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มหาวิทยาลัยศรีปทุม

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สารบัญบทความ (ต่อ)

กลุ่มย่อยที่ 4: Science, Technology, Engineering

A HYBRID SOLAR-WASTE POWER PLANT OF LUANGPRABANG

Khamxay Yangchongthuochuaya[a], Nattaporn Chaiyat[a,b,c,*]

[a] School of Renewable Energy, Maejo University, Chiang Mai, Thailand

[b] Thermal Design and Technology Laboratory (TDeT Lab), Thailand

[c] Excellence Center on Environmental Friendly Smart Agriculture and Renewable Energy Technology (ECoT), Thailand

[*] Corresponding author: benz178tii@hotmail.com

ABSTRACT

This research presents a hybrid solar-waste power generation system. The waste management problem in Luangprabang district of Lao people's democratic republic (Lao PDR) is focused based on a waste-to-energy (WtE) technology. The amount of municipal waste of Luangprabang is approximately 19,546.52 Ton in 2021. A combustible waste of 33.52% is used to be fuel (refuse derived fuel type 1, RDF-1) in combustion process of an incinerator of 21 Ton/day. The solar radiation of Luangprabang shows a lowest value of 15.43 MJ/(m^2•day) in October and a highest value of 18.09 MJ/(m^2•day) in March. A supply heat from the combined solar-waste system of 2,527 kW is used to drive an organic Rankine cycle (ORC) of 184.19 kW_e. The hybrid solar-waste system efficiency is approximately 6.62% from a net power of 135.80 kW_e. A total investment cost of 1,221,871 USD is mainly affected to a levelized energy cost (LEC) of 0.202 USD/kWh. The environmental impact in terms of carbon dioxide emission for a life span of 20 years is 1,427 Ton CO_2. The result implies that a carbon dioxide emission per functional unit (1 kWh) is approximately 0.138 kg CO_2/kWh.

Keywords: Hybrid Renewable Energy, Incinerator, Solar Water Heating System, Levelized Electricity Cost, Carbon Dioxide Emission

1. Introduction

Luangprabang district of Lao people's democratic republic (Lao PDR) is one of the cities under a united nations educational, scientific, and cultural organization (UNESCO) world heritage city since 1995 (Asian Notes, 2022). This city has advantage of a natural tourist, archaeological site, and cultural city. The tourists of approximately 755,019 in 2018 (JICA, 2021) directly effects to tourism business in Luangprabang. Tourism policy is the firstly priority in the province's economic and social development. (Zawan et al., 2017), and (Phonsongkham & Thitiluck, 2020) studied municipal solid waste (MSW) in Luangprabang. The averages MSW volume was found approximately 70 Ton/d (Development and administration of Luang Prabang, 2022). Thus, in this study, a new energy technology will be focused to solve the MSW problem in Luangprabang.

From the literature works, (Kaewmueang & Chaiyat, 2020) studied the thermal performance of small incinerator at a combustion rate of 1 Ton/d. The results showed that the R-236ea and R-245ca refrigerants were the maximum power efficiencies of 7.58% and 11.70%, respectively. (Chaiyat & Kiatsiriroat, 2015) reported a power generation system by organic Rankine cycle (ORC) combination with an absorption chiller. The enhance efficiency by using the cold water from the absorption chiller and cooling tower decreased the refrigerant temperature at condenser. The ORC efficiency could be increased 2%. (Sung & Kim, 2017) applied a low-water heat source of ORC system to be a high-steam heat source of ORC system. Steam at a temperature of 143.5°C and pressure of 302 kPa was used to test the ORC system. The testing results found that steam heat source showed without any major system changes. (Wang et al., 2019) used a thermal mathematical model to select the appropriate active substance for the ORC effectively. In addition, (Sirisamphanwong et al., 2012) reported solar energy technology from the flat-plate and vacuum-tube collectors to produce thermal energy at a high temperature level. (Chumnumwat et al., 2018) studied the costs of evacuated tube and compound parabolic concentrator solar collectors, which were higher than that of the flat plate solar collector of 153.22 USD/m^2. (Yongchalearn & Malahom, 2011) presented efficiency of a solar water heating system using flat plate solar panels, which was higher than that of a heat pipe solar collector under the low temperature conditions. In addition, environmental investigation is a hot issue at the present time. (Kantiya et al., 2018) studied the environmental impact based on carbon footprint and economic cost. Greenhouse gas emission was 36,546,216 kg CO_2-eq under a factory lifetime of 30 years. The greenhouse gas emissions per functional unit was 0.58 kg CO_2-eq/Piece. The economic cost of product was 0.05 USD/Piece. (Chusuwan et al., 2020) reported tourism industry of the Phra Mahathat Woramahawihan temple, Nakhon Si Thammarat province. Greenhouse gases from MSW to waste disposal site was focused. Open dumping was a main impact of 98% in the carbon footprint perspective.

From the above research mentioned, a novel waste-to-energy (WtE) should be investigated to solve the waste deposal in Luangprabang, Lao PDR. This district does not have the waste deposal technology. All MSWs is transported into the Landfill Site Ban Lak Ped, Luangprabang. The energy, economic, and environmental assessments are reported on an optimal WtE system under the proportional, volume, and real waste situation of Luangprabang. A hybrid technology of solar and waste renewable energies is selected to produce power from the ORC system. A mathematical model simulation is used to evaluate the thermal performance, economics cost, and environmental impact.

2. System Description

A systematic of hybrid solar-waste power plant presents in Figure 1. Water in a storage tank is supplied to a solar collector by a hot water pump at the points 1s-2s. Hot water is generated from the solar collector at the point 3s. Then, solar heat is kept in the water tank to accumulate heat combined with combustion heat from the waste energy. On the other hand, combustion heat at the point 1w-2w from waste incinerator at a temperature of approximately 1,300 °C is transferred to water through a heating tube of incinerator at the point 1HW-2HW. A hot air blower and a spray pump are designed for exhaust treatment. An incineration pump transports heat from the waste incinerator to the storage tank at point 3HW. Hot water in the storage tank is controlled by a setting temperature point of 95 °C. When, hot water temperature is higher than the setting temperature point, heat from the solar-waste heating system is pumped from the storage tank at the points 4s-5s by a useful pump to the ORC system. Hot water temperature at the point 6s reduces temperature level, and returns to receiving heat again at the storage tank. Heat exchanger is used as a boiler of the ORC system. R-245fa is selected as the ORC refrigerant. Heat from the hybrid renewable energy boils refrigerant in the boiler at the point 3. Then, vapor at a pressure higher than 10 bar gauge flows into an expander under an isentropic efficiency for generating power at a generator. A lubricant oil is used to reduce friction in the expander at the point 2O. The mixed R-245fa and oil fluid at the point 4 distinguishes in an oil and vapor separator at the points of 1O and 5, respectively. Vapor at a low pressure of approximately 2 bar gauge changes to be liquid phase in a condenser by using a cooling tower at the point 1c-2c. R-245fa in liquid phase at the point 1 is pumped to transfer heat again at the boiler. The new heat-to-power cycle is restarted.

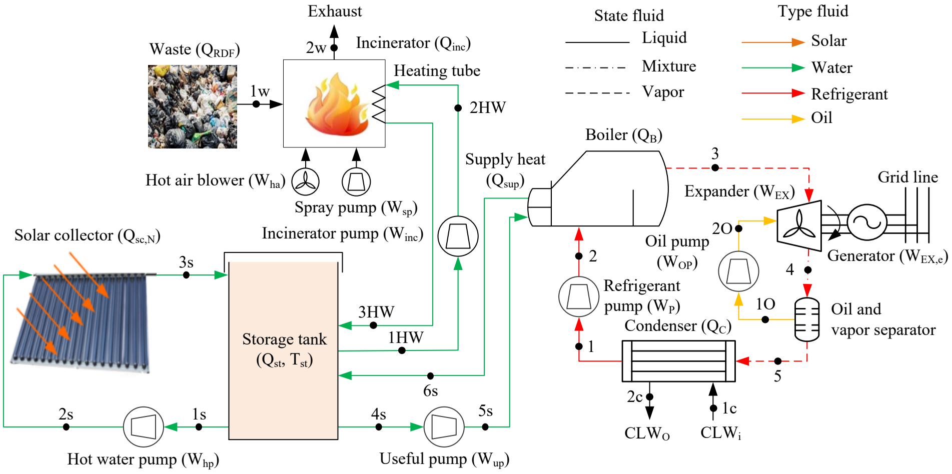


Figure 1: A schematic diagram of the hybrid solar-waste power plant

3. Methodology

3.1 Thermal performance of the novel solar-waste technology is performed. The solar thermal system is analyzed by using the solar radiation and location (longitude and latitude) of Luangprabang. In addition, this energy system is integrated by the WtE system for supporting the heat-to-power process. The amount and proportion of combustible waste of Luangprabang from the survey data are used to optimization the novel solar-waste system.

3.2 Simulation technique is selected to investigate the novel system efficiency. The operating conditions for simulation the combined solar-waste processes are described in Table 1. In addition, the mathematical model and correlation diagram depict in Figure 2.

Table 1 The operating conditions for simulation.

Condition	Value	Unit	Reference
Longitude angle (L_{loc})	102.154	°	Janjai,S. (2006)
Latitude angle (ϕ)	19.861	°	Janjai,S. (2006)
Heat removes factor ($F_R(\tau\alpha)$)	0.642	-	Schroder. (2022)
Heat loss factor (F_RU_L)	0.885	$W/(m^2 \cdot K)$	Schroder. (2022)
Heat transfer of storage tank (UA_{st})	3.000	W/K	Chaiyat & Kiatsiriroat. (2014)
Area of solar collector (A_{sc})	4.800	m^2/Unit	Schroder. (2022)
Efficiency isentropic expander ($\eta_{S,EX}$)	80	%	Yatsuntea & Chaiyat. (2019)
Efficiency isentropic turbine ($\eta_{S,tur}$)	69.20	%	Yatsuntea & Chaiyat. (2019)
Efficiency generator (η_G)	76.61	%	Chaiyat, N. (2021)
Efficiency isentropic pump ($\eta_{S,P}$)	90.44	%	Chaiyat, N. (2021)
Efficiency machine pump ($\eta_{machine,P}$)	65	%	Chaiyat, N. (2016)
Temperature inlet system ($T_{5s,i}$)	95	°C	Yatsuntea & Chaiyat. (2019)
Temperature cooling inlet condenser ($T_{CLW,i}$)	25	°C	DEP. (2011)
Difference temperature water and refrigerant (ΔT_{CW-ref})	3	°C	Yatsuntea & Chaiyat. (2019)
Difference temp water inlet and outlet ($\Delta T_{4s,6s}$)	10	°C	Yatsuntea & Chaiyat. (2019)
Superheating (SH)	9.2	°C	Yatsuntea, (2019); Chaiyat,(2019)
Subcooling (SC)	1.5	°C	Chaiyat, N. (2019)
Efficiency incinerator (η_{inc})	31.66	%	Yatsunthea & Chaiyat. (2020)

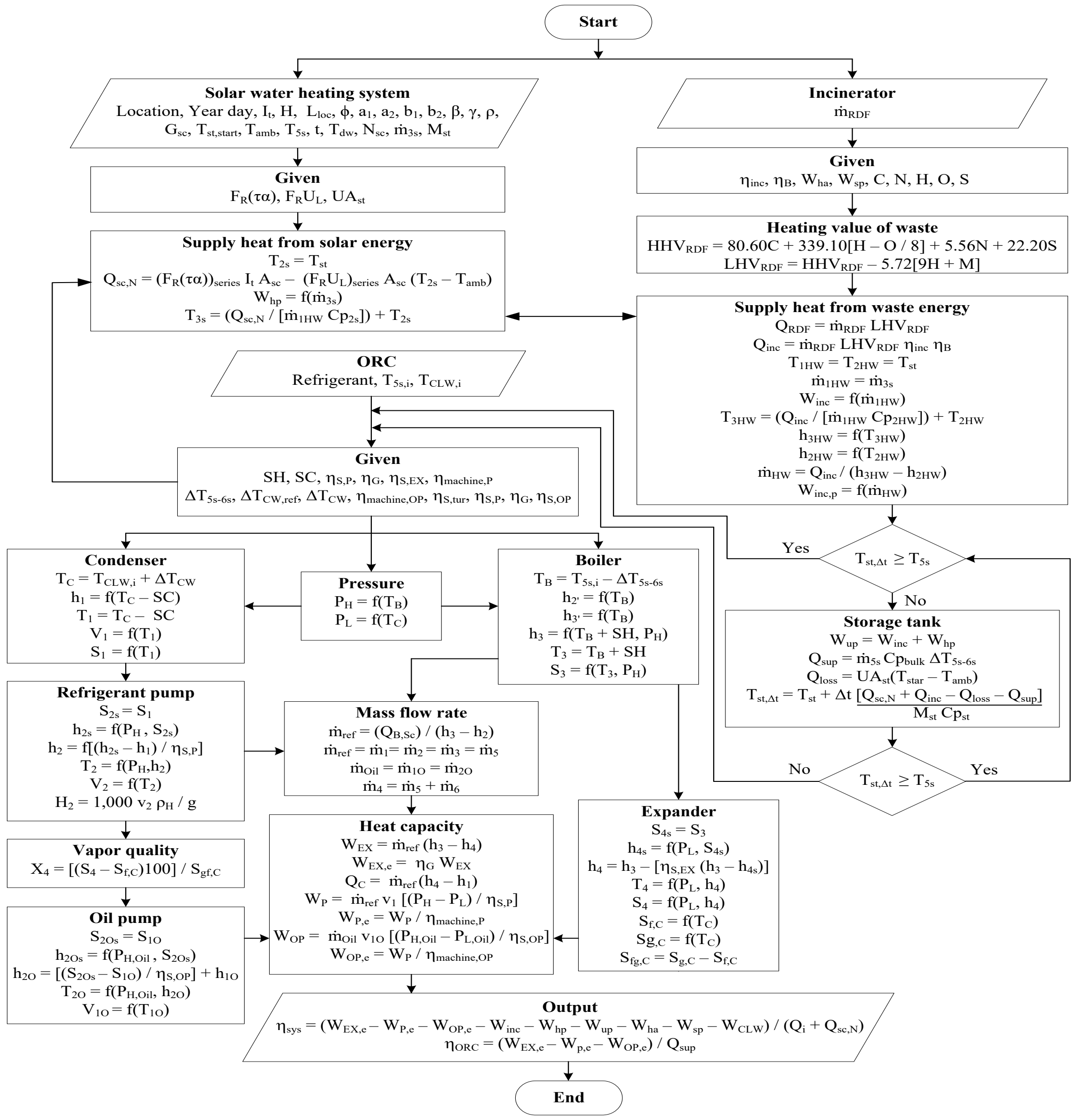


Figure 2: A mathematical model of the novel solar-waste system.

3.3 The economic result in terms of a levelized electricity cost (LEC) is used to focus the output energy and investment cost. The factors of discount rate (r), bank interest rates (i_{Real}), inflation rate ($i_{Inflation}$), investment cost (Inv), deterioration factor (DF), net output energy (E_{net}) are considered the LEC value as presented in Equations 1-2 (Chaiyat, 2021),

$$LEC = [\,Inv + \sum_{t=1}^{n} \frac{PEC}{(1+r)^{t}}\,] / [\,\sum_{t=1}^{n} \frac{E_{net} t_{OP}}{(1+DF)^{(t-1)}}\,], \quad (1)$$

$$r = ([1 + i_{Real}]\,[1 + i_{Inflation}]) - 1. \quad (2)$$

3.4. The environmental assessment in terms of carbon dioxide (CO_2) emission evaluates under a standard of ISO4040. A life cycle assessment (LCA) method is conducted from four steps of goal and scope definition, inventory analysis, impact assessment, and interpretation, as shown in Figure 3.

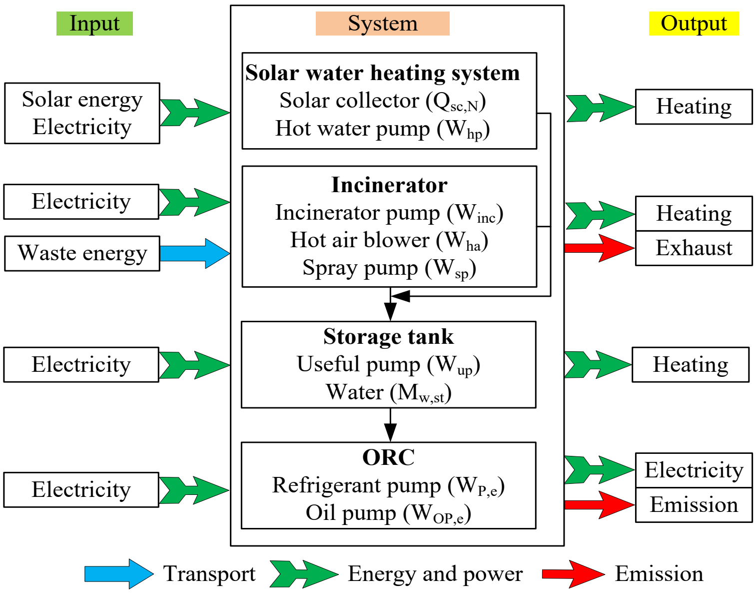


Figure 3: The environmental assessment.

Inventory analysis of the ORC combined with incinerator and solar thermal energy is used to evaluate carbon dioxide emission. A life span of 20 years and a functional unit of 1 kWh are considered for the gate-to-gate boundary condition. Equation 3 (Birol, 2017) shows correlation between activity data (AD), low heating value (LHV), carbon content (CC), and carbon oxidation factor (COF) to predict carbon dioxide emission from combustion process, after throughs the exhaust stack as follows:

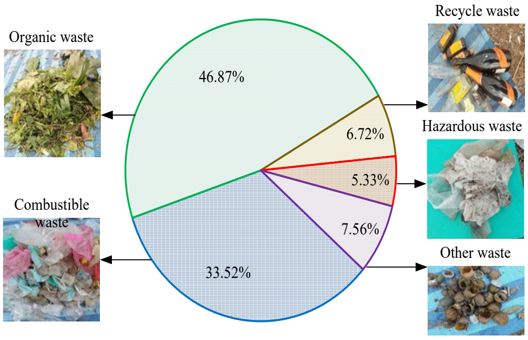
$$CO_2 = [(AD)(LHV)(CC)(COF)]. \tag{3}$$

4. Results and discussion

4.1. The hybrid solar-waste system

The amount of municipal waste in Luangprabang is 19,546.52 Ton in 2021. The average values are 1.855.36 Ton/month and 61.85 Ton/day. The survey results on the Landfill Site Ban Lak Ped, Luangprabang reveal the proportion of waste, which consist of the combustible waste 33.52%, organic waste 46.87%, recycle waste 6.72%, and hazardous waste 7.56%, as shown in Figure 4. In this study, the combustible waste is used to be fuel (refuse derived fuel type 1, RDF-1) in combustion process of an incinerator volume of approximately 21 Ton/day.

Luangprabang is located at 19.861 °N and 102.154 °E. The solar radiation in the Luangprabang shows a low value of 15.43 MJ/(m^2•day) in October and a high value of 18.09 MJ/(m^2•day) in March. The yearly solar radiation is 15.28 MJ/(m^2•day) (Janjai, 2006). The monthly solar radiation, as shown in Figure 5, is an independent variable of a solar water heating system simulation program (NIST, 2022). An evacuate tube solar collector at an absorb area of 4.8 m^2 uses to transfer solar heat into hot water.



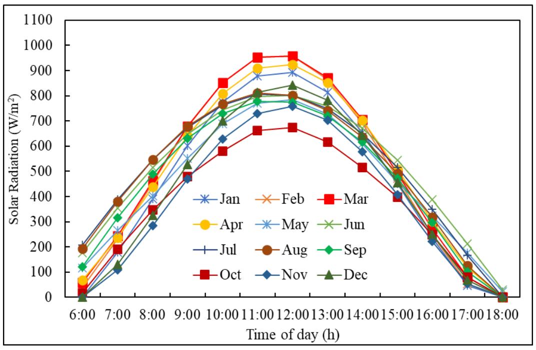
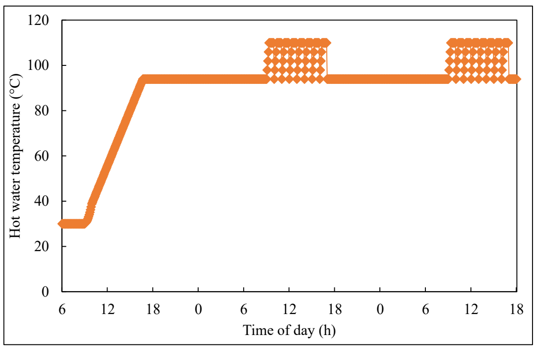


Figure 4: The waste proportion of Luangprabang. Figure 5: The monthly solar radiation of Luangprabang.

4.2. System efficiency

From the mathematical simulation, a storage tank volume (V_{st}) of 22,000 L is the optimization value for the combined solar-waste system. A combustible waste (M_{RDF}) of 20.73 Ton/day or 2.59 Ton/h at a high heating value (HHV_{RDF}) of 11.88 MJ/kg and a low heating value (LHV_{RDF}) of 11.14 MJ/kg is fuel for a commercial incinerator capacity of 21 Ton/day. An RDF-1 combustion heat (Q_{RDF}) of approximately 2,056 kW transfers though the heating pipe for generate hot water at a heat rate (Q_{inc}) of 2,538 kW. A start water temperature (T_{st}) of 30 °C and a useful water temperature (T_{5s}) of 105 °C are the set points of water temperature in the storage tank. An average ambient temperature (T_{amb}) of 25 °C (DEP, 2011) is directly driven a heat loss (Q_{loss}) of 10.84 kW. A solar heat ($Q_{sc,N}$) of approximately 82.76 kW is boosted from a solar collector parallel connection (N_{sc}) of 50 units (Chaiyat, N., 2016). The combined solar-waste system can supply a heat (Q_{sup}) of 2,527 kW for an ORC system ($W_{EX,e}$) of 184.19 kW_e and a commercial ORC capacity of 200 kW_e (gross power) at a continuously operating time of 8 h/d.

Hot water temperature (T_{3HW}) from the incinerator is decreased to be approximately 93 °C, when solid waste is hourly fed to combustion chamber, as shown in Figure 6. Thus, solar water heating system is used to parallel heat for generate a higher temperature heat (T_{5s}) of 95 °C, as shown in Figure 7.



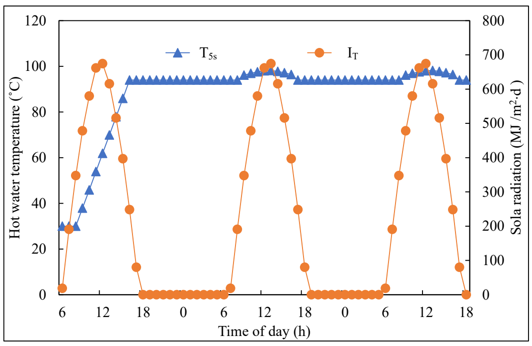


Figure 6: Hot water temperature from the incinerator. Figure 7: Thermal performance of the hybrid system.

The ORC system operates continuously between 9.00-16.00 at an average cycle efficiency (η_{ORC}) of 8.24% and a net power ($W_{ORC,net}$) of 168.02 kW_e. On the other hand, the hybrid solar-waste system efficiency

(η_{sys}) of 6.62%, a net power ($W_{sys,net}$) of 135.80 kW_e, and a power generation (E_{sys}) of 1,086.52 kWh/day, as presented in Figure. 8

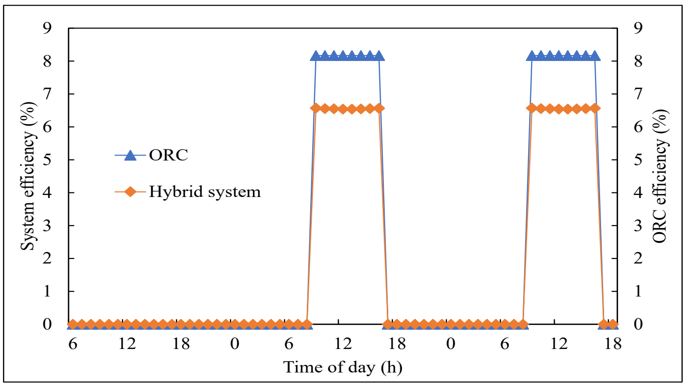


Figure 8: The hybrid system and ORC efficiencies.

4.3. Economic results

A total investment cost of 1,221,871 USD is found from incinerator, ORC, building, solar water heating system, storage tank, and fluid pumps. A maintenance cost of 61,094 USD/y is assumed from an investment cost rate of 5%. A real interest rate and an inflation rate are used to calculate a discount rate of 10.66%. The hybrid solar-waste system can generate a net power of 511,602 kWh/y at the operating time of 8 h/y and lifespan of 20 y, as specified in Table 2. The LEC value is 0.202 USD/kWh, as shown in Table 2.

Table 2 The economic results.

Property	Value	Unit	References
Capacity cost of incinerator and building (Z_{inc})	724,234	USD	Chaiyat, N. (2021)
Capacity cost of ORC and piping (Z_{ORC})	437,500	USD	Chaiyat, N. (2021)
Capacity cost of solar collector and piping (Z_{Sc})	33,225	USD	Chaiyat, N. (2021)
Capacity cost of storage tank (Z_{tank})	19,305	USD	Eurolux, (2022)
Capacity cost of all pumps (Z_P)	7,607	USD	KTW, (2022)
Total investment cost (Inv)	1,221,871	USD	Calculation
Maintenance at 5% of investment cost ($\dot{Z}_{OM}$)	61,094	USD/y	Chaiyat, N. (2021)
Real interest rate (i_{Real})	6.65	%	BCEL, (2022)
Inflation rate ($i_{Inflation}$)	3.76	%	Worlddata, (2022)
Life span (t)	20	y	Chaiyat, N. (2021)
Discount rate (r)	10.66	%	Calculation
Annual output energy generation (W_{EX},e)	511,602	kWh/y	Calculation
Levelized electricity cost (LEC)	0.202	USD/kWh	Calculation

4.4 Environmental impact

Carbon dioxide equivalent estimates from testing data as shown in Table 4. A carbon dioxide of 58% is used to calculate an overall carbon dioxide emission of 41,611 Ton CO_2 form combustion process. A treatment process can reduce carbon dioxide emission to be 1,427 kg CO_2. A carbon dioxide emission per functional unit (1 kWh) is approximately 0.138 kg CO_2/kWh, as displayed in Table 5. In addition, this carbon dioxide equivalent is lower than other WtE results of (Ozge Kaplan et al., 2009) 0.4 kg CO_2/kWh, (Alyssa et al., 2021) 0.775 kg CO_2/kWh, and (Department of industrial works, 2022) 0.5468 kg CO_2/kWh. Carbon dioxide emission of this study focuses on the gate-to-gate boundary condition. Thus, this result is lower than the cradle-to-grave boundary condition of other works.

Table 4 Testing data of RDF-1.

Property	Value		Unit
	As received basis	Moisture free basis	
Carbon (C)	58.00	61.47	%
Nitrogen (N)	0.73	0.77	%
Oxygen (O)	25.35	21.54	%
Hydrogen (H)	9.33	9.23	%
Sulfur (S)	0.14	0.15	%
Ash	6.45	6.84	%

Table 5 The environmental impact results.

Property	Value	Unit	Reference
Low heating value (LHV)	0.011	GJ/kg	Calculation
Carbon content (CC)	25	kg/GJ	Birol, F. (2017)
Carbon oxidation factor (COF)	1	-	Birol, F. (2017)
Activity data (AD)	151,314	Ton	Calculation
Carbon dioxide from combustion process (CO_2)	41,611	Ton CO_2	Calculation
Carbon dioxide from treatment process (CO_2)	1,427	Ton CO_2	Calculation
Power output per life span (E_{ORC})	10.31	10^6 kWh	Calculation
Carbon dioxide emission per 1 kWh (CO_2/E_{ORC})	0.138	kg CO_2/kWh	Calculation

5. Conclusions

From the above study results, it can be concluded as follows:

- The amount of municipal waste of Luangprabang is 19,546.52 Ton in 2021. The combustible waste of 33.52% is used to be fuel (RDF-1) in combustion process for the incinerator volume of 21 Ton/day.

- The solar radiation of Luangprabang shows a lowest value of 15.43 MJ/(m^2•day) in October and a highest value of 18.09 MJ/(m^2•day) in March.

- The combined solar-waste system can supply a heat of 2,527 kW for the ORC system of 184.19 kW_e.

- The ORC system operates continuously 8 h/d at the hybrid solar-waste system efficiency of 6.62%, the net power of 135.80 kW_e, and the power generation of 1,086.52 kWh/day

- Total investment cost of 1,221,871 USD directly effects to the levelized energy cost of 0.202 USD/kWh.

- The carbon dioxide emission per life span of 1,427 Ton CO_2 reveals the carbon dioxide emission per functional unit (1 kWh) of 0.138 kg CO_2/kWh.

6. Acknowledgments

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7. Abbreviations and symbols

Nomenclature

AD	activity data (kg)	M	mass (kg)
C	carbon (kg)	$\dot{m}$	mass for rat (kg/s)
CC	carbon content (kg/GJ)	O	oxygen (kg)
CO_2	carbon dioxide (kg CO_2)	PEC	production electricity cost (USD/y)
COF	carbon oxidation factor (-)	Q	heat capacity (kW)
DF	deterioration factor (%)	r	discount rate (%)
E	energy (kW)	S	sulfur (kg)
h	enthalpy (kJ/kg)	SC	subcooling (°C)
HHV	high heating value (MJ/kg)	SH	superheating (°C)
i	interest rates (%)	SO_2	Sulfur dioxide (kg)
Inv	investment cost (USD)	t	time (h)
LEC	levelized electricity cost (USD/kWh)	W	electrical power (kW)
LHV	low heating value ((MJ/kg)		

Greek

η	efficiency (%)	v	specific volume (m^3/kg)
ρ	density (kg/m^3)	Δ	difference

Abbreviation

ORC	organic Rankine cycle	RDF	refuse derived fuel

Subscript

amb	ambient	CLW	cooling water
B	boiler	dw	different temperature of supplied hotwater
C	condenser	EX	expander

e	electricity	P	pump
H	high	ref	refrigerant
ha	hot air pump	SC	solar collector
Hp	hot water pump	sd	solar radiation
HW	hot water	sp	splay pump
G	generator	St	storage tank
I	incinerator	tur	turbine
i	input	TM	treatment process of incinerator
L	low	up	useful pump
Op	oil pump		

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