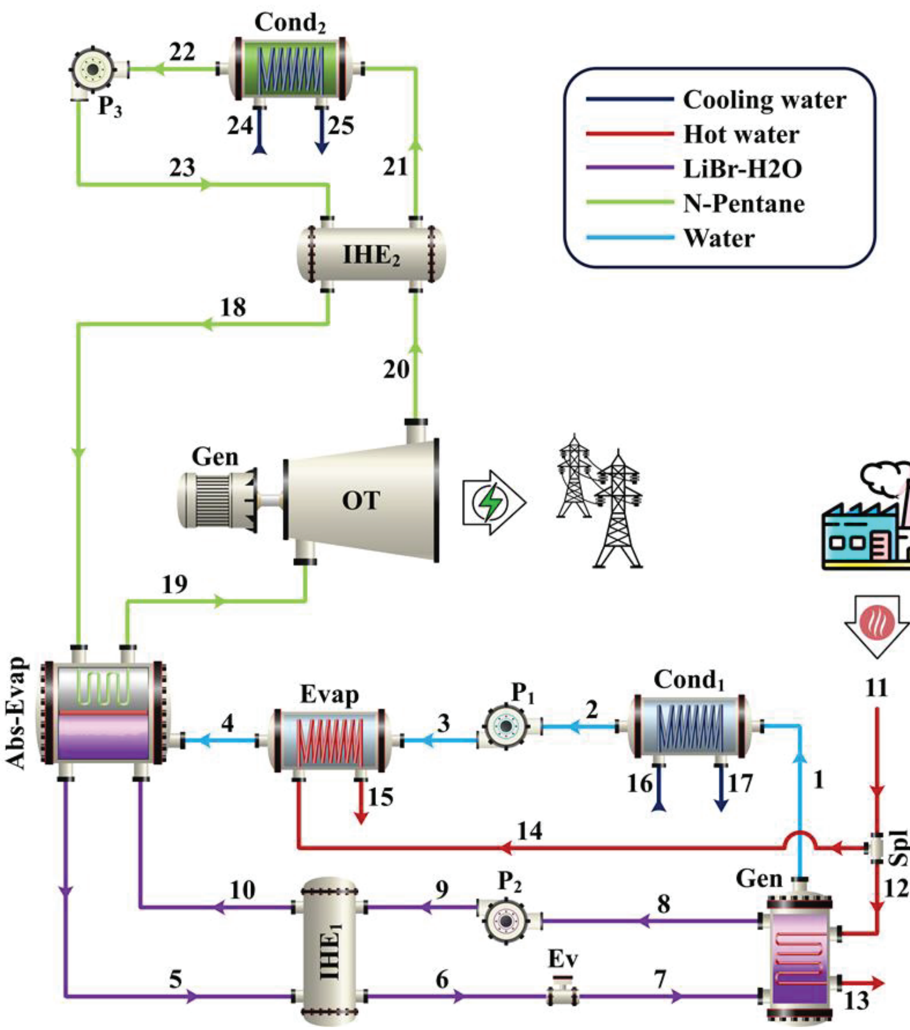

Figure 1: Schematic of the proposed AHT-ORC integrated cycle.

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Table 1: Operational conditions of the proposed system (Horuz and Kurt, 2010; Behnam, Arefi and Shafii, 2018).

Parameter	Value	Unit
Absorber temperature	120	ºC
Generator and evaporator temperature	80	ºC
Heat losses through the absorber	5	%
Inlet pressure of ORC turbine	691	kPa
Isentropic efficiency of the ORC turbine	85	%
Isentropic efficiency of the pumps	80	%
ORC condenser pressure	90	kPa
Waste heat temperature	90	ºC

2.2 Thermodynamic analysis

The first law of thermodynamics was applied to each control volume to evaluate the performance of each subsystem and the overall system. The following equations present the mass balance and energy balance for each control volume and the concentration of the solution, respectively (Akbari *et al.*, 2014).

$$\sum_{In} \dot{m} = \sum_{Out} \dot{m} \tag{1}$$

$$\sum_{In} (\dot{m}\, h) + \dot{Q} = \sum_{Out} (\dot{m}\, h) + \dot{W} \tag{2}$$

$$\sum_{In} (X\, \dot{m}) = \sum_{Out} (X\, \dot{m}) \tag{3}$$

where $\dot{m}$ represents the mass flow rate, h denotes specific enthalpy, while, $\dot{Q}$ and $\dot{W}$ stand for heat and power, respectively. In addition, X represents the mass fraction of LiBr in the solutions.
For the AHT system, the COP is defined as the ratio between the absorber heat capacity and the input heat through the generator and evaporator. This ratio indicates the AHT system's ability to transfer heat across different temperature levels. Equation 4 provides a means to calculate this COP (Horuz and Kurt, 2010).

$$COP_{AHT} = \frac{\dot{Q}_{Abs}}{\dot{Q}_{Gen} + \dot{Q}_{Evap}} \tag{4}$$

The ORC cycle generates power by harnessing the heat released by the AHT. The energy efficiency of the cycle, denoted by the ratio of generated power to input heat, can be defined as follows (Horuz and Kurt, 2010):

$$\eta_{En\text{-}ORC} = \frac{\dot{W}_{Net\text{-}ORC}}{\dot{Q}_{In\text{-}ORC}} = \frac{\dot{W}_{OT} - \dot{W}_{P3}}{\dot{m}_{19}\, h_{19} - \dot{m}_{18}\, h_{18}} \tag{5}$$

Finally, for the entire integrated system, the energy efficiency can be expressed as the ratio of the generated power to the input heat to the entire system.

$$\eta_{En\text{-}Total} = \frac{\dot{W}_{Net\text{-}ORC} - \dot{W}_{P1} - \dot{W}_{P2}}{\dot{Q}_{Gen} + \dot{Q}_{Evap}} \tag{6}$$

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To evaluate the performance of both the AHT and ORC cycles from the second law of thermodynamics point of view, two different indicators have been defined. The exergy-based coefficient of performance (ECOP) for AHT is given by Equation 7, and the exergy efficiency of the ORC cycle is given by Equation 8 (Sözen and Arcaklioğlu, 2007).

$$ECOP_{AHT} = \frac{\dot{Q}_{Abs}\,(1 - \frac{T_0}{T_{Abs}})}{\dot{Q}_{Gen}\,(1 - \frac{T_0}{T_{Gen}}) + \dot{Q}_{Evap1}\,(1 - \frac{T_0}{T_{Evap}})} \tag{7}$$

$$\eta_{Ex\text{-}ORC} = \frac{\dot{W}_{Net\text{-}ORC}}{\dot{Q}_{in\text{-}ORC}\,(1 - \frac{T_0}{T_{Abs}})} \tag{8}$$

The total exergy efficiency of the system can be defined as the ratio of the produced electrical power, a product of the system, to the input exergy through the waste heat to the system:

$$\eta_{Ex\text{-}Total} = \frac{\dot{W}_{Net}}{\dot{Q}_{Gen}\,(1 - \frac{T_0}{T_{Gen}}) + \dot{Q}_{Evap1}\,(1 - \frac{T_0}{T_{Evap}})} \tag{9}$$

2.3 Economic analysis

To assess the economic performance of the system, the cost balance is applied to each component and the system overall in the following manner (Bejan, Tsatsaronis and Moran, 1995):

$$\dot{C}_T = \dot{C}_{CI} + \dot{C}_{OM} \tag{10}$$

where $\dot{C}_{CI}$ stands for the capital investment cost rate, $\dot{C}_{OM}$ represents the operational cost rate including maintenance, while $\dot{C}_T$ is the total cost rate. The total cost rate for each component can be calculated as:

$$\dot{C}_T = \frac{(PEC \times CFR \times \varphi)}{N} \tag{11}$$

where PEC represents the purchasing cost of each component, and the function for each component in this study is available in the literature. N is the total number of hours the system operates annually, and φ is the equivalent coefficient for the operation and maintenance cost rate, which is 1.06 in this case. Additionally, CRF is the capital recovery factor and can be determined as follows (Bejan, Tsatsaronis and Moran, 1995):

$$CRF = \frac{i\,(1+i)^{BL}}{(1+i)^{BL} - 1} \tag{12}$$

The interest rate, denoted as i in the Equation 12, is taken to be 1.06, and the system lifetime is denoted by BL. The following formula can be used to determine the levelized cost of electricity (LCOE) for the entire integrated system (Bejan, Tsatsaronis and Moran, 1995):

$$LCOE = \frac{\text{Total cost rate}}{\text{Generated electrical power}} \tag{13}$$

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3 RESULTS AND DISCUSSIONS

3.1 Verification of the results

The simulations of the proposed AHT-ORC cycle, based on the operating conditions detailed in Table 1, are carried out using the Engineering Equation Solver (EES) software. To ensure the accuracy of the developed model, simulation was carried out for the AHT and ORC models, utilizing the methodology described in the references (Horuz and Kurt, 2010) and (Sadreddini *et al.*, 2018), respectively. Following the validation of the model's precision, adjustments were made to the cycle to match the design parameters specified in this study. Table 2 provides a summary of the validation results for the model employed in this research.

Table 2: AHT-ORC cycle verification with the results of the references (Horuz and Kurt, 2010; Sadreddini *et al.*, 2018)

Parameters	Unit	Reference	This study	Error (%)
q_{Evap1}	kJ/kg	2490.80	2493.90	0.13
q_{Gen}	kJ/kg	2413.67	2415.21	0.06
q_{Abs}	kJ/kg	2361.55	2363.75	0.09
COP_{AHT}	-	0.4815	0.4816	0.02
$\dot{W}_{ORC}$	kW	95.00	95.00	0.00
$\eta_{En,\,ORC}$	%	11.20	11.20	0.00

A comparison of the results demonstrates a favorable alignment between the model developed in this study and the findings presented in the literature. The model verification process involved identical design parameters and operational conditions. Following verification, the AHT and ORC systems were designed and simulated using the parameters outlined in this study.

3.2 Techno-economic analysis results

The designed integrated AHT-ORC cycle aims to utilize low-grade industrial heat, elevate its temperature, and facilitate the generation of electrical power at an appropriate temperature level. The waste heat at 90°C is utilized in the generator and evaporator of the AHT system, and after transforming the low-grade heat in this cycle, heat is released from the absorber of the AHT at 120°C.

The designed AHT cycle achieved a COP of 0.435 and ECOP of 0.651, indicating efficient AHT design and effective temperature elevation. An ORC cycle was integrated into the AHT to utilize the released heat from the absorber to generate electrical power. The integrated system, with total energy and exergy efficiencies of 6.07% and 35.46% respectively, generates 307.4 kW net electrical power.

The system's overall cost rate was determined to be 13.28 $/h, a large amount of which was ascribed to the ORC cycle's expenses. This suggests that, despite the low cost related to the AHT, the temperature boosting and transformation of low-grade heat into a suitable form for power generation, as facilitated by the proposed configuration, are available at a relatively low expense. Due to electrical power generation throughout the entire system and the total cost rates, the LCOE of the system is obtained to be 0.0333 $/kWh.

From a technical point of view, utilizing this waste heat directly in the stand-alone ORC cycle seems irrational and impossible. This is because, considering at least a 5°C temperature difference on both sides of the ORC evaporator, the available heat in the ORC cycle is of very low grade and unreasonable to use directly in the ORC cycle. However, in this case, theoretically, approximately 190 kW of electrical power with approximately the same LCOE (0.0313 $/kWh) can be produced.

According to calculations, the ORC cycle's energy efficiency in this instance is 8.50%. Despite the technical problems associated with direct utilization, the integrated system exhibits a 117.40 kW improvement in power generation and a 5.45% enhancement in the energy efficiency of the ORC cycle.

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This proves the effect of the AHT on all performance indicators, thanks to its lowest cost share in the integrated system. Table 3 summarizes the techno-economic analysis results for the integrated AHT-ORC cycle.

Table 3: Techno-economic analysis results for the proposed system

Parameter	Value	Unit
Heat input to the generator of AHT	2529.67	kW
Heat input to the evaporator of AHT	2538.14	kW
Heat released through the absorber	2203.59	kW
Net total electrical power generation	307.4	kW
COP of AHT	0.435	-
ECOP of AHT	0.651	-
Energy efficiency of ORC cycle	13.95	%
Total energy efficiency	6.07	%
Exergy efficiency of the ORC cycle	54.85	%
Total exergy efficiency	35.46	%
Total cost rate	13.28	$/h
LCOE	0.0333	$/kWh

3.3 Parametric analysis

To investigate the influence of the independent key parameters on the AHT-ORC cycle, a parametric analysis was carried out.

Figure 2 illustrates the impact of the condenser temperature of the AHT on the performance of each subsystem and the entire system. As the condenser temperature of the AHT rises, both the COP of the AHT and the heat-released flow rate through the absorber decrease. This can be attributed to the increase in the low pressure of the AHT cycle caused by the higher condenser temperature, leading to a decrease in the concentration of the strong solution. In this case, the available heat in the ORC cycle through the AHT cycle decreases, leading to lower power generation and energy efficiency in the whole system compared to the low temperatures in the AHT condenser.

Followed by the decrease in the net power output, the LCOE of the system also decreases. From an exergy point of view, the effect of the AHT condenser on the ECOP of the AHT is significant, which can be justified by the lower heat capacity of the absorber with constant heat input to the system through the waste streams. Despite the constant exergy efficiency in the ORC cycle, due to decreasing ECOP, the total exergy efficiency of the entire cycle also experiences a decrease.

The low pressure of the ORC cycle, as the second independent parameter, can play a vital role in the performance of the ORC cycle and the whole integrated system. The low pressure of the ORC cycle increases causing a drop in outlet pressure and temperature of the ORC turbine, which lowers the ORC turbine's generated power. Following these changes, the energy efficiency of the ORC cycle and the entire system will drop. There is no change in the AHT cycle by low pressure of the ORC cycle; however, due to significant changes in the ORC cycle in the entire system, similar changes can be observed with slight sharpness.

As shown in Figure 3, at higher low pressure of the ORC cycle, the energy and exergy efficiency, net power output in the ORC cycle, and overall system are less than at lower pressures. Following the decrease in the net power generation and non-significant changes in the total cost rate of the system, the LCOE of the system experiences an increase with increasing low pressure of the ORC cycle.

Similar to the low pressure of the ORC cycle, which is linked to the turbine outlet and condenser pressure, the high pressure of the ORC cycle, associated with the turbine inlet pressure, significantly influences the ORC cycle's performance.

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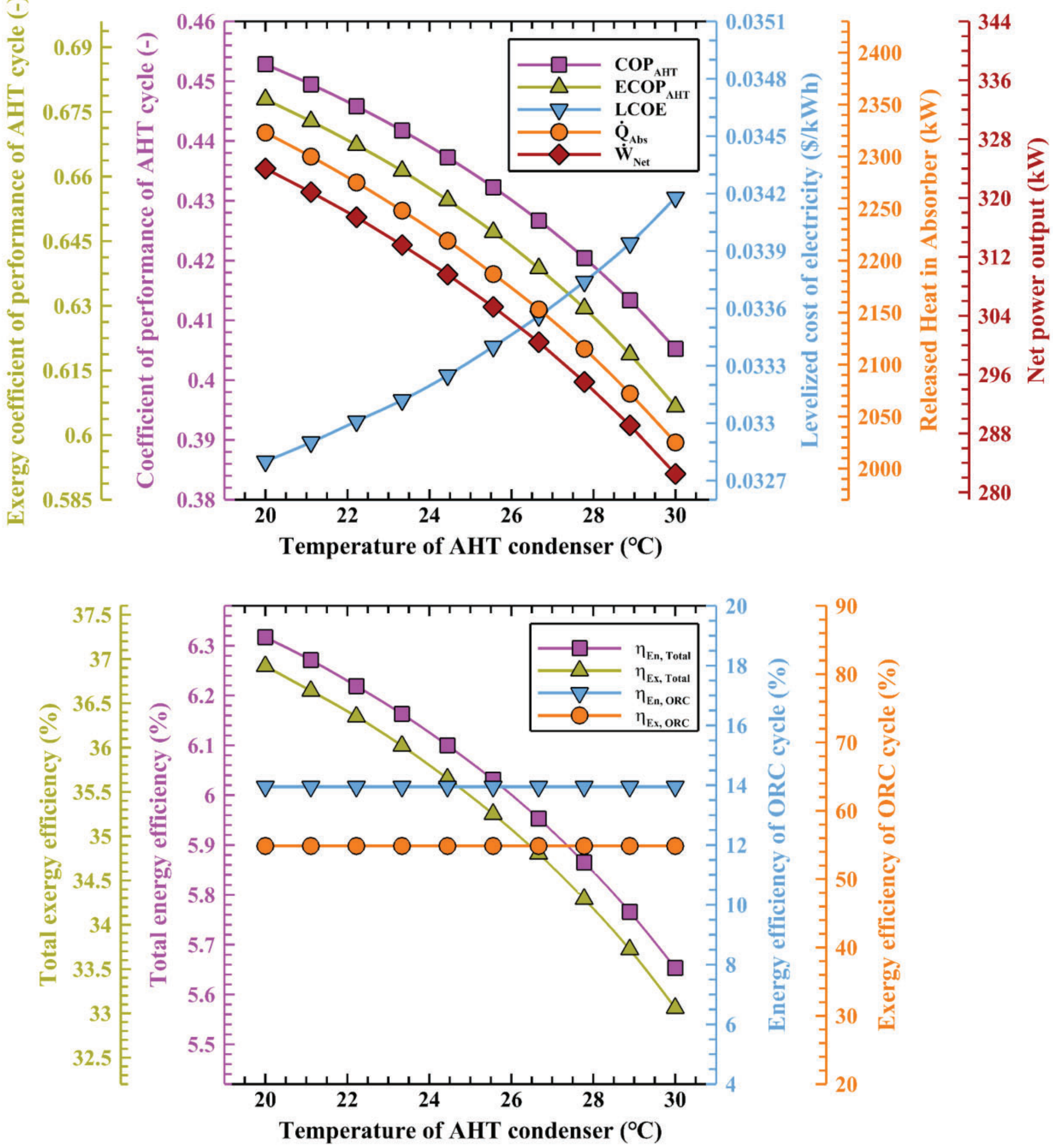

Figure 2: Effect of the AHT condenser temperature on the performance of the system

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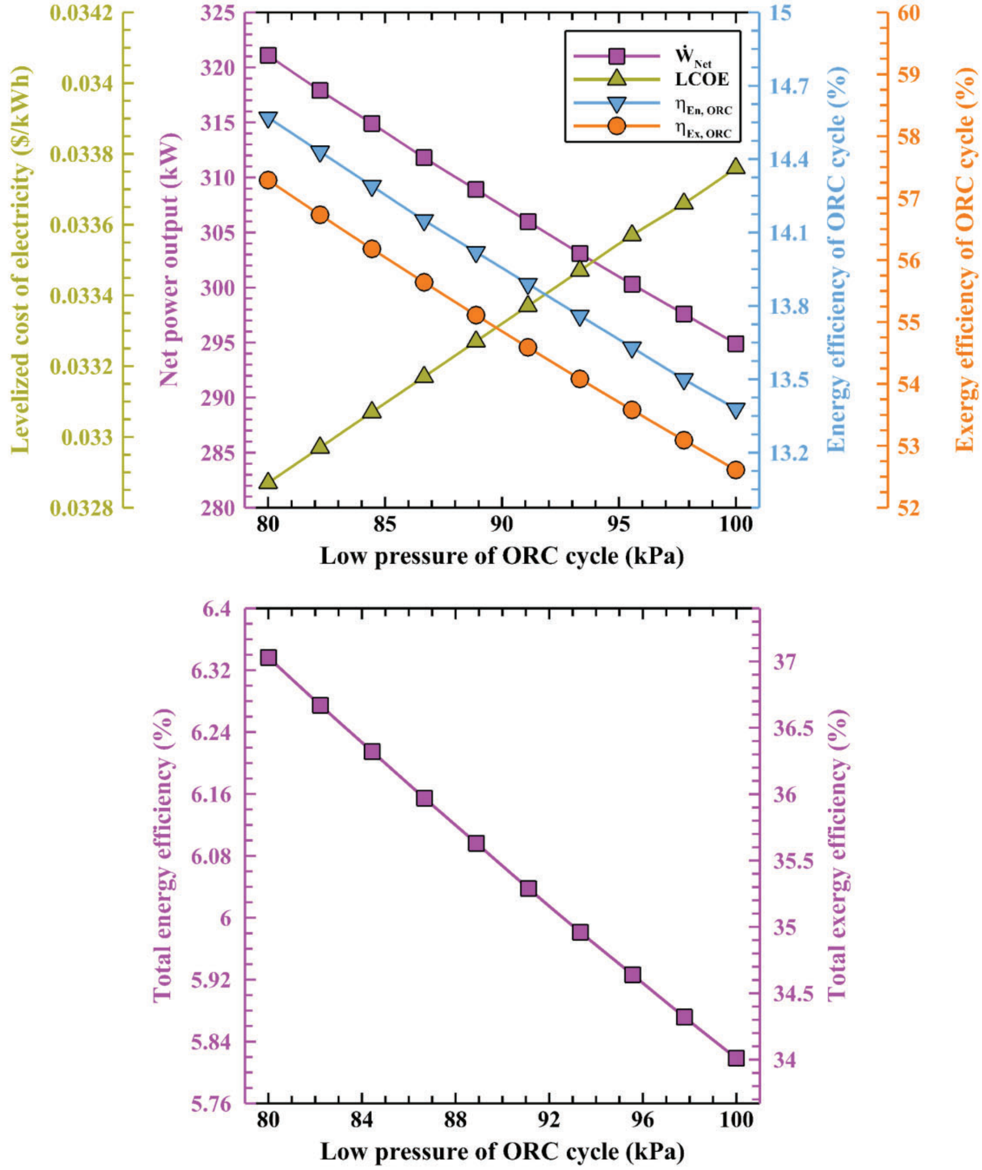

Figure 3: Effect of the low pressure of ORC cycle on the performance of the system

Figure 4 illustrates the impact of the high pressure of the ORC cycle on system performance. As shown, increasing the high pressure of the ORC cycle leads to greater expansion of the ORC working fluid in the turbine, thus boosting power generation. Despite the rise in power consumption by the ORC pump to elevate pressure, it is negligible compared to the power generated in the turbine. Consequently, net power generation through the ORC cycle increases while maintaining a constant available heat through the absorber, thereby enhancing the energy efficiency of both the ORC cycle and the entire system. Furthermore, from an exergy perspective, the generation of more electrical power in the ORC cycle and the integrated system increases the exergy efficiency of the ORC cycle and the entire system with increasing high pressure. This increase in net power generation offsets the rise in cost rates, leading to a reduction in the LCOE of the system as the high pressure of the ORC cycle increases.

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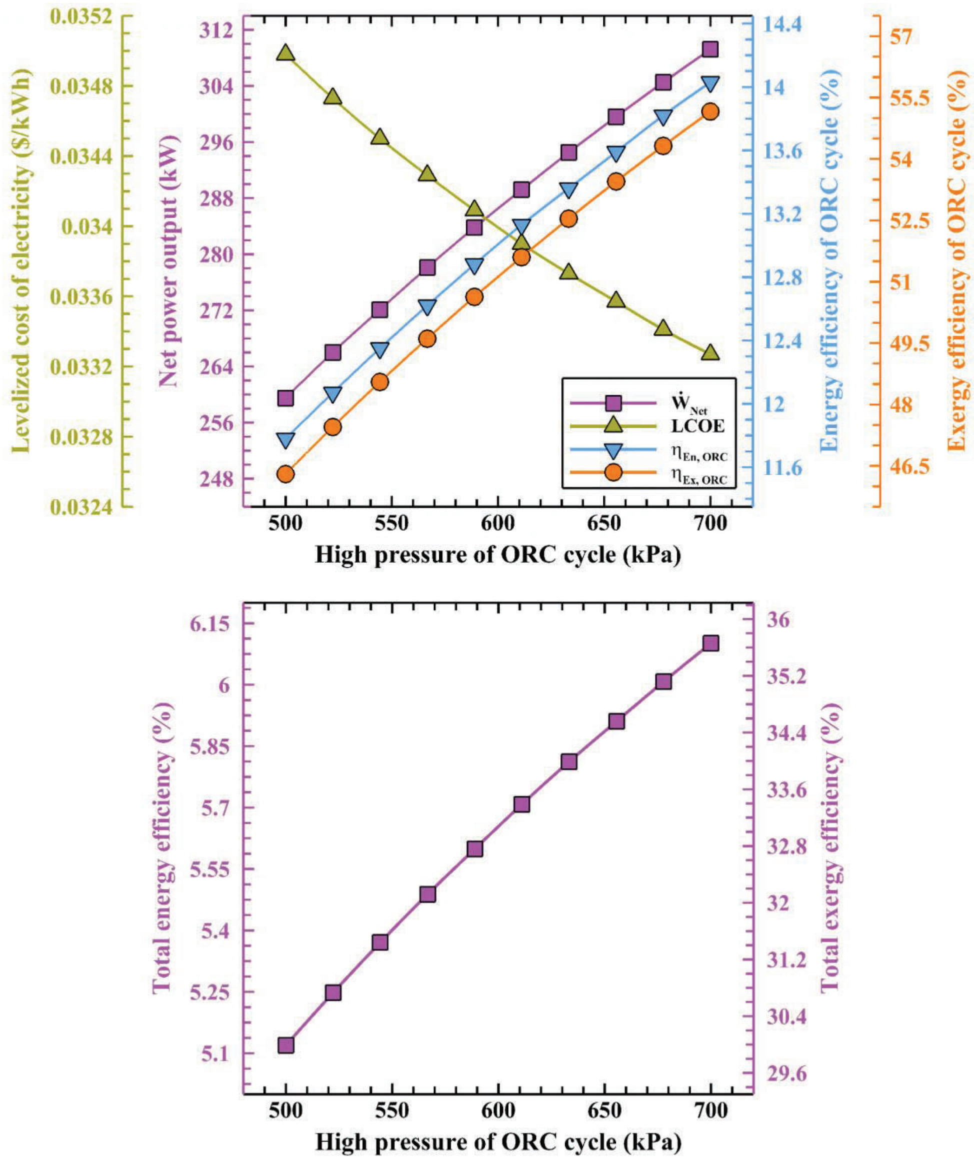

Figure 4: Effect of the high pressure of ORC cycle on the performance of the system

4 CONCLUSIONS

This study proposed an integrated AHT-ORC cycle to elevate the temperature of low-grade waste heat, making it suitable for use in a power generation cycle. In this regard, a LiBr-H_2O AHT is designed to increase the temperature from 90°C to 120°C. Based on the findings, employing an efficient AHT with a COP of 0.435 allows the designed system to produce 307.40 kW of net electrical power at a LCOE of 0.0333 $/kWh. The overall system energy and exergy efficiencies are calculated to be 6.07% and 35.46%, respectively.

The parametric analysis reveals that the temperature of the AHT has a reverse effect on the system performance, as well as the low pressure of the ORC cycle, exhibiting better performance at lower ranges of these parameters. Conversely, the high pressure of the ORC cycle directly enhances the performance of the integrated system, with better performance observed at high values of the high pressure of the ORC cycle.

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NOMENCLATURE

Nomenclature		*OT*	ORC turbine
BL	Lifetime (year)	*P*	Pump
$\dot{C}$	Cost rate ($/h)	*Spl*	Splitter
CFR	Capital recovery factor	*WHR*	Waste heat recovery
COP	The coefficient of performance (-)	*LCOE*	Levelized cost of electricity
ECOP	Exergy-based coefficient of performance (-)		
h	Specific enthalpy (kJ/kg)	**Subscripts**	
i	Interest rate (%)	*0*	Dead condition
$\dot{m}$	Mass flow rate (kg/s)	*Abs*	Absorber
N	Total number of operational (hr/year)	*AHT*	Absorption heat transformer
PEC	Purchasing cost of each component ($)	*CI*	Capital investment
$\dot{Q}$	Rate of heat transfer (kW)	*En*	Energy
T	Temperature (°C)	*Evap*	Evaporator
$\dot{W}$	Electrical power (kW)	*Gen*	Generator
X	Mass fraction of LiBr in the solutions	*In*	Inlet
		OM	Operational maintenance
Abbreviations		*ORC*	Organic Rankine cycle
Abs-Evap	Absorber and Evaporator	*OT*	ORC turbine
AHT	Absorption heat transformer	*Out*	Outlet
Cond	Condenser	*P*	Pump
Ev	Expansion valve	*T*	Total
Evap	Evaporator		
Gen	Generator	**Greek symbols**	
IHE	Internal heat exchanger	η	Efficiency
ORC	Organic Rankine cycle	φ	Equivalent coefficient

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