Analysis of Low-Heat Upgrading Technologies for Organic Rankine Cycle Power Generation

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ABSTRACT

Heat energy from industrial effluent at temperatures below 70 °C is common, but is mostly discarded to the environment as waste heat due to difficulties involved in its exploitation. In this work, three temperature-upgrading technologies for recovering industrial waste heat to work in conjunction with Organic Rankine Cycle power (ORC) generation are evaluated and compared. These three systems: (i) Electrical heat pump system (EHPs), (ii) Gas engine-driven heat pump system (GEHPs), and (iii) Absorption heat transformer system (AHTs), are mathematically modeled considering a thermal capacity of 250 kW for all three systems. For EHPs and GEHPs, the working fluid is R365mfc, while the AHTs uses H_2O-LiBr. In each combination, a 20 kW_e ORC power generator with R245fa as working fluid is connected. The systems are mathematically simulated with a heat source above 60 °C. Among the proposed technological combinations, EHPs is considered the most suitable in terms of its compactness, and simplicity in installation, operation and maintenance. According to economic analysis, when the heat source is around 63 °C, EHP-ORC also achieves the lowest Levelized Cost Of Electricity (LCOE) of 0.065 USD/kWh, while AHT-ORC and GEHP-ORC, 0.066 and 0.086 USD/kWh, respectively. Considering environmental impact, the AHT-ORC has the potential to reduce CO_2 emissions by 86.4 Ton CO_2 eq./Year due to the low energy consumption of the system, while EHP-ORC and GEHP-ORC can reduce 63.0, and 37.8 Ton CO_2 eq./Year, respectively.

Keywords: ORC power generator, Electrical heat pump, Gas engine-driven heat pump, Absorption heat transformer, Low-grade industrial waste heat.

INTRODUCTION

Energy is a fundamental necessity for life and economic development. Currently many countries are coping with environmental and global energy crises, which attracted attention in the research of advanced technologies for energy production. From BP Energy reports, the world's primary energy consumption increased from 10.9 GTOE in 2005 to 13.2 GTOE in 2015, with a growth rate of 1.9 percent per year (BP Statistical Review of World Energy, 2016). Energy consumption is expected to rise by 34 percent between 2014 and 2035 (BP Energy Outlook, 2016). The industrial sector consumed more energy than any other end-use sectors (e.g., building sector, and transportation sector), amounting to one-half of the world's total energy consumption (International Energy Outlook, 2016). In industry processes, approximately 50 percent of the total energy introduced to the system is released to the environment and wasted. About 60 percent of the heat disposed has temperatures lower than 230 °C, which presents a large opportunity for heat recovery (Sogut et al., 2010; Pellegrino et al., 2004). Unfortunately, it is only marginally profitable to recover energy from heat source below 340 °C (BSC Incorporated, 2008) to convert such low-temperature heat into electricity using steam-operated Rankine cycle. Nevertheless it is viable for power generation if Organic Rankine Cycle (ORC), which uses an organic compound as working fluid instead of water, is deployed (Gang et al., 2010; Calise et al., 2015).

ORC technology has several other advantages such as simple and autonomous operation, low-maintenance, favorable operating pressures, long lifetime (> 20 years) and has no requirement for demineralizing water. Thus, ORC has become increasingly interesting for small sized power plants with low-temperature heat sources.

Recently, many researchers had been working on the design, analysis, and development of ORC systems for low-temperature waste heat conversion. Tchanche et al., (2011) showed that the market of ORC in waste heat recovery applications are growing faster among all other ORC solutions, with an enormous potential in industry and combined cycle power plants. Campana et al., (2013) evaluated the energy savings and CO_2 emission of ORC units based on real operating data of cement, steel, glass, and oil & gas industries. Liu et al., (2015) designed and modified a hybrid energy supply system, including gas engine-driven heat pumps systems and ORC using gas engine waste heat as a low-grade heat source in order to transfer the low-grade gas engine waste heat into electricity through ORC. Bor et al., (2015) investigated the potential of several alternative technologies for upgrading low-temperature waste heat such as compression-resorption, vapor compression and trans-critical heat pumps, or for the conversion using organic Rankine, Kalina and trilateral cycle engines. The waste heat has a temperature level of 46 – 60 °C with large amounts of heat released to the environment. Chaiyat, (2014) proposed a concept to generate electricity from low-temperature heat using an absorption heat transformer (AHT) coupled with ORC. Sonsaree et al., (2016) presented power generation using an ORC system combined with a gas engine-driven heat pump (GEHP) by utilizing the low-grade industrial waste heat. Their results suggest that GEHP-ORC system is feasible for industries that have low-temperature heat sources available.

From current literature, it is evident that ORC is a well-developed waste heat recovery technology that is capable of generating mechanical or electrical work. Nevertheless, for heat source below 70 ºC heat sources it is less attractive due to a combination of market and technical barriers (Quoilin et al., 2013; Tchanche et al., 2014), resulting in a large amount of heat from industrial processes is disposed into environment. If an ORC system could be applied for power generation at heat-source temperature below 70 ºC, the industrial sector could benefit from the utilization of such energy source and save costs in energy consumption (Fang et al., 2013), as well as in the reduction in operation cost, increased energy efficiency of the industrial processes (Huang et al., 2016), and reduce emission of pollutants (greenhouse gas emissions (GHG), and thermal pollution). Considering the above mentioned, by augmenting the temperature of low-temperature heat source, to achieve a higher temperature difference between the heat reservoir to the heat sink, is an attractive approach for ORC power generation. In this research, the objective is to mathematically model and analyze three different heat boosting technologies to rise a low-temperature heat sufficiently for effective power generation using ORC in the interest of economic and environmental impact. These heat boosters, currently available in the market, are (i) Electrical heat pump system (EHPs): a thermal upgrading device driven by electrical power, (ii) Gas engine-driven heat pump system (GEHPs): a vapor compression refrigeration type with an open compressor driven by gas-fuel (i.e. Natural Gas (NG), Liquid Petroleum Gas (LPG)) using an internal combustion engine instead of an electrical motor, and (iii) Absorption heat transformer system (AHTs): is a type of heat pump technology with driven by thermal energy.

SYSTEM DESCRIPTIONS

The schematic diagram of an ORC power generation system combined with different heat boosting technologies, as modeled in the present study, is shown in Figure 1. The main components of the system are: heat boosting technology (EHPs, GEHPs, and AHTs), the ORC system, and the storage tank. Waste heat from an industry process, with prescribed quantity and quality, is stored in thermal storage tank 1. The heat grade is then augmented by any one of the proposed heat boosters to an equal-to or higher temperature heat and then is stored in the heat reservoir/thermal storage tank 2. Finally, the heat from the thermal storage tank 2 is supplied to the ORC system to generate electricity.

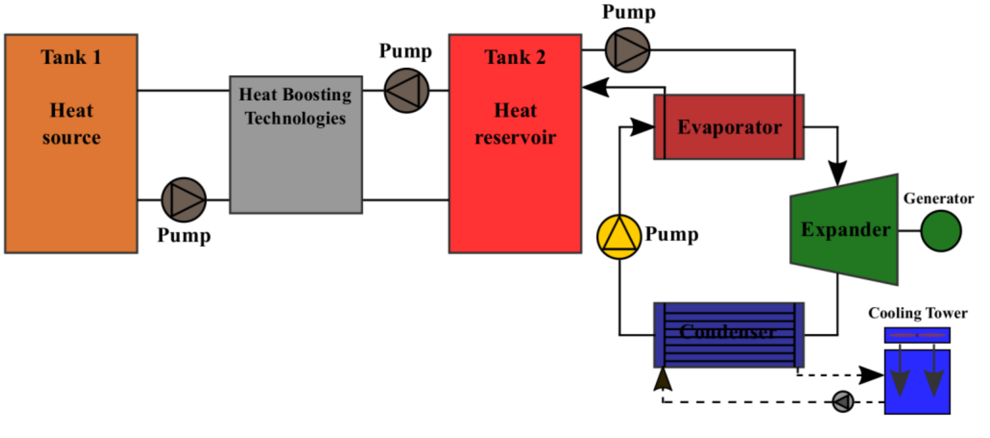

Figure 1. Schematic diagram of the proposed system.

SIMULATION PARAMETERS

In the modeling of the three systems, the EHP-ORC, the GEHP-ORC, and the AHT-ORC systems, it is assumed that steady state conditions are maintained and pressure drop in the overall system is neglected, with the exception of the turbine and pump from the ORC system. Heat loss to the environment from the evaporator, condenser, generator, and the piping system are also neglected. The temperature in the thermal storage tank is assumed to be uniform and non-stratified. The operation conditions of the systems are shown in Table 1 to Table 3. In the system, the degree of superheating (SH), sub-cooling (SC) and the pinch-point temperature difference (PT) are set at 5.0 °C. In addition, heat exchanger effectiveness (ε_{HX}) is assumed to be 90%. The thermodynamic properties of the EHPs, the GEHPs and the ORCs are calculated using REFPROP NIST7.0 (NIST, 2000). The properties of H_2O-LiBr solution, in accordance to ASHRAE Handbook, (2001), Khairulin et al., (2006), and Kaita, (2001), are adopted. The cycle of the three systems were simulated in MATLAB.

Table 1. Initial condition of the ORC system.

Descriptions	**Data**
Cycle power (W_{ORC}), kW_e	20
Isentropic turbine efficiency ($\eta_{Tur,s}$), %	85
Mechanical turbine efficiency ($\eta_{Tur,ME}$), %	90
Isentropic pump efficiency ($\eta_{ORC,P,s}$), %	85
Mechanical pump efficiency ($\eta_{ORC,P,ME}$), %	95
Motor pump efficiency ($\eta_{ORC,P,MO}$), %	95
ORC condenser temperature ($T_{ORC,Cond}$), °C	30

Table 2. Initial condition of the EHP/GEHP system.

Descriptions	**Data**
The Electrical Heat Pump system (EHPs):	
Isentropic compressor efficiency ($\eta_{EHP,s}$), %	90
Mechanical compressor efficiency ($\eta_{Comp,ME}$), %	95
Motor compressor efficiency ($\eta_{Comp,MO}$), %	95
The Gas Engine-driven Heat Pump system (GEHPs):	
Isentropic compressor efficiency ($\eta_{GEHP,s}$), %	90
Gas engine mechanical efficiency ($\eta_{ge,ME}$), %	82
Gas engine combustion efficiency ($\eta_{ge,comb}$), %	95
Efficiency of power transmission (η_{belt}), %	95
Gas engine thermal efficiency ($\eta_{ge,th}$), %	35
Fuel lower heating value (q_{LHV}) of Natural Gas (NG), kJ/kg (Hepbasli, 2008)	44000
Chemical exergy content of Natural Gas (NG), kJ/kg (Hepbasli, 2008)	45760
Capacity, kW_{th}	250
Working fluid (Kondou and Koyama, 2015)	R365mfc

Table 3. Initial condition of the AHT system.

Descriptions	Data
Minimum concentration of weak H_2O-LiBr solution (X_{min}), %LiBr	45
Minimum concentration difference of strong and weak H_2O-LiBr solution ($\Delta X_{s,min}$), %LiBr	2
Isentropic efficiency of the water pump ($\eta_{AHT,P,s}$) and the solution pump ($\eta_{AHT,SP,s}$), %	85
Mechanical efficiency of the water pump ($\eta_{AHT,P,ME}$) and the solution pump ($\eta_{AHT,SP,ME}$), %	95
Motor efficiency of the water pump ($\eta_{AHT,P,MO}$) and the solution pump ($\eta_{AHT,SP,MO}$), %	95
AHT condenser temperature ($T_{AHT,Cond}$), °C	30
Capacity, kW_{th}	250

ECONOMIC ANALYSIS

Economic analysis of the integrated system are carried out in respect of the Levelized Cost Of Electricity (LCOE) as presented in the studies of Chaiyat and Kiatsiriroat, (2015). In the economic assessment, the initial condition and the commercial cost of the three heat boosting technologies used to evaluate the capital cost of the system are as shown in Table 4. Capital costs of the ORC power plant varies between 2,000 – 3,400 USD/kW_e (Rowshanzadeh, 2011; Turboden, 2016; Arvay et al., 2011) as given in Table 5. As shown, a micro scale ORC power plant for this study at around 2,500 USD/kW_e was selected for the study.

Table 4. Initial condition, and cost data used for the economic evaluation.

Descriptions	Data
Condition	
Operation time, hour/day	24
Operation day, day/year	350
Investment cost	
Electrical Heat Pump system (EHPs) (BSC Incorporated, 2008), USD/kW_{th}	261
Gas Engine-dirven Heat Pump system (GEHPs) (BSC Incorporated, 2008), USD/kW_{th}	326
Absorption Heat Transformer system (AHTs) (BSC Incorporated, 2008), USD/kW_{th}	641
Cost of the NGV (PTT Public Company Limited, 2016), USD/kg	0.37
Surcharge for construction and engineering, %	10
Operating & maintenance (O&M) cost	
Operating & maintenance cost (% of investment cost per year)	1
Life time of plant (N), year	25

Table 5. Commercial cost of the ORC power plant.

Company	ORC capacity (kW_e)	Cost (USD/kW_e)
Ormat (Arvay et al., 2011)	250 – 20000	2000
Infinity turbine (Rowshanzadeh, 2011)	2 – 3000	2500
Electratherm (Arvay et al., 2011)	50	2530
Turboden (Turboden, 2016)	200 – 15000	3400

RESULT AND DISCUSSION

Three different heat boosting technologies were mathematically applied to elevate the temperature of the heat source, from the low-grade industrial waste heat at temperatures below 70 °C, to the high temperature of the heat sink/heat reservoir before supplying the heat to the ORC power generation system, were simulated. The EHP-ORC, the GEHP-ORC, and the AHT-ORC systems are compared based on net power output, energy consumption, thermal systems performance, life-time cost, the

LCOE, CO_2 reduction, foot print of the heat boosting technologies, and effect of the heat source temperature on the systems are detailed as following:

Net power output and energy consumption of the system

Comparison of the net power output of the systems suggests that the GEHP-ORC and the AHT-ORC systems output are higher than that of the EHP-ORC system, as electrical consumption of these two heat boosting technologies is low since GEHPs uses fuel for energy while AHTs deploys thermal energy as their main source to operate, instead of electrical energy. For instance, when the temperature of the heat source is 60 °C, the net power output and electrical consumption of the EHP-ORC, the GEHP-ORC, and the AHT-ORC systems are 79.2 and 88.7 MWh/Year, 163.7 and 4.1 MWh/Year, and 159.0 and 4.7 MWh/Year, respectively.

It should be noted that the net power output of the EHP-ORC system has decreasing electrical consumption as the temperature of the heat source increases, due to the reduction in power requirement of the EHPs to augment the temperature of the heat source. For example, when the temperature of the heat source is 64 °C, the net power output and electrical consumption of the system are 112.3 and 53.3 MWh/Year, respectively. Figure 2 shows the net power output (MWh/Year) and energy consumption (MWh/Year) of the EHP-ORC system, when the heat source temperature increases (°C).

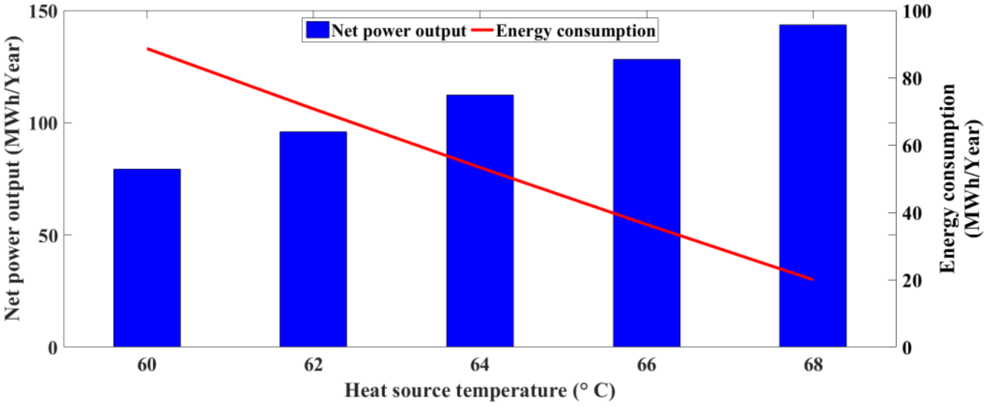

Figure 2. Net power output (MWh/Year) and energy consumption (MWh/Year) of the EHP-ORC system, when the heat source temperature increases (°C).

Also, it is pointed out that the fuel consumption of the GEHP-ORC system had the downward trend when the temperature of heat source increases due to reduced fuel energy requirements of the GEHPs to raise the low-temperature of the heat source. Figure 3 shows the effect of the heat source temperature (°C) on the fuel consumption (Ton of NGV/Year) of the GEHP-ORC system. When the temperature of heat source is 60 °C, the fuel consumption of the system is 24.1 Ton of NGV/Year, is higher when compared to the fuel consumption of system of 14.0 Ton of NGV/Year with heat source temperature at 64 °C.

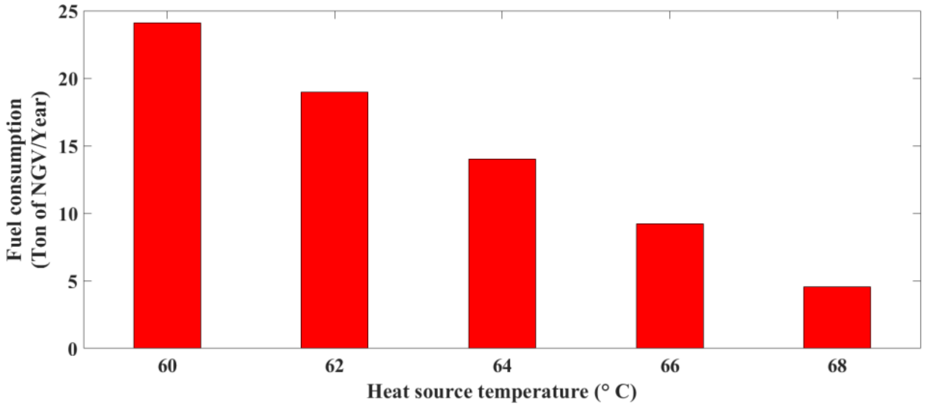

Figure 3. Effect of the heat source temperature (°C) on the fuel consumption (Ton of NGV/Year).

Thermal system performance

When the temperature of heat source varies from 60 to 68 °C, the thermal system performance of the GEHP-ORC system is the highest followed by that of the EHP-ORC system and AHT-ORC system, since the total energy input required by the GEHPs to raise the low-temperature heat is the lowest among the three. Moreover, the results indicate that the thermal system performance of the GEHPs and the AHTs combined with an ORC for power generation suffers insignificant change from variations in the heat source temperature. For instance, when the temperature of heat source is 60 °C, the thermal performance of the EHP-ORC, the GEHP-ORC, and the AHT-ORC systems is 4.2, 6.5, and 4.1% respectively. Whereas, when the temperature of heat source is 64 °C, the thermal performance of the systems is 5.4, 6.7, and 4.4% respectively. The thermal system performance (%) is shown in Figure 4, and for more understanding the results of exergy analysis and the diagram of energy and exergy balance for each system is presented in the APPENDIX.

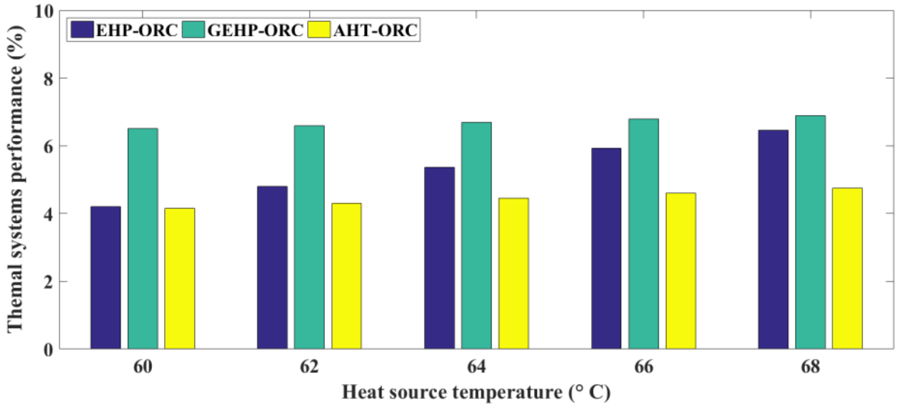

Figure 4. Thermal system performance (%) of three systems.

Economic assessment

Lifetime cost of the systems

The cost incurred throughout the lifetime of the system can be calculated from the summation of the investment cost, the operation & maintenance cost, and the fuel cost of the systems. In terms of the investment cost of heat boosting technologies per capacity, the AHTs has the highest at 641 USD/kW$_{th}$, whereas the GEHPs and the EHPs have 326, and 261 USD/kW$_{th}$, respectively (BSC Incorporated, 2008). In terms of the operation & maintenance cost, the same trend repeats with AHTs incurring the highest cost followed by GEHPs and EHPs. Finally, in terms of the fuel cost, only GEHPs is considered since it is driven by gas-fuel (Natural Gas (NG)) and uses an internal combustion engine.

From the above mentioned, when the temperature of heat source is 60 °C, the cost throughout the lifetime of these three systems are illustrated in Figure 5. The lifetime cost of the GEHP-ORC system is the highest at around at 413×10^3 USD due to the high fuel cost of GEHPs, followed by AHT-ORC and EHP-ORC systems with 270×10^3, and 166×10^3 USD of expenses respectively. It may be noted that the lifetime cost of the GEHP-ORC is 1.5 and 2.5 times higher than that of the AHT-ORC system and the EHP-ORC system, respectively. Moreover, the lifetime cost of the AHT-ORC system was 1.6 times higher than that of the EHP-ORC system. According to these results, it is conclusive that the EHP-ORC system stands out as the best candidate in terms of cost throughout the lifetime of the systems.

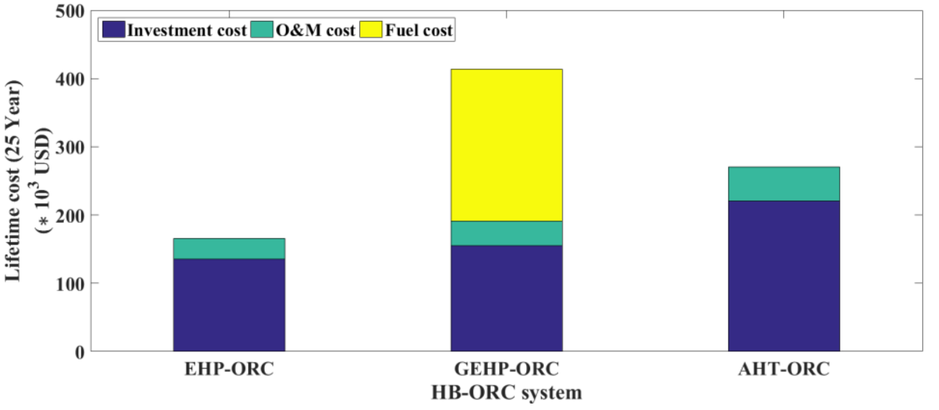

Figure 5. Costs throughout the lifetime of three systems.

The Levelized Cost Of Electricity (LCOE) of the system

The LCOE was selected to represent the economic results of the ORC power generation combined with three different heat boosters. Table 6 illustrates the LCOE of three systems, when the heat source temperature increases. The analysis revealed that when the temperature of the heat source is 60 °C, the LCOE of the AHT-ORC system is the lowest at 0.068 USD/kWh, due to the high net power output and moderate cost throughout the lifetime of the system. On the other hand, the EHP-ORC and GEHP-ORC LCOE are 0.084, and 0.101 USD/kWh, respectively. Although the net power output of the GEHP-ORC system is higher than that of the EHP-ORC system, the lifetime operation cost of the GEHP-ORC system is still very high which in turn impacts the LCOE.

Table 6. The Levelized Cost Of Electricity (LCOE) of three systems.

Heat source (°C)	**LCOE (USD/kWh)**					
	EHP-ORC		**GEHP-ORC**		**AHT-ORC**	
	ORC cost[A]	**ORC cost[B]**	**ORC cost[A]**	**ORC cost[B]**	**ORC cost[A]**	**ORC cost[B]**
60	0.084	0.070	0.101	0.094	0.068	0.061
62	0.069	0.058	0.090	0.083	0.069	0.062
64	0.059	0.050	0.079	0.073	0.069	0.062
66	0.052	0.043	0.069	0.062	0.069	0.062
68	0.046	0.039	0.058	0.052	0.070	0.063

ORC cost[A]; Cost of the ORC power plant: 2,500 USD/ kW_e
ORC cost[B]; Cost of the ORC power plant: 1,500 USD/ kW_e

Considering the effect of the cost of the ORC power plant, if the cost were in the order of 1,500 USD/kW_e for a 20 kW_e while keeping the other costs the same, and assuming a 60 °C heat source temperature, the LCOE for the EHP-ORC, the GEHP-ORC, and the AHT-ORC systems would be of 0.070, 0.094, and 0.061 USD/kWh. Table 6 also shows values for other temperatures. It can be noted that the cost of the ORC system has a moderate impact on the LCOE; and therefore the economic results improve when it decreases.

Environment assessment

To estimate CO_2 emissions in this study, the carbon dioxide intensity of electricity in Thailand is used. This value is calculated from the amount of fuel energy, such as Natural Gas (NG), Oil, and Coal/Lignite, that an electricity generation power plant requires in Thailand. In terms of the environmental impact, carbon dioxide intensity of electricity is referenced at 0.548 kg CO_2 eq./kWh (EPPO, 2015) for CO_2 reduction of the three systems.

The capability to reduce CO_2 emissions of the system depends on the amount of the electricity that the system can generate and its energy consumption. Then, based on net power output and energy consumption of the system, in term of the environmental impact the results indicates that the tendency of CO_2 reduction of the three systems increases when the heat source temperature increases. These results are shown in Figure 6. The AHT-ORC system has the highest potential to reduce CO_2 emission because of the low energy consumption in the system, followed by the EHP-ORC system, and the GEHP-ORC system. For instance, when the temperature of heat source is around 60 °C, the AHT-ORC, the EHP-ORC, and the GEHP-ORC systems reduce the CO_2 emissions in the order of 87.1, 43.4, and 20.7 Ton CO_2 eq./Year, respectively.

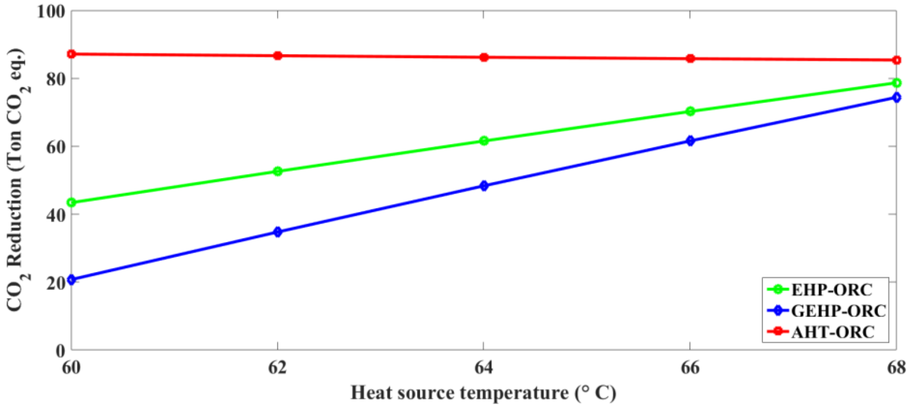

Figure 6. Effect of the heat source temperature (°C) on the CO_2 reduction (Ton CO_2 eq).

Foot print of the heat boosting technologies

Dimension, installation, operation, and maintenance of the three different heat boosting technologies are taken into consideration. The data specification of each technology is shown in Table 7. The commercial products for these three heat boosting technologies are shown in Figure 7. The study finds that the EHPs has the smallest foot print per heat capacity compared to that of the GEHPs and the AHTs. The EHPs is compact for combination/integration, easy installation, and simply operation & maintenance. Moreover, the AHTs is more appropriate for large-scale waste heat recovery, because it needs more energy or heat sources to supply the system. On the other hand, an industrial installation that already uses fuel-gas in some of its equipment, would benefit more from GEHPs, since the infrastructure can easily accommodate it.

Table 7. Data specification of three different heat boosting technologies (Mitsubishi Heavy Industries, 2016; Ilios, 2016; Hope Deepblue, 2016).

Company	Model	Heat Capacity [kW_{th}]	Size [mm]			Total weight [Ton]	Foot print [kW_{th}/m^2]
			Length	Width	Height		
Electrical Heat Pump system (EHPs)							
Mitsubishi Heavy Industries, Ltd.	ETW-L	545	1550	1200	2065	2.7	293.01
Gas Engine-Driven Heat Pump system (GEHPs)							
Ilios dynamics	HEWH-500-WS	220	1524	914.4	1829	1.6	157.87
Absorption Heat Transformer system (AHTs)							
Hope Deepblue Air-conditioner Manufacture Co., Ltd	RB II58	580	3480	1655	2100	6.4	100.70

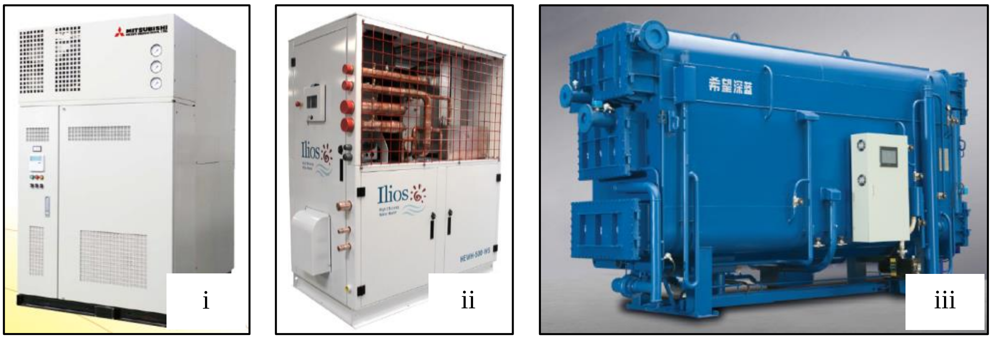

Figure 7. Heat boosting technologies,
(i) Electrical heat pump system (Mitsubishi Heavy Industries, 2016),
(ii) Gas engine-driven heat pump system (Ilios, 2016),
(iii) Absorption heat transformer system (Hope Deepblue, 2016).

Effect of the heat source temperature

From the above results, it can be concluded that the heat source temperature has significant effect on the net power output and energy consumption, the economic, and the environmental impact of the system. However, when the three systems are compared, and focusing on the systems lifetime cost and the foot print of the heat boosting technologies, the results point out that, the EHP-ORC system is the most appropriate because of its lowest the cost throughout the lifetime, compactness, easy installation, and simple operation & maintenance.

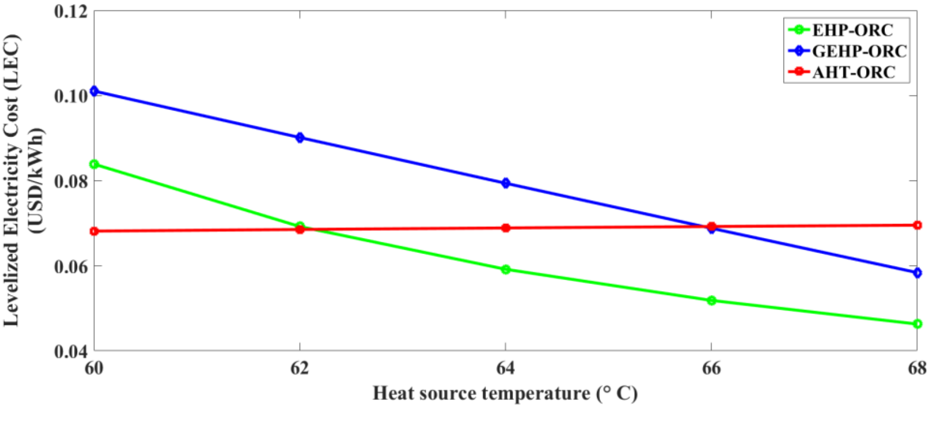

Figure 8. Effect of the heat source temperature (°C)
on the Levelized Cost Of Electricity (LCOE).

Moreover, when considering the results of the LCOE of the system, the EHP-ORC system was the most appropriate when the temperature of heat source is around 63 °C. Figure 8 shows the effect of the heat source temperature (°C) on the LCOE. The study suggests that when the heat sources temperature increases, the LCOE of the EHP-ORC and the GEHP-ORC systems follow a downward trend. If the temperature of heat source is 63 °C, then the LCOE of the EHP-ORC system is the lowest at 0.065

USD/kWh. Whereas, the LCOE of the GEHP-ORC and AHT-ORC systems are 0.086, and 0.066, respectively.

CONCLUSION

In this research, a concept for an ORC power generation from low-grade industrial waste heat with temperature below 70 °C, combined with heat boosting technologies, was investigated. Three technologies consisting of Electrical heat pump system (EHPs), Gas engine-driven heat pump system (GEHPs), and Absorption heat transformer system (AHTs) were compared in their capacity to rise the low-temperature heat source to the high-temperature heat sink/heat reservoir. The system was mathematically modeled and simulated to evaluate the net power output, the environmental impact, and the LCOE of the system. The conclusions are as follows:

- The ORC power generation combined with the proposed heat boosters is applicable for below 70 °C heat source, which is available in large quantities from industrial processes. Moreover, it is a technically feasible solution for power generation from low-grade industrial waste heat recovery, which otherwise is wasted on releasing into the environment.
- This technique may enable the industrial sector to reduce operating cost of the facilities by increasing their energy productivity, as well as help to reduce pollution (greenhouse gas emissions (GHG), and thermal pollution).
- For the heat boosting technologies: the EHPs is more appropriate when compared with the GEHPs and the AHTs, because of its compactness, easy to installation, and simple operation & maintenance.

In future works, the development of a dynamic model of an ORC power generator combined with heat bosting technologies should lead to a better understanding and improvement of this system, and could also allow it to be adapted to exploit other heat sources such as solar, geothermal, and biomass.

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APPENDIX

Comparisons of energy and exergy balance of three systems

In this part, energy and exergy balance of three systems: the EHP-ORC, the GEHP-ORC, and the AHT-ORC systems are compared as shown in Figure 9 to Figure 11, respectively. These figures offer a more detailed explanation on how the results were calculated for thermal systems performance. The input data for simulation are provided in the Table 1 to Table 3, and exergy rate from heat transfer is calculated from Ex = $\dot{Q}_H(1 - T_{Amb}/T_H)$. For the calculation, we know the exergy of electrical energy, because it can be completely converted into work. In addition, the exergy of thermal energy can be calculated given the temperature of heat source and heat sink/heat reservoir. Finally, the exergy loss can be estimated because the energy input and output are the same.

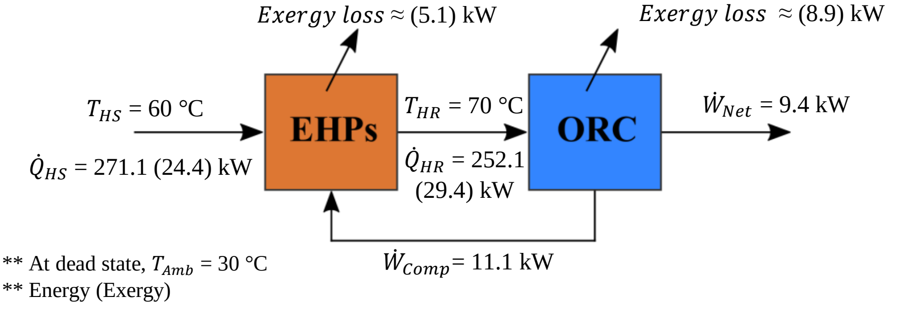

Figure 9. Energy and exergy balance of the EHP-ORC system.

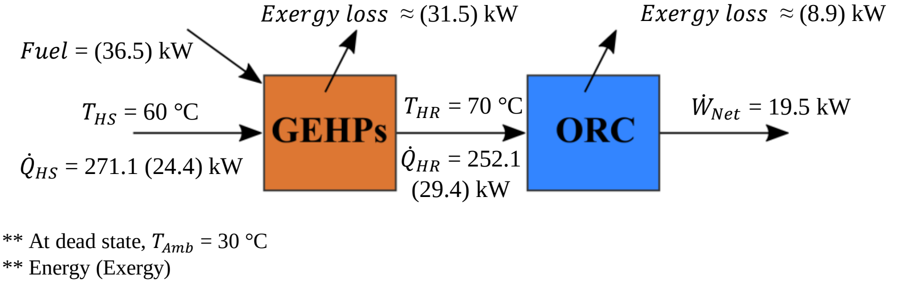

Figure 10. Energy and exergy balance of the GEHP-ORC system.

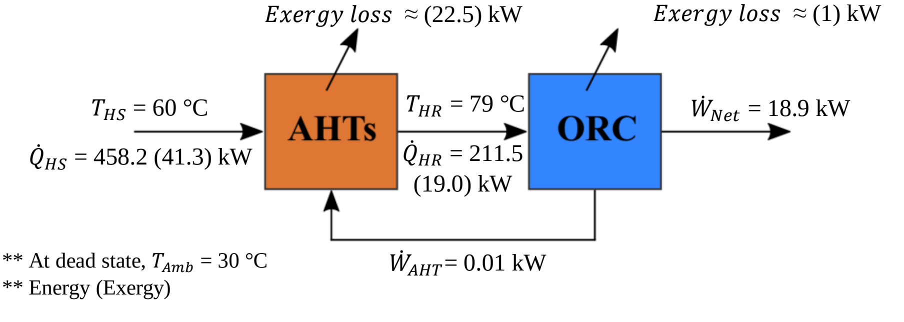

Figure 11. Energy and exergy balance of the AHT-ORC system.