Application of Low-Grade Industrial Waste Heat for Power Generation Using Organic Rankine Cycle Power Generator Combined with Gas Engine-Driven Heat Pump

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Abstract
This paper presents a power generation using Organic Rankine Cycle (ORC) power generation combined with Gas Engine-Driven Heat Pump (GEHP) by utilizing the low-grade industrial waste heat. In addition, the GEHP is used to upgrade the heat with temperature below 70 °C before supplying to a 20 kW_e ORC power generator. In this study, the GEHP-ORC system is mathematically modeled and simulated in order to evaluate the economics and the environmental impact of the system. The simulated results showed that as the system consumed the 60 °C waste heat for power generation, in term of the economic analysis, the levelized electricity cost (LEC), and the payback period were 0.095 USD/kWh, and 18.7 Year, respectively. In term of the environmental impact, the system could reduce CO_2 emission around at 22.8 Ton CO_2 eq./Year. From this study, it can be concluded that the GEHP-ORC system is applicable for an industry with low-temperature waste heat. This heat can generate more income back to the industry. However, the payback period is normally long for a renewable energy technology. Thus, a subsidy from the government is in need.

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

Introduction

Energy is primarily significant for the living and economic development. From international Energy Outlook published by EIA, the world's total energy consumption increased from 403×10^{15} Btu in 2001 to 524.00×10^{15} Btu in 2010 [U.S. Energy Information Agency,2004; U.S. Energy Information Agency, 2013]. In addition, the industrial sector consumed more energy than any other end-use sectors (e.g., building sector, and transportation sector). It is also considered as one half of the world's total energy consumption. In industry processes, there is approximately 20 to 50 percent of energy inputs wasted and released into the environment [U.S. Departement of Energy, 2006; BSC, Incorporated, 2008]. Unfortunately, the wasted has the lower temperature than 230 °C and cannot directly be converted into electricity by steam Rankine cycle because this type of the cycle become less profitable at low-temperature below 340 °C [BSC, Incorporated, 2008]. However, it is still productive for power generation by employing the Organic Rankine Cycle (ORC) [Quoilin, S. et al., 2013; Bonilla, J.J. et al., 1997; Bao, J. J. et al., 2011].

Recently, there are many researchers working on the design, analysis, and development of the ORC system for low-temperature waste heat conversion. Le, V. L. et al., (2014) carried out the Exergy efficiency and Levelized Cost of Electricity (LCOE) optimizations of a waste heat to power plant driven by subcritical ORC using a pure or zeotropic mixture working fluid. Tchanche, B.F., (2011) showed that business of an Organic Rankine Cycles (ORCs) for waste heat recovery (ORC-WHR) application grow faster among ORC solution, with an enormous potential in industry and combined cycle power plant. Liu, H. et al., (2015) designed and modified a hybrid energy supply system, including the gas engine-driven heat pump system and ORC using the gas engine waste heat as low-grade heat source in order to transfer the low-grade gas engine waste heat into high-grade electricity by ORC. Chaiyat, N. (2014) proposed a concept to generate electricity from low-temperature heat by using an absorption heat transformer (AHT) coupled with an ORC.

From the literature review, it was found that the ORC power generation systems were generally supplied by heat sources having the temperature above 70 °C [Tchanche, B.F. et al., 2014; Quoilin, s. et al., 2013]. However, the system is less applicable with the below 70 °C heat source, having a large amount from the industrial process. If the ORC system is applied for power generation at below 70 °C heat source, the industrial sectors could benefit from this waste heat and save money from energy consumption, as well as reduce operation cost, and pollution (greenhouse gas emission, and thermal pollution). Upgrading the low-temperature heat to the high-temperature is an interesting approach for ORC power generation. In this research, the objective is to propose the concept of upgrading the low-grade industrial waste heat with the temperature below 70 °C by Gas Engine-driven Heat Pump (GEHP) and producing the electricity by Organic Rankine Cycle (ORC). The Gas Engine-driven Heat Pump integrated with Organic Rankine Cycle (GEHP-ORC) system is mathematically modeled and simulated in order to evaluate the economics and the environmental impact of the system.

Industrial Waste Heat

Industrial waste heat is the unusable heat generated from a combustion in industrial processes, and then directly exhausted to the environment. From the research publication of BSC, Incorporated, it was reported that the quantity of industrial waste heat was as much as 20 to 50% of industrial energy consumption [BSC, Incorporated, 2008]. Moreover, the exhausted gases are mostly at relatively high-temperature while water streams are mostly liquids at low-temperature [Bonilla, J.J. et al., 1997].

Waste heat sources from industries can be classified in 3 different temperature levels as low temperature (< 230 °C), medium temperature (230 – 650 °C), and high temperature (> 650 °C). This temperature classification of industrial waste heat sources with typical recovery method is listed in Table 1 [BSC, Incorporate, 2008]. From the list, none of available technologies can recovery the heat with temperature below 70 °C heat source. Thus, this source of heat will become more beneficial and interesting for industrial sectors.

Table 1: Temperature classification of industrial waste heat sources with typical recovery methods [BSC, Incorporate, 2008].

Categories	Example sources	Temperature (°C)	Typical Recovery Methods / Technologies
High	Nickel refining furnace	1,370 – 1,650	Combustion air preheater
[>650 °C]	Steel electric arc furnace	1,370 – 1,650	
	Basic oxygen furnace	1,200	Steam generation for process
	Aluminum reverberatory furnace	1,100 – 1,200	heating or for mechanical /
	Copper refining furnace	760 – 820	electrical work
	Steel heating furnace	930 – 1,040	
	Copper reverberatory furnace	900 – 1,090	Transfer to med-low
	Hydrogen plants	650 – 1,430	temperature processes
	Fume incinerators	1,300 – 1,540	
	Coke oven	650 – 1,000	
	Iron cupola	820 – 980	
Medium	Steam boiler exhaust	230 – 480	Combustion air preheat
[230 - 650 °C]	Gas turbine exhaust	370 – 540	Steam / power generation
	Reciprocating engine exhaust	320 – 590	Organic Rankine cycle for
	Heat treating furnace	430 – 650	power generation
	Drying & baking ovens	230 – 590	Furnace load preheating,
	Cement kilin	450 – 620	feedwater preheating
			Transfer to low-temperature processes
Low	Exhaust gases exiting recovery	70 – 230	Space heating
[<230 °C]	Devices in gas-fired boilers,		
	Ethylene furnaces, etc.		Domestic water heating
	Process steam condensate	50 – 90	
	Cooling water from:		Upgrading via a heat pump to
	Furnace doors	30 – 50	Increase temp for end use
	Annealing furnaces	70 – 230	Organic Rankine Cycle
	Air compressors	30 – 50	
	Internal combustion engines	70 – 120	
	Air conditioning and	30 – 40	
	Refrigeration condensers		
	Drying, baking, and curing ovens		
	Hot processed liquids/solids		

Mathematical Modeling of Organic Rankine Cycle combined with Gas Engine-driven Heat Pump (GEHP-ORC)

In this research work, an Organic Rankine Cycle power generation system combined with Gas Engine-driven Heat Pump (GEHP) is proposed and named as GEHP-ORC system as shown in Figure 1. As the concept of this system, a waste heat from industries is stored in the heat source/thermal storage tank 1. This heat is then upgraded by GEHP to high-temperature heat. Then the heat is stored in the heat reservoir/thermal storage tank 2. After that, a high-temperature thermal energy in the heat reservoir/thermal storage tank 2 is supplied to the ORC system to generate electricity.

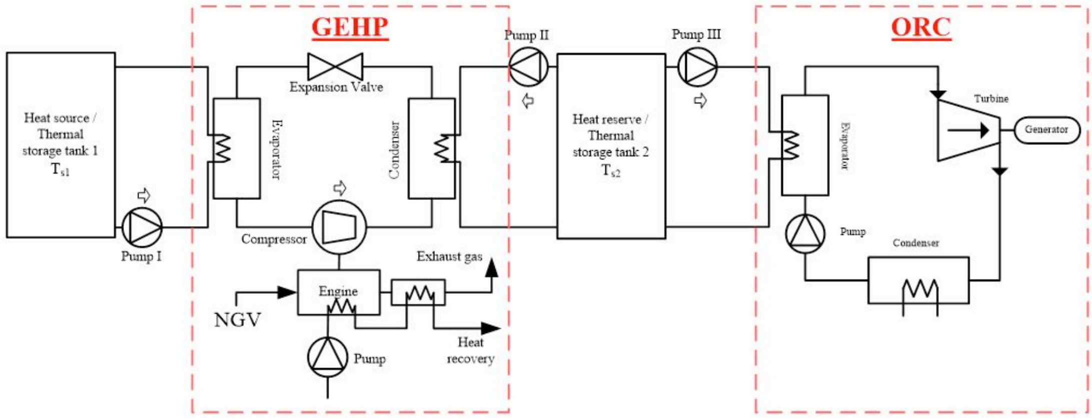

Figure 1: Schematic diagram of the proposed systems (GEHP-ORC system).

Conventional Organic Rankine Cycle system (ORCs)

Organic Rankine Cycle system (ORCs) is an alternative technology applicable for small-scale power generation. It is used for low-temperature heat recovery, by converting low-temperature thermal energy to electricity. Moreover, its operation is similar to that of the steam Rankine cycle but an organic working fluid is used instead of water.

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

A schematic diagram of the conventional ORC system and the corresponding T-s diagram are shown in Figure 2 and Figure 3, respectively. A low-temperature heat transfer fluid (HTF) of the ORC system is heated by the stored heat in the heat source/thermal storage tank 1 via a heat exchanger (state 2). Then, the HTF is at saturated organic fluid vapor state with high pressure through an evaporator (from state 2 to state 3). Then the vapor is expanded through a turbine to generate power (from state 3 to state 4). Finally, it is condensed to a saturated liquid (state 1) in the condenser to complete the cycle.

The energy equations of the ORC system are summarized as follows.
The rate of heat transfer to the ORC evaporator:

$$\dot{Q}_{Evap,ORC} = \dot{m}_{r,ORC}(h_3 - h_{2a}) = (mc_p)_w(T_{w,i} - T_{w,o}) \quad (1)$$

The power output from the turbine:

$$\dot{W}_{Tur,th} = \dot{m}_{r,ORC}(h_3 - h_4)\eta_{Tur,s} \quad (2)$$
$$\dot{W}_{Tur,el} = \dot{m}_{r,ORC}(h_3 - h_4)\eta_{Tur,s}\eta_{Tur,ME} \quad (3)$$

$$\eta_{Tur,s} = (h_3 - h_{4a})/(h_3 - h_4) \tag{4}$$

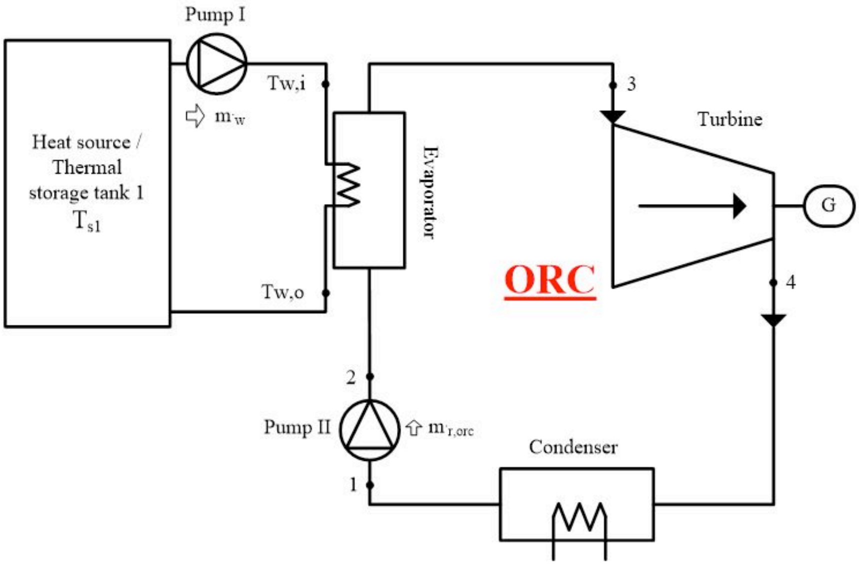

Figure 2: Schematic diagram of the conventional ORC system.

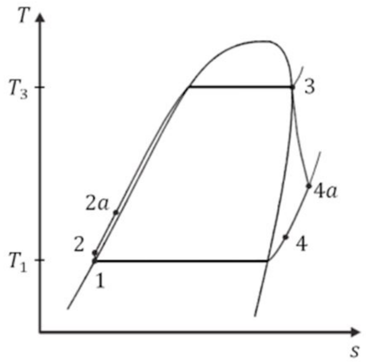

Figure 3: T-s diagram of the conventional ORC system.

The rate of heat transfer removal from the ORC condenser:

$$\dot{Q}_{Cond,ORC} = \dot{m}_{r,ORC}(h_{4a} - h_1) \tag{5}$$

The power input to the ORC pump:

$$\dot{W}_{P,ORC,th} = \dot{m}_{r,ORC}v_1(P_2 - P_1)/\eta_{P,s} = \dot{m}_{r,ORC}(h_{2a} - h_1) \tag{6}$$

$$\dot{W}_{P,ORC,el} = \dot{W}_{P,ORC,th}/(\eta_{P,ME}\eta_{P,MO}) \tag{7}$$

$$\eta_{P,s} = (h_2 - h_1)/(h_{2a} - h_1) \tag{8}$$

The thermal efficiency of the ORC system:

$$\eta_{ORC} = (\dot{W}_{Tur,th} - \dot{W}_{P,ORC,th})/\dot{Q}_{Evap,ORC} \tag{9}$$

Gas Engine-driven Heat Pump system (GEHP)

The Gas Engine-driven Heat Pump system (GEHP) is a vapor compression refrigeration type with an open compressor. It is driven by gas-fuel (i.e. Natural Gas (NG), Liquid Petroleum Gas (LPG)) internal combustion engine instead of an electrical motor. The GEHP mainly consists of two parts: (i) heat pump consisting of compressor, condenser, expansion valve, and evaporator, and (ii) gas engine system to drive the compressor. A schematic diagram of the GEHP system and corresponding T-s diagram are shown in Figure 4 and Figure 5, respectively.

A low-temperature HTF of the GEHP system is heated by the stored heat in the heat source/thermal storage tank 1 via a heat exchanger (state 1). Then, the HTF is compressed in the compressor to increase its temperature and pressure (state 2). The high-temperature HTF is condensed by releasing the heat at the condenser. The released heat is stored in the heat reservoir/thermal storage tank 2 via a heat exchanger. After that, the HTF (state 3) enters a capillary tube where its pressure and temperature drop drastically due to throttling effect. Finally, the low-temperature HTF enters the evaporator (state 4) to restart next cycle.

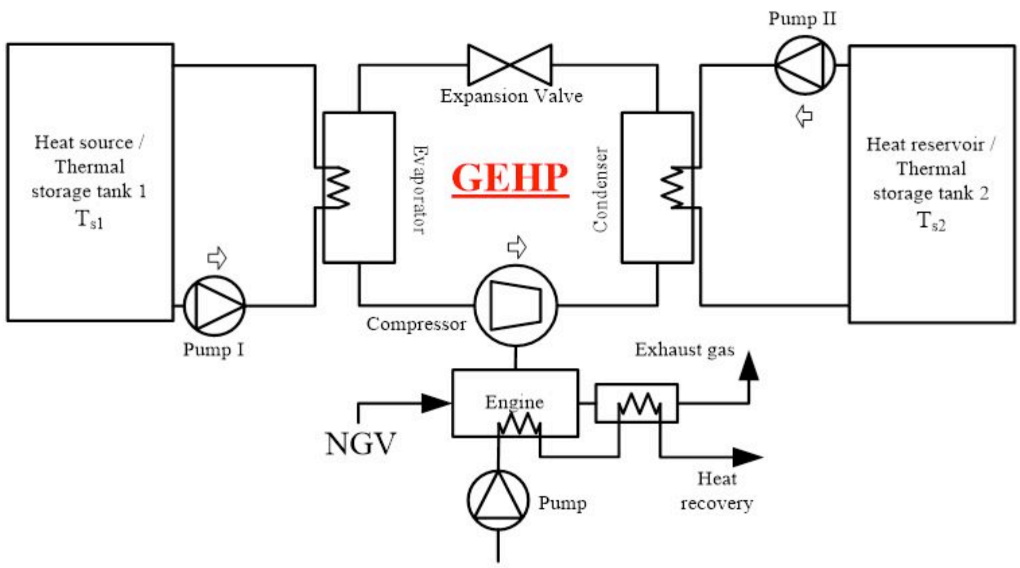

Figure 4: Schematic diagram of the GEHP system.

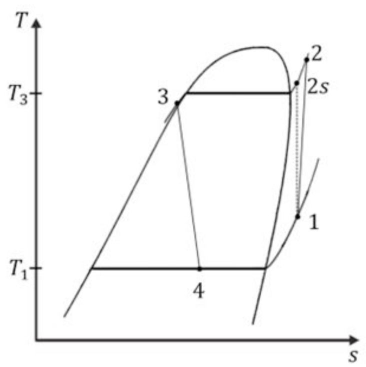

Figure 5: T-s diagram of the GEHP system.

The energy equations of the GEHP system are summarized as follows.
The rate of heat transfer to the GEHP evaporator:

$$\dot{Q}_{Evap,GEHP} = \dot{m}_{r,GEHP}(h_1 - h_4) = (mc_p)_{w1}(T_{w1,i} - T_{w1,o}) \tag{10}$$

The rate of heat transfer to the GEHP condenser:

$$\dot{Q}_{Cond,GEHP} = \dot{m}_{r,GEHP}(h_2 - h_3) = (mc_p)_{w1}(T_{w2,o} - T_{w2,i}) \tag{11}$$

The work input to the GEHP system:

$$\dot{W}_{Comp,GEHP,th} = \dot{Q}_{Cond,GEHP} - \dot{Q}_{Evap,GEHP} = \dot{m}_{r,GEHP}(h_2 - h_1) \tag{12}$$
$$H_{Comp,GEHP,s} = (h_{2s} - h_1)/(h_2 - h_1) \tag{13}$$

Gas engine power consumption:

$$\dot{W}_{Comp,GEHP,th} = \dot{W}_{ge,i}\eta_{ME,GEHP}\eta_{belt} \tag{14}$$

Gas engine thermal efficiency:

$$\eta_{ge,th} = \dot{W}_{ge,i}/\dot{Q}_{in,GEHP} = \dot{W}_{ge,i}/(\dot{m}_{fuel}q_{LHV}\eta_{comb}) \tag{15}$$

Fuel mass flow rate:

$$\dot{m}_{fuel} = \dot{W}_{ge,i}/(\eta_{comb}\eta_{th}q_{LHV}) = \dot{W}_{Comp,GEHP,th}/(\eta_{comb}\eta_{MO}\eta_{belt}\eta_{th}q_{LHV}) \tag{16}$$

Coefficient of performance of the GEHP system:

$$COP_{GEHP} = \dot{Q}_{Cond,GEHP}/\dot{Q}_{in,GEHP} \tag{17}$$

Thermal Storage tank
The water temperature in the thermal storage tank, can be estimated from a lumped model by considering that the thermal storage tank is non-stratified [Kiatsiriroat, T. et al., 1998]:

$$(T_w)^{t+\Delta t} = (T_w)^t + (\Delta t/(Mc_p))(\text{Heat Input} - \text{Heat Output} - \text{Heat Loss}) \tag{18}$$

System conditions

The GEHP-ORC system was mathematically modeled based on steady state condition. The pressure drop was neglected except in the turbine and the pump of an ORC system. Heat loss of system components such as the evaporator, the condenser, the generator, and the piping system was neglected. The temperature inside the thermal storage tank of the system was assumed to be uniform and non-stratified. Initial conditions of the system are shown in Table 2 and Table 3.

In the simulation, the low-grade industrial waste heat as a heat source/thermal storage tank 1 was varied from 60 to 68 °C, and heat reservoir/thermal storage tank 2 was set at 70 °C. The degree of superheating, subcooling and the pinch-point temperature difference was set at 5.0 °C. In addition, heat exchanger effectiveness (ε) was assumed to be 90%. The thermodynamic properties of the GEHP system and the ORC system were calculated by REFPROP NIST7.0 [National Institute of Standard and Technology (NIST)., 2000]. From the above mentioned, the calculation steps of the GEHP-ORC system is shown in Figure 6.

Table 2: Initial condition of the GEHP system.

Descriptions	Data
Gas engine mechanical efficiency ($\eta_{ge,ME}$) [%]	82.0
Gas engine combustion efficiency ($\eta_{ge,comb}$) [%]	95.0
Efficiency of power transmission (η_{belt}) [%]	95.0
Gas engine thermal efficiency ($\eta_{ge,th}$) [%]	35.0
Fuel lower heating value (q_{LHV}) of the Natural Gas (NG) [kJ/kg]	47141
HP capacity [kWth]	250
Working fluid of HP system	R365mfc

Table 3: Initial condition of the conventional ORC system.

Descriptions	Data
Cycle power (W_{ORC}) [kW_e]	20.0
Isentropic turbine efficiency ($\eta_{Tur,s}$) [%]	85.0
Mechanical turbine efficiency ($\eta_{Tur,ME}$) [%]	90.0
Isentropic pump efficiency ($\eta_{P,s}$) [%]	85.0
Mechanical pump efficiency ($\eta_{P,ME}$) [%]	95.0
Motor pump efficiency ($\eta_{P,MO}$) [%]	95.0
ORC condenser temperature [°C]	30.0
Working fluid of the ORC system	R245fa

Economic analysis

The economic analysis was carried out in term of the payback period and the levelized electricity cost (LEC). The initial conditions and cost data used for the economic evaluation of the GEHP-ORC system is shown in Table 4, which could be calculated by

Payback Period:

Payback Period = (Initial investment cost)/(Cash inflow per period) (19)

Levelized Electricity Cost (LEC):

LEC = (Investment cost + O&M cost×N + Fuel cost×N)/(Net power output×N) (20)

Capital costs of the ORC power plant, the present cost of the ORC power plant varies between 2,500 – 3,000 USD/kW_e. A micro scale of the ORC power plant at capacity lower than 50 kW_e is around 2,500 USD/kW_e [Chaiyat, N., & Kiatsiriroat, T., 2015]. According to the information, 2,500 USD/kW_e for a 20 kW_e power plant was used in this study.

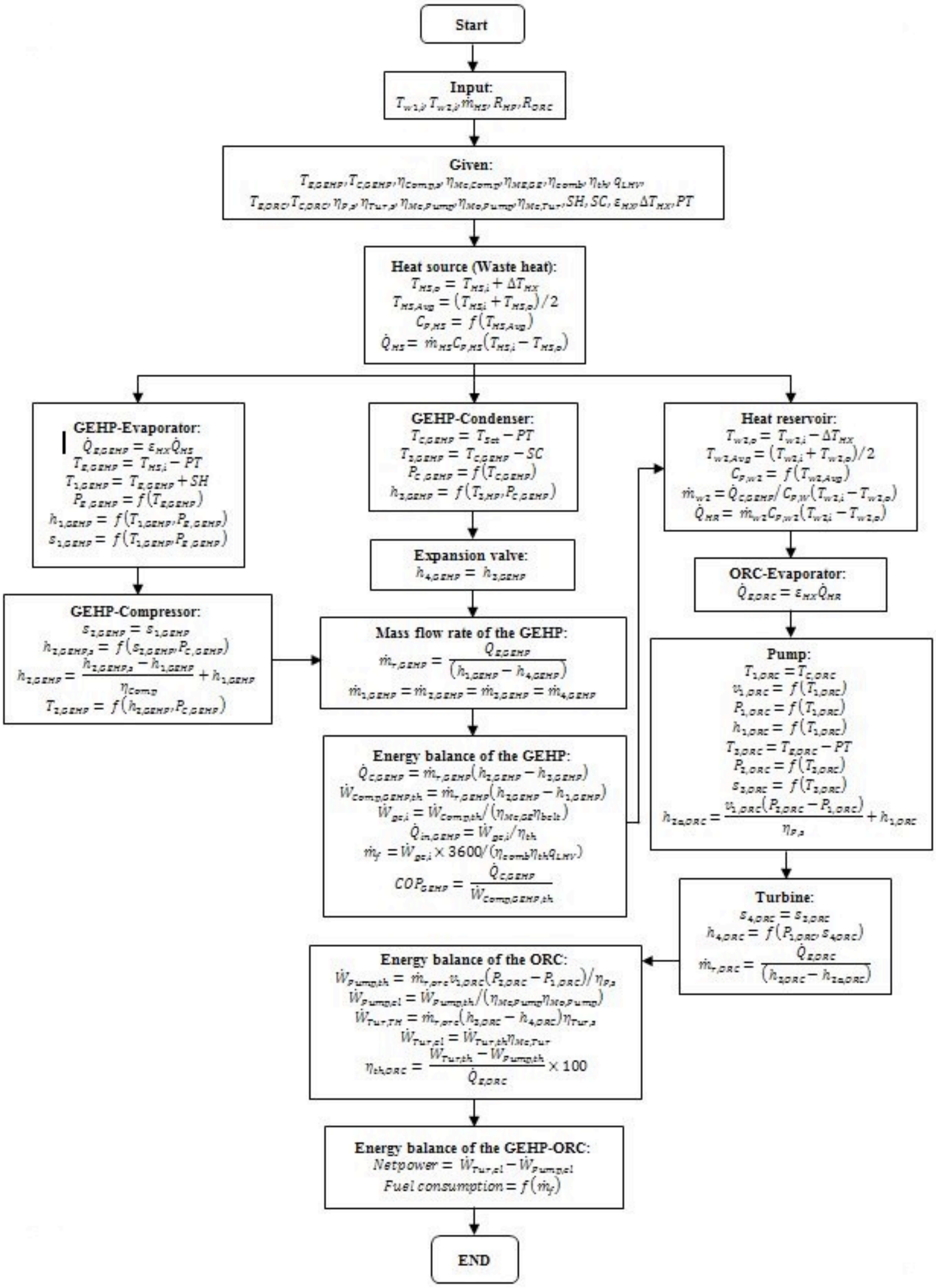

Figure 6: Calculation steps of the GEHP-ORC system.

Table 4: Initial condition, and cost data used for the economic evaluation of the GEHP-ORC system.

Descriptions	Data
Condition	
Operation time [h/d]	24
Operation day [d/y]	350
Investment cost	
Electricity cost [USD/kW_e]	0.108
Gas Engine Heat Pump (GEHP) [USD/kW_{th}]	326
Cost of the NGV [USD/kg]	0.37
Surcharge for construction and engineering [%]	10.0
Operating & maintenance (O&M) cost	
Operating & maintenance cost (% of investment cost per year)	0.5
Life time of plant [year, N]	25

Result and discussion

The net power output, levelized electricity cost (LEC), the payback period, and CO_2 reduction of the GEHP-ORC system when using the low-grade industrial waste heat were estimated based on the developed mathematical modeling. The results are shown as follows:

Net power output

The net power output and electrical consumption of the GEHP-ORC system, when the temperature of heat source increases from 60 to 68 °C, are constant approximately at 147, and 0.012 MWh/Year, respectively. However, the fuel consumption (Ton of NGV/Year) of the system has the downward trend when the temperature of heat source increases. Figure 7 shows the effect of a change in the heat source temperature (°C) on the fuel consumption (Ton of NGV/Year) of the system. The result found that when the temperature of heat source increases from 60 to 68 °C; the fuel consumption of the system was 20.3, 16.1, 12.0, 7.91, and 3.9 Ton of NGV/Year, respectively.

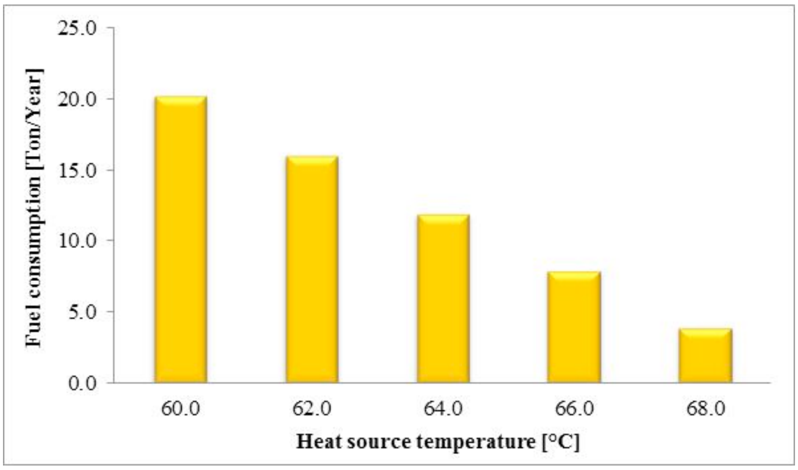

Figure 7: Effect of a change in the heat source temperature (°C) on the fuel consumption (Ton of NGV/Year).

Economic result

The levelized electricity cost (LEC) and the payback period of the GEHP-ORC system was found that when the temperature of heat source is 60 °C, the LEC and the payback period of the system were 0.095 USD/kWh, and 18.7 Year, respectively.

Moreover, the investment of the ORC power plant has an effect on the LEC and the payback period of the GEHP-ORC system. For instance, if the cost of the ORC power plant was set at 1,500 USD/kW_e for a 20 kW_e ORC power plant when the temperature of heat source is 60 °C, the LEC and the payback period of the system were 0.088 USD/kWh, and 15.7 Year, respectively. It can be concluded that the lower investment of the system is, the shorter of the payback period become.

Environment assessment

For environmental impact, carbon dioxide intensity of electricity of Thailand [Energy Policy and Planning, Thailand, 2015] at 0.548 kg CO_2 eq./kWh was used to estimate the CO_2 reduction of the GEHP-ORC system. Figure 8 shows the effect of a change in the heat source temperature (°C) on the CO_2 reduction (Ton CO_2 eq./Year) of the system. The result was found that the CO_2 reduction (Ton CO_2 eq./Year) of the system has the upward trend when the temperature of heat source increases. When the temperature of heat source increases from 60 to 68 °C, the system can reduce the CO_2 emission by approximately 22.8, 34.8, 46.6, 58.2, and 69.6 Ton CO_2 eq./Year, respectively.

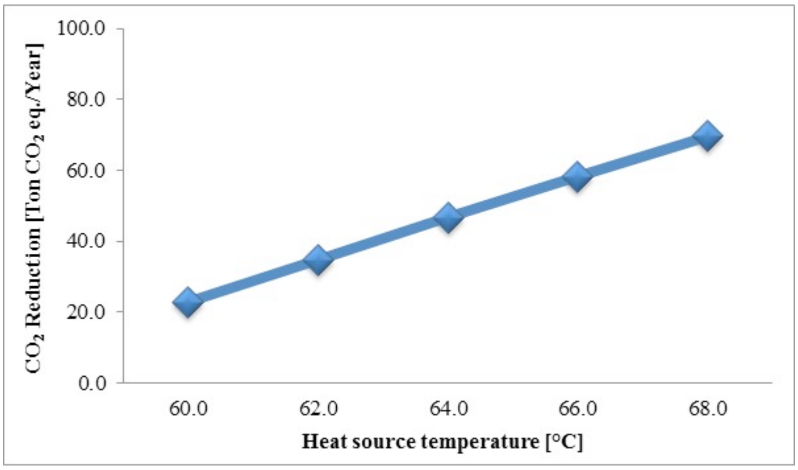

Figure 8: Effect of a change in the heat source temperature (°C) on the CO_2 reduction (Ton CO_2 eq./Year).

Effect of the heat source temperature

The heat source temperature has an effect on the economic and the environment impact. The study was found that the LEC and the payback period of the system decrease when the temperature of heat source increases. Figure 9 and Figure 10 shows the effect of the heat source temperature (°C) on the levelized electricity cost (USD/kWh), and the payback period (Year) of the system, respectively. The results were found that when the temperature of heat source increases from 60 to 68 °C, the LEC and the payback period of the system were 0.095 USD/kWh and 18.7 Year, 0.085 USD/kWh and 15.6 Year, 0.074 USD/kWh and 13.4 Year, 0.064 USD/kWh and 11.8 Year, 0.054 USD/kWh and 10.5 Year, respectively.

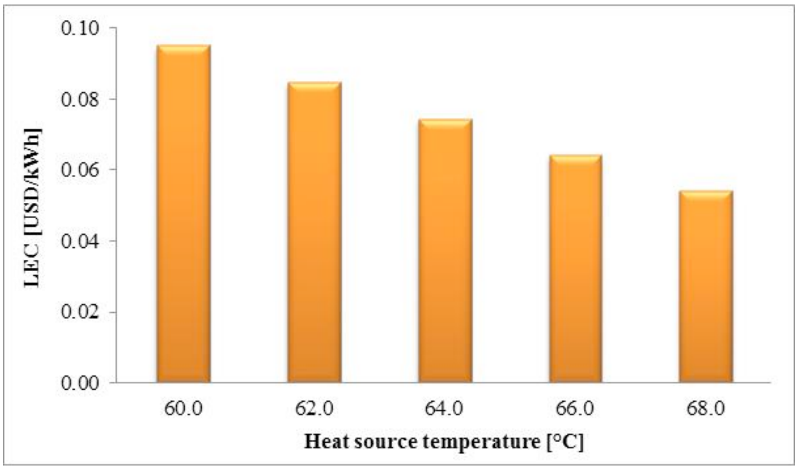

Figure 9: Effect of a change in the heat source temperature (°C) on the levelized electricity cost (LEC).

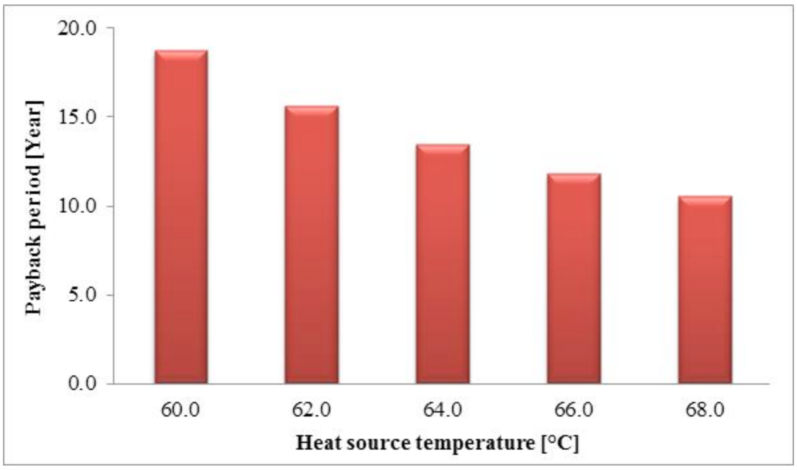

Figure 10: Effect of a change in the heat source temperature (°C) on the payback period (PB).

Conclusions

In this research, a concept of upgrading the low-grade industrial waste heat with the temperature below 70 °C by Gas Engine-driven Heat Pump (GEHP) and integrated by Organic Rankine Cycle (GEHP-ORC) for power production, was proposed and investigated. The system is mathematically modeled and simulated in order to evaluate the economics and the environmental impact of the system. The main conclusions were summarized as follows:

- The GEHP-ORC system can be applied to the low-temperature heat source for heat upgrading before supplying to the ORC power generation.

- The temperature of heat source effects on the GEHP-ORC system in term of the economic and the environmental impact. In term of the economic, the LEC and the payback period of the system have the decreasing tend when the temperature of heat source increases. In term of the environment impact, the CO_2 reduction increases when the temperature of heat source increases.

- When the temperature of heat source is at 60 °C, the levelized electricity cost (LEC) and the payback period were 0.095 USD/kWh, and 18.7 Year, respectively. The system can reduce the CO_2 emission by approximately 22.8 Ton CO_2 eq./Year. However, the payback period is normally long for a renewable energy technology. Thus, a subsidy from the government is needed.

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