Thermodynamic and Economic Analysis of 1.4 MWe Rice-Husk Fired Cogeneration in Thailand

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Abstract

Rice husk is a residue from rice milling process. Rice husk can be used in an economical way to meet the energy demand within the rice milling industry by using rice husk as fuel for heat and power production to supply the heat and electricity in the processes, and to produce surplus electricity for selling to the national grid. Two cases of the study: thermal-match and rice husk-match of different energy utilization are considered for economic evaluation of power plants to meet different demand categories. The capacity of the plant is 576 tons paddy/day. The total load of thermal energy consumption is 1,062 MJ/ton paddy and the electrical energy consumption of the rice mill is 6,518 MWh/year. The total capital cost of the thermal-match cogeneration plant is 1 million US$ while the total capital cost of the rice husk-match cogeneration is 1.24 million US$. Results show that the rice husk-match cogeneration is more economically feasible than the thermal-match cogeneration. The capacity of back pressure steam-fired boiler is 18 tons/hour of steam at 25 bar (absolute) and 400°C. The rice husk-match cogeneration can generate power of 1,432 kW while the thermal-match cogeneration can produce power only 923 kW. The economic analyses in terms of the net present value (NPV), simple pay-back period (PBP), and internal rate of return (IRR) are also evaluated. Results show that the rice husk-match cogeneration has NPV of 0.30 million US$/year, PBP of 3.7 years and IRR of 27%, while the thermal-match cogeneration has NPV of 0.18 million US$/year, PBP of 5.5 years and IRR of 17%. The two cases of the study are based on 180 days/year of operation of rice mill cogeneration. Results of the study also show that rice husk-match cogeneration is more profitable than the thermal-match cogeneration.

Keywords Rice husk cogeneration, Rice mill, Economic analysis, Back-pressure steam turbine, Electricity generation.

1. Introduction

Thailand, an agricultural-based country, is one of the world's leading producers of paddy rice. Rice husk generated as a by product of rice mill processes can be utilized as an energy source for husk-fuelled rice mills. The annual production of rice husk is estimated to be approximately 5 million tons or equivalent to 7.5×10^7 GJ [1, 2]. Taken into account as a widely available CO_2-neutral fuel source, containing Higher Heating Value (HHV) of about 15 MJ/kg[15,16], rice husk is a renewable energy resource with high potential. Over the last 10 years, rice husk has been utilized widely in Thailand for combined heat and power or cogeneration power plants [3]. The proposed combined heat and power (CHP) generation system in this study using rice husk as fuel coverts biomass to energy with the acceptable efficiencies with low costs. Also, in Thailand, the Ministry of Energy has strongly promoted the use of rice husk and other biomass fuels for electricity generation with an incentive through feed-in tariffs scheme for Small Power Producer (SPP) and Very Small Power Producer (VSPP).

2. Methodology

Analysis of power generation system is of scientific interest and also essential for the efficient utilization of energy resources. The most commonly used basis for analysis of energy conversion process is the first law of thermodynamics. However, there are increasing interests of combined utilization of the first law and the second law of thermodynamics, using such concepts as exergy and exergy destructions in order to evaluate the efficiency with the available energy. Exergy analysis provides the tool for the clear distinction between energy losses to the environment and internal irreversibility in the process. Exergy analysis is a methodology for evaluation of the performance of devices and processes, and involves examining the exergy at different points in a series of energy conversion steps. With this information, efficiencies can be evaluated, and the process steps having the largest losses can be identified. For these reasons, the modern method approach to process analysis uses the exergy analysis which provides a more realistic view of the process and a useful tool for engineering evaluation. The objective of this study is to analyze the 1.4 MW rice husk power plant from energy and exergy perspective. Sites of primary energy loss and exergy destruction are determined. The effects of varying the environment state or dead state on the exergy analysis are also discussed.

Nomenclature

ε_o	chemical exergy of fuel (kJ/kg)		
η_{Ex}	exergy efficiency	B	boiler
φ	ratio of chemical exergy to net calorific value	DM	de-mineral water
I_B	boiler irreversibility (kW)	m	steam flow rate (kg/s)
I_{ST}	turbine irreversibility (kW)	I_T	total irreversibility (kW)
HP/HT	high pressure/high temperature	I_{EXG}	exergy loss to exhaust gases (kW)
W	cogenerated power (kW)	$\dot{X}$	exergy rate (kW)
Q_{CG}	process heat (kW)		
NCV	net calorific value (kJ/kg)		
ψ	specific exergy (kJ/kg)		

3. Plant Description

The rice husk power plant has a total installed power capacity of 1,500 kW. The rice mill cogeneration has capacity of 576 tons paddy/day. The generated electricity is supplied to the heat processes in the mill, and the surplus electricity is exported to the grid. The topping cycle cogeneration with back-pressure turbine has been designed on the thermal match, which can produce electricity and thermal heat for the processes, and the rice husk match, which can produce surplus electricity as much as the rice husk fuel can be available. The capacity of boiler to produce the superheated steam to drive the turbine is 18 ton/h at inlet pressure of 2.5 MPa and inlet temperature of 400^{o}C. In thermal match case, the turbine can generate electricity of 943 kW or total electricity of 4,071.6 MWh/year. In rice husk match, it can generate electricity of 1,432 kW or total electricity of 6,187.9 MWh/year. Both cases are based on 180-working day operation. Rice husk and coal properties based on proximate and ultimate analyses are compared in Table 1.

The schematic diagram of the rice husk power plants is presented in Fig. 1 for the thermal match process and Fig. 2 for the rice husk match process. The thermal match process defined by the energy consumption is based on heating process requirement while the rice husk match process defined by the electricity can be produced as much as the rice husk is available. The operating conditions of rice husk plant are shown in Table 2.

Table 1 Analysis of rice husk and compares with coal.

Parameters	Rice husk	Bituminous coal
Proximate analysis (% as received)		
Fixed carbon	20.1	38.92
Volatile matter	55.6	32.20
Moisture	10.3	24.69
Ash	14.0	4.19
Ultimate analysis (% as received)		
C	38.0	52.71
H	4.55	3.04
O	32.4	13.08
N	0.69	1.11
S	0.06	1.18
Higher heating value (MJ/kg)	14.980	24.5
Lower heating value (MJ/kg)	12.340	-

Source: Therdyothin A. and Wibulswas P.[4].

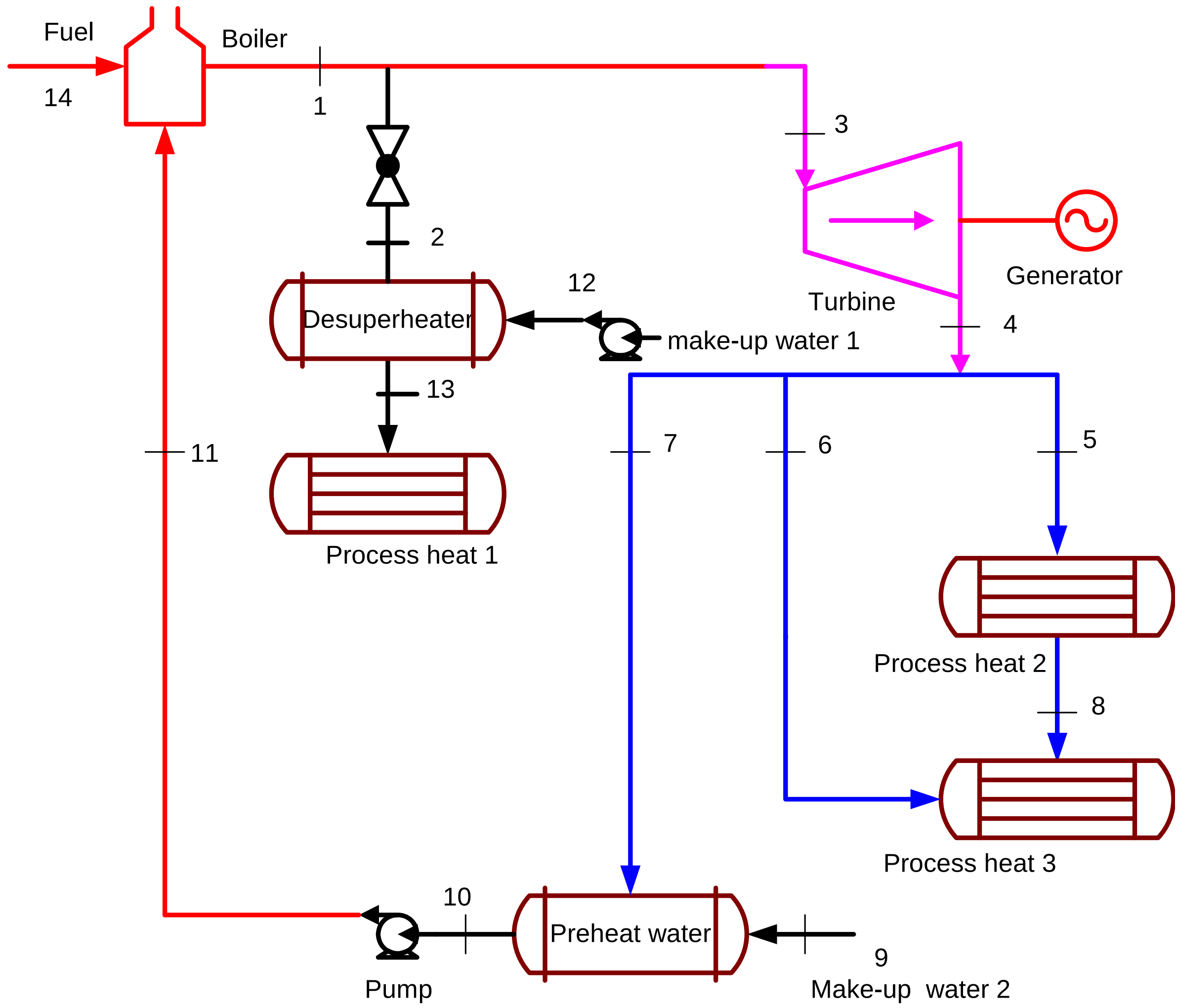


Fig 1. Schematic diagram of rice husk power plant based on the thermal match.

Table 2 Operating conditions of the rice husk power plant.

Operating condition	Thermal match	Rice husk match
Mass flow rate of fuel (kg/s)	0.8722	1.2405
Steam flow rate (kg/s)	3.18	4.53
Steam temperature (^{o}C)	400	400
Steam pressure (MPa)	2.5	2.5
Max. Turbine capacity (MW)	1 MW	1.5 MW
Electrical power output (MW)	0.943 MW	1.432 MW

Source: Sanit Athasart [5].

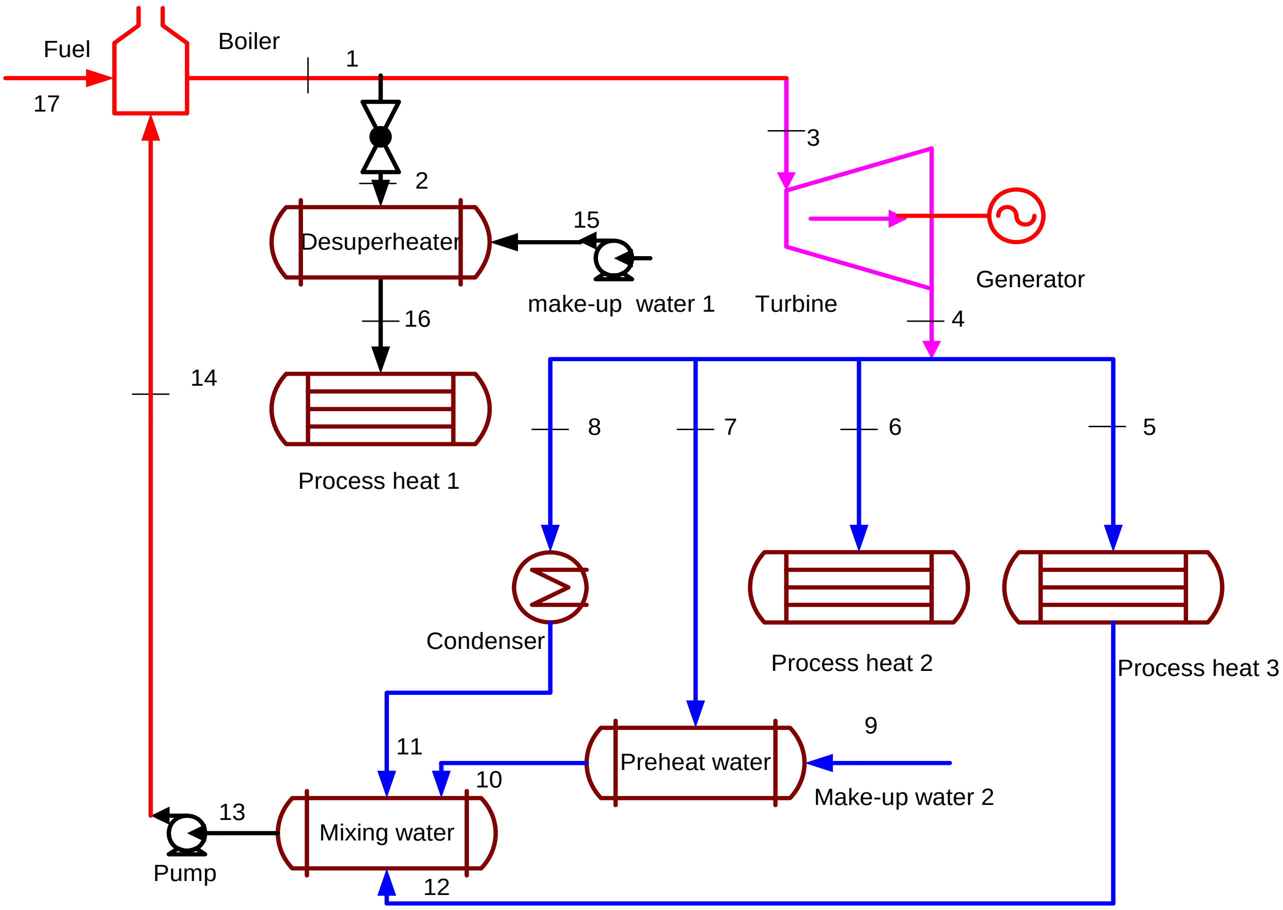


Fig 2. Schematic diagram of rice husk power plant based on rice husk match.

4. Energetic and Exergetic Performance Analysis

Energy performance analysis is based on the first law of thermodynamics; the main performance criteria are commonly power output and thermal efficiency [14,17].(Note: The reference citation is not in proper order!) The parameters are also decisive performance criteria in economic analysis of power plants [12,13]. Exergy performance analysis is based on the second law of thermodynamics. Exergy destruction is the measure of irreversibility that is the source of performance loss. Therefore, an exergy analysis assessing the magnitude of exergy destruction identifies the location, the magnitude and the source of thermodynamic inefficiencies in a thermal system [6]. Mass, energy, and exergy balance for any control volume at steady state with negligible potential and kinetic energy changes can be expressed [7-11].

4.1 Energetic Performance Analysis

The power output of steam turbine is calculated as follows:

$$\sum \dot{m}_i = \sum \dot{m}_e \, . \tag{1}$$

$$\dot{Q} - \dot{W} = \sum \dot{m}_e h_e - \sum \dot{m}_i h_i \, . \tag{2}$$

$$\dot{W}_T = \dot{m}_{in}(h_{in} - h_1) + (\dot{m}_{in} - \dot{m}_1)(h_1 - h_2) + (\dot{m}_{in} - \dot{m}_1 - \ldots - \dot{m}_n)(h_n - h_{out}) \, . \tag{3}$$

Where, the subscripts of *1*, *2*, …, *n* represent the number of steam extractions in steam turbine. As internal power consumption in the plants, the calculation of pump power can be simply given as following:

$$\dot{W}_P = \frac{\dot{m}(h_{out} - h_{in})}{\eta_P} \, . \tag{4}$$

Where, η_P is the pump efficiency. Net electrical power output is given by,

$$\dot{W}_{Net} = \sum \dot{W}_T - \sum \dot{W}_P \, . \tag{5}$$

The total required heat energy in the boiler can be determined from,

$$\dot{Q}_B = \frac{[\dot{m}_{sh}(h_{sh,out} - h_{sh,in}) + \dot{m}_{rh}(h_{rh,out} - h_{rh,in})]}{\eta_B} \, . \tag{6}$$

Where, the subscripts *sh* and *rh* indicate superheated and reheat condition, respectively. Also, η_B is the boiler efficiency and boiler inlet enthalpy $h_{sh,in}$ in Eq.(6) is calculated from energy balance at feed water heater.

$$(\dot{m}_s h_s)_{in} + (\dot{m}_{fw} h_{fw})_{in} = (\dot{m}_s h_s)_{out} + (\dot{m}_{fw} h_{fw})_{out} \, . \tag{7}$$

Where, *s* and *fw* of the subscripts represent steam and feed water, respectively and thermal efficiency of the power plants can be calculated as follows:

$$\eta_{th} = \frac{\dot{W}_{Net}}{\dot{m}_{fuel} LHV} \, . \tag{8}$$

Where, LHV is lower heating value of fuel and $\dot{m}_{fuel}$ is the mass flow rate of fuel (kg./s) and it can be calculated from Eq.(9):

$$\dot{m}_{fuel} = \frac{\dot{Q}_B}{LHV} \, . \tag{9}$$

4.2 Exergetic Performance Analysis

For control volume of any plant component at steady-state conditions, a general equation of exergy destruction rate derived from the exergy balance can be given as,

$$\dot{E}x_D = \sum (\dot{E}x)_{in} - \sum (\dot{E}x)_{out} + [\sum (\dot{Q}(1 - \frac{T_o}{T})_{in} - \sum (\dot{Q}(1 - \frac{T_o}{T})_{out}] \pm \dot{W} \, . \tag{10}$$

Where, the first two terms of right hand side represent exergy of steam entering and leaving the control volume. The third and the fourth terms are the exergy related to heat transfer, T_0 is the ambient temperature of the systems and $\dot{Q}$ represents heat transfer rate across the boundary of the system at a constant temperature *T*, and the last term is the work transfer to or from the control volume.

The exergy transfer by heat ($\dot{X}_{heat}$) at temperature *T* is given by,

$$\dot{X}_{heat} = \sum (1 - T_0/T)\dot{Q}\,. \tag{11}$$

And the specific exergy is given by heat required,

$$\psi = h - h_0 - T_0(s - s_0)\,. \tag{12}$$

Then the total exergy rate associated with a fluid stream becomes,

$$\dot{E}x = \dot{X} = \dot{m}\psi = \dot{m}(h - h_0) - T_0(s - s_0)\,. \tag{13}$$

Where, *h* and *s* represent specific enthalpy and entropy, respectively.

Total exergy destruction rate in the plant can be determined as sum of exergy rate of components:

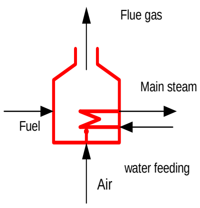
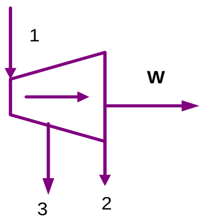
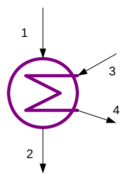
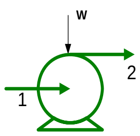
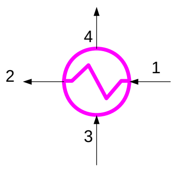
$$\dot{E}x_{D,total} = \sum \dot{E}x_{D,i} = \dot{E}x_{D,B} + \dot{E}x_{D,T} + \dot{E}x_{D,C} + \dot{E}x_{D,P} + \dot{E}x_{D,H}\,. \tag{14}$$

For the whole power plant, the exergy efficiency can be given as:

$$\eta_{Ex} = \frac{\dot{W}_{Net}}{\dot{m}_{fuel}\, ex_{fuel}}\,. \tag{15}$$

The exergy performance equations for main components of the thermal power plant are presented in Table 3.

Table 3. Exergy performance equations for main components of a thermal power plant.

Component name	Component figure	Exergy destruction rate	Exergy efficiency
1. Boiler		$\dot{E}x_{D,B} = \dot{X}_{fuel} - \dot{X}_{in} - \dot{X}_{out}$	$\eta_{EX,B} = \frac{\dot{X}_{out} - \dot{X}_{in}}{\dot{X}_{fuel}}$
2. Turbine		$\dot{E}x_{D,T} = \dot{E}x_1 - \dot{E}x_2 - \dot{E}x_3 - \dot{W}$	$\eta_{EX,T} = \frac{\dot{W}}{\dot{E}x_1 - \dot{E}x_2 - \dot{E}x_3}$
3. Condenser		$\dot{E}x_{D,C} = \dot{E}x_1 + \dot{E}x_3 - \dot{E}x_2 - \dot{E}x_4$	$\eta_{EX,C} = \frac{\dot{E}x_4 - \dot{E}x_3}{\dot{E}x_1 - \dot{E}x_2}$
4. Pump		$\dot{E}x_{D,P} = \dot{E}x_1 - \dot{E}x_2 + \dot{W}$	$\eta_{EX,P} = \frac{\dot{E}x_2 - \dot{E}x_1}{\dot{W}}$
5. Heat Exchanger		$\dot{E}x_{D,H} = \dot{E}x_1 + \dot{E}x_3 - \dot{E}x_2 - \dot{E}x_4$	$\eta_{EX,H} = \frac{\dot{E}x_2 - \dot{E}x_1}{\dot{E}x_3 - \dot{E}x_4}$

5. Results and Discussion

Exergy analysis of rice husk cogeneration both for thermal match and rice husk match are shown in Table 4 and Table 5, respectively.

Table 4 Exergy analysis of the rice husk cogeneration power plant for thermal match at T_o=303.15 K , P_o=101.35 kPa.

Point	T (°C)	P (MPa)	Flow rate (kg/s)	h (kJ/kg)	s (kJ/kg.°C)	Energy (kW)	Exergy (kW)
0	30	0.101		125.9	0.437	-	-
1	400	2.5	3.18	3229	7.015	9899.66	3558.16
2	389	1.1	0.58	3229	7.384	1805.60	584.090
3	400	2.5	2.60	3229	7.015	8094.06	2909.19
4	182.8	0.2	2.60	2836	7.432	7046.26	1532.71
5	182.8	0.2	1.89	2836	7.432	5122.09	1114.16
6	182.8	0.2	0.34	2836	7.432	921.43	200.43
7	182.8	0.2	0.37	2836	7.432	1002.74	218.18
8	120	0.2	1.89	503.7	1.528	714.04	88.84
9	30	0.101	2.81	125.9	0.437	0	0
10	105	0.2	3.18	440.1	1.363	999.16	106.28
11	105	2.5	3.18	441.9	1.361	1004.88	113.94
12	30	2.2	0.084	127.8	0.436	0.16	0.18
13	184.1	1.1	0.667	2782	6.554	1771.62	534.71

Table 5 Exergy analysis of the rice husk cogeneration power plant for rice husk match at T_o=303.15 K, P_o=101.35 kPa.

Point	T (°C)	P (MPa)	Flow rate (kg/s)	h (kJ/kg)	s (kJ/kg.°C)	Energy (kW)	Exergy (kW)
0	30	0.101		125.9	0.437	-	-
1	400	2.5	4.53	3229	7.015	14102.34	5068.70
2	389	1.1	0.583	3229	7.384	1814.94	587.11
3	400	2.5	3.947	3229	7.015	12287.41	4416.37
4	182.8	0.2	3.947	2836	7.432	10696.77	2326.78
5	182.8	0.2	1.89	2836	7.432	5122.09	1114.17
6	182.8	0.2	1.58	2836	7.432	4281.96	931.42
7	182.8	0.2	0.1388	2836	7.432	376.16	81.82
8	182.8	0.2	0.338	2836	7.432	916.10	199.25
9	30	0.101	0.922	125.9	0.437	0	0
10	105	0.2	1.06	440.2	1.363	333.16	35.53
11	120	0.2	1.58	503.7	1.378	596.92	74.26
12	120	0.2	1.89	503.7	1.528	714.04	88.84
13	116.5	0.2	4.53	488.8	1.490	1643.94	197.61
14	116.5	2.5	4.53	490.5	1.488	1651.64	208.06
15	30	2.2	0.084	127.8	0.4362	0.1600	0.1800
16	184	1.1	0.667	2782	6.554	1771.62	534.71

The rice husk cogeneration was analyzed at ambient condition of 30°C and 0.101 MPa. The mass flow rate of rice husk fuel of the power plant shown in Fig.1 is 0.8722 kg/s, while the mass flow rate of rice husk fuel of the power plant shown in Fig.2 is 1.2405 kg/s. The energy balance in both thermal match and rice husk match cogeneration are shown in Table 6 and in Table 7.

Table 6. Energy balance of rice husk cogeneration on thermal match.

Components	Heat loss (kW)	Percentage (%)
Boiler	1,868.17	17.36
Net power output	942.50	8.76
Heat process 1	1,771.62	16.46
Heat process 2	4,468.05	41.51
Heat process 3	1,635.47	15.20
Desuperheater	34.00	0.316
Preheat water	3.58	0.034
Pump (make up water 1)	0.16	0.002
Pump (water feed)	5.72	0.054
Turbine	33.68	0.31
Total	10,762.95	100.00

Table 7. Energy balance of rice husk cogeneration on rice husk match.

Components	Heat loss (kW)	Percentage (%)
Boiler	2,857.19	18.67
Net power output	1,432.40	9.36
Heat process 1	1,771.62	11.58
Heat process 2	4281.96	27.97
Heat process 3	4,408.04	28.80
Condenser	319.09	2.09
Desuperheater	43.481	0.28
Preheat water	43.00	0.28
Pump (make up water 1)	0.16	0.001
Pump (water feed)	7.70	0.05
Turbine	141.90	0.93
Total	15,306.54	100.00

Table 8. Exergy destruction and exergy efficiency of rice husk cogeneration in thermal match.

Components	Exergy destruction (kW)	Exergy destruction (%)	Exergy efficiency (%)
Boiler	7,964.50	71.34	30.02
Turbine	353.70	3.170	74.43
Heat process 1	534.71	4.760	-
Heat process 2	1,851.06	16.58	-
Heat process 3	289.27	2.590	-
Desuperheater	51.96	0.466	80.08
Preheat water	111.83	1.002	48.72
Pump (make up water 1)	0.175	0.002	78.82
Pump (water feed)	7.652	0.069	96.25
Total / exergy efficiency	11,164.85	100.00	32.40

Table 9. Exergy destruction and exergy efficiency of rice husk cogeneration in rice husk match.

Components	Exergy destruction (kW)	Exergy destruction (%)	Exergy efficiency(%)
Boiler	11,366.95	77.90	29.95
Heat process 1	534.71	3.67	-
Heat process 2	931.42	6.38	-
Heat process 3	1,025.33	7.03	-
Condenser	124.99	0.86	27.97
Desuperheater	52.4	0.36	91.07
Preheat water	46.29	0.32	43.43
Pump (make up)	0.175	0.001	70.62
Pump (water feed)	10.447	0.072	97.97
Turbine	498.95	3.42	76.21
Total / Cycle	14,591.66	100.00	26.38

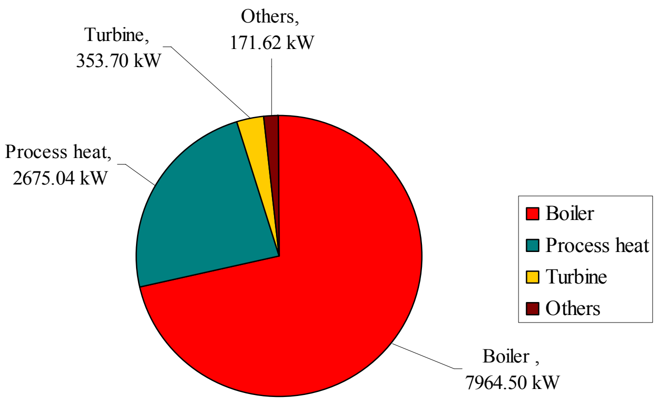


Fig 3. Exergy diagram of thermal match cogeneration.

The exergy losses are also shown in Fig. 3 and Fig. 4 of thermal match and rice husk match, respectively. It can be concluded that the process heat consumes most of energy in the rice husk cogeneration. It means that the cogeneration needs much thermal heat in the processes. Exergy and percentage of exergy destruction along with the exergy efficiencies are summarized in Tables 8 and 9.

For all components presented in the power plant of both cases of rice husk cogeneration, it was found that the exergy destruction in the boiler is dominant over all other irreversibilities in the cycle. The exergy destruction in boiler is accounted for 71.34% of total system exergy destruction in thermal match and 77.90% in rice husk match. The exergy destruction in the condenser is only 0.86%. The real loss is primarily back to the boiler where entropy was produced. Contrary to the first law analysis, the second law analysis demonstrates that significant improvements exist in the boiler system rather than in the condenser.

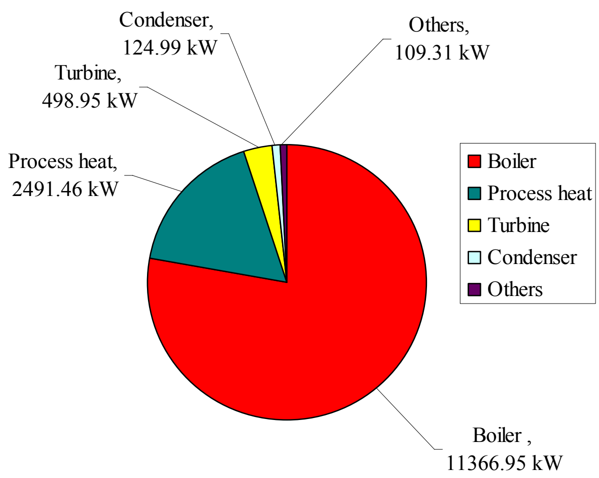


Fig.4 Exergy diagram of rice husk match cogeneration.

The calculated exergy efficiency of power cycle in thermal match and rice husk match is 32.40% and 26.38 % respectively. It is relatively low in the case of rice husk match because the exergy loss and the exergy destruction in boiler are much more than in the thermal match cogeneration.

In order to quantify the exergy of the systems, both system and the surrounding must be specified. It is assumed that the environment does not significantly change in properties of the process. The dead state is the state of a system in which it is in equilibrium with its surroundings. When a system has the same temperature and pressure with the surroundings, there exists no work potential in such instances, as shown in Table 10.

The reference environment state is irrelevant to calculation of a change in thermodynamic properties by the first law analysis. However, it is expected that, in the second law analysis, the dead state has some effects on the results of exergy. As shown in Table 10, by varying the ambient temperatures, it was found that the differences in ambient temperatures have little effect on the exergy efficiencies of major components in the rice husk cogeneration for the rice husk match case.

Table 10 Exergy efficiency of major components at different ambient temperature**.**

Components	26^{o}C	28^{o}C	30^{o}C	32^{o}C	34^{o}C
Boiler	30.57	30.26	29.95	29.67	29.34
Turbine	76.36	76.24	76.21	76.00	75.88
Condenser	28.35	28.16	27.97	27.80	27.62

6. Economic Evaluation

The two cases of rice husk cogeneration are compared on the economic costs and the revenues from electricity sold to the grid based on 180-day plant operation (Table 11). It shows that the rice husk match cogeneration has higher electricity generation capacity of 1,432.4 kW and more total revenues with around 0.30 million US$/year, but lower payback period of 3.7 years.

Table 11 Summary of economic evaluation of rice husk cogeneration.

Items	Thermal match	Rice husk match
Plant capacity	942.5 kW	1,432.4 kW
Capital investment cost	33.567 million Baht	39.317 million Baht
Variable cost		
Rice husk	0.262 million Baht	1.980 million Baht
Maintenance cost	1.678 million Baht	1.966 million Baht
Man power	0.540 million Baht	0.540 million Baht
Water cost and other	0.35 million Baht	0.365 million Baht
Total cost (*A*)	2.829 million Baht	4.851 million Baht
Electricity sold and avoided	8.602 million Baht	14.857 million Baht
From selling ash	0.403 million Baht	0.579 million Baht
Total revenue (*B*)	9.005 million Baht	15.436 million Baht
Net present value (*B*-*A*)	6.176 million Baht	10.585 million Baht
Payback period	5.5 years	3.7 years
% IRR	17.1%	26.7%

(Exchange rate: US$ 1 = Baht 35)

7. Conclusion

In this study, energy and exergy analyses as well as the effects of varying the reference ambient temperatures on the exergy analysis of an actual rice husk cogeneration are presented. In the considered power plant, exergy analysis of the rice husk cogeneration power plant shows that the exergy destruction in boiler is accounted for 71.34% of total system exergy destruction in thermal match and 77.90% in rice husk match. The exergy losses in turbine of both cases are around 3%. It can be concluded that the boiler is the major source of irreversibility in the rice husk cogeneration power plant.

In thermal match case, the calculated exergy efficiency of cogeneration is 32.40% while in the rice husk match case, the exergy efficiency is 26.38 %. Both are acceptable because this rice husk cogeneration plant not only generates electricity but also requires so much energy in its thermal processes, and the calculation of output exergy efficiency is based on both electricity and heat process output. In case of rice husk match, the exergy efficiency is relatively low because of the exergy destruction in boiler is much more than in the thermal match case and it gives the guideline for engineers on process improvement. It also means that its power to heat ratio is too low. Although the exergy efficiency of each component in the system changes with ambient temperature, the changes are found to be insignificant in this study.

Finally, considering in both cases of rice husk cogeneration based on economic evaluation, it can be concluded that the rice husk match is more economically feasible and is more profitable than the thermal match because the rice husk match cogeneration can generate power of 1,432.4 kW_e , or it can generate electricity around 6,187,968 kWh/year, and it has NPV of 0.30 million US$/year, PBP of 3.7 years and IRR of around 27%.

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