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Energy, Exergy, and Externalities Cost Rate Analysis of 300 MW Coal-Fired Power Plant: A Case Study

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ABSTRACTS

Three types of analysis conducted at one of Thailand's coal-fired power plants were reported in this paper. The analyses consisting of energy, exergy, and externalities cost rate analysis are aimed to analyse the largest energy loss and exergy destruction that occurs in the system, to assess the contribution of Energy externalities cost rate based on fuel price, and to determine potential cost saving. Energy loss at the condenser was the highest among major units of the Thai power plants, which contributed around 49.11% at full load condition and was followed by a boiler, turbine, etc. Furthermore, the boiler was identified as the highest exergy destruction producer, with around 57.73% of total exergy input into the system, followed by turbines, heaters, etc. Moreover, the energy and exergy efficiency of Thai's power plant was calculated to be around 35.60% and 31.76%, respectively. The highest externalities cost rate due to energy loss occurred in the condenser was about 0.56 $/s, whereas the highest externalities cost rate due to exergy destruction identified in the boiler was about 0.67 $/s. By improving boiler and turbine components, Thai's PP has a potential cost saving of around 21.2 million $/year, reducing 88.44% of the externalities cost of exergy destruction.

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INTRODUCTION

Thailand is a developing country that utilizes natural gas, LPG, LNG, CNG, etc., as primary energy in many sectors, such as industries, households, and transportation. During the last five years, natural gas has contributed more than 41.1 % of total domestic production of primary energy, followed by renewable energy, which contributed around 30.2 % [1-2]. From 2008 to 2009, natural gas accounted for 71.8 % of total electricity generation, accompanied by coal, which contributed around 21.4% of electricity generation [3].

In terms of acquiring Thailand electricity, the coal-fired power plant was built to support and help the gas-fired power plant in sufficing national electricity demand. Compared to power plants that do not use coal as an energy source, coal-fired power plants have more difficulties in terms of technical, chemical, and mechanical processes that affect the performance of the

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power plants. Typically, the coal-fired power plant can only reach an overall efficiency of about 40% to 45%, depending on the loads and types, and more than 50% of heat energy was rejected in the condenser [4]. In 2009, energy losses from coal in Thailand reached 18.62% of the total energy losses from overall resources. Referring to the total coal used to generate electricity, energy losses from coal utilization in Thailand are about 5.29% [5]. Analysis to improve streams, systems, and process of the coal-fired power plant is required.

Coal-fired power plant performance will be quantified by energy, heat, and work using the first law of thermodynamics analyses. Energy analysis is a tool to analyse energy balance and energy loss in a system. In energy analysis, an energy loss term appears when the energy or heat balance of the system is not achieved. It shows that some amount of energy disappears or is dissipated during the process without explaining about the direction instead the quality of energy loss [6-7].

However, in recent years, exergy analysis based on the second law of thermodynamics has been applied in the performance evaluation of thermal power plants, i.e., geothermal power plants [8-10], steam power plant [11-15], gas turbine power plant [16-17], combined cycled power plant [18]. Unlike energy analysis, exergy analysis considers energy destruction by entropy generation, which is caused by the imperfect material microstructure or temperature difference, to evaluate energy quality and to track energy losses in the system. Many researchers, who focused on energy conservation, implemented energy and exergy methods to investigate numbers of plants around the world. Lior N studied the concept of energy and exergy methods based on the second law thermodynamics criteria [19]. The methods described that energy analysis alone is inadequate since the quality of energy was not taken into consideration. Kamate S. C. emphasized that integration with exergy analysis can obtain more accurate information about potential work produced and recycled energy [20]. Aljundi determined the location of most energy and exergy losses for the Al-Hussein steam power plant with a power capacity of 66 MW in Jordan through energy and exergy analyses and investigated the effects of variation of the reference ambient conditions on exergetic performance [21]. Kopac and Hilalci used the exergy concept to investigate the effects of environmental temperature reference of power plant components (boiler, turbines, condenser, heaters, pumps, and pipe) on Catalagzi power plant performance in Turkey [22]. Erdem et al. analysed and compared the irreversibilities and the exergy performances of the main components (boiler, steam turbine, condenser, pump, feed water heater) of nine thermal power plants in Turkey [23]. Another research also compared the actual design and simulated results. Regulagadda et al. estimated the value of exergy for Tecpro Power Systems Ltd. in Chennai, India, under various operating conditions, and determined the parameters that optimize plant performance [24]. Saidur, R. et al. conducted exergy and energy calculation of power plant components (combustor, boiler, and heat exchanger) and made a correlation between exergy and energy cost saving [25].

Furthermore, externalities cost rate analysis was proposed to investigate the performance of a power plant in terms of economics. It describes the amount of loss of money rate distribution due to energy loss and exergy destruction based on the price of fuel by adopting exergo-economic method from our previous research. Henceforth, both energy and exergy analyses are conducted as initial investigation for selected coal-fired power plant in Thailand. (Thai’s-PP) and both methods will be combined to analyse effect of energy in fuel cost. By applying energy, exergy, and externalities cost rate concepts, energy losses and exergy destruction distribution and externalities cost rate are determined and hence identify possible improvements in the future

MATERIAL AND METHODS

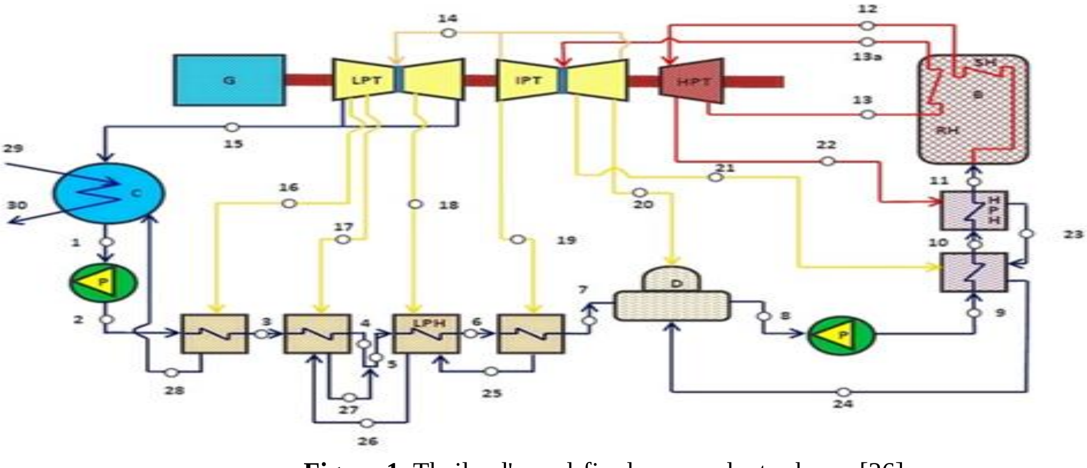

Figure 1. Thailand's coal-fired power plant scheme [26]

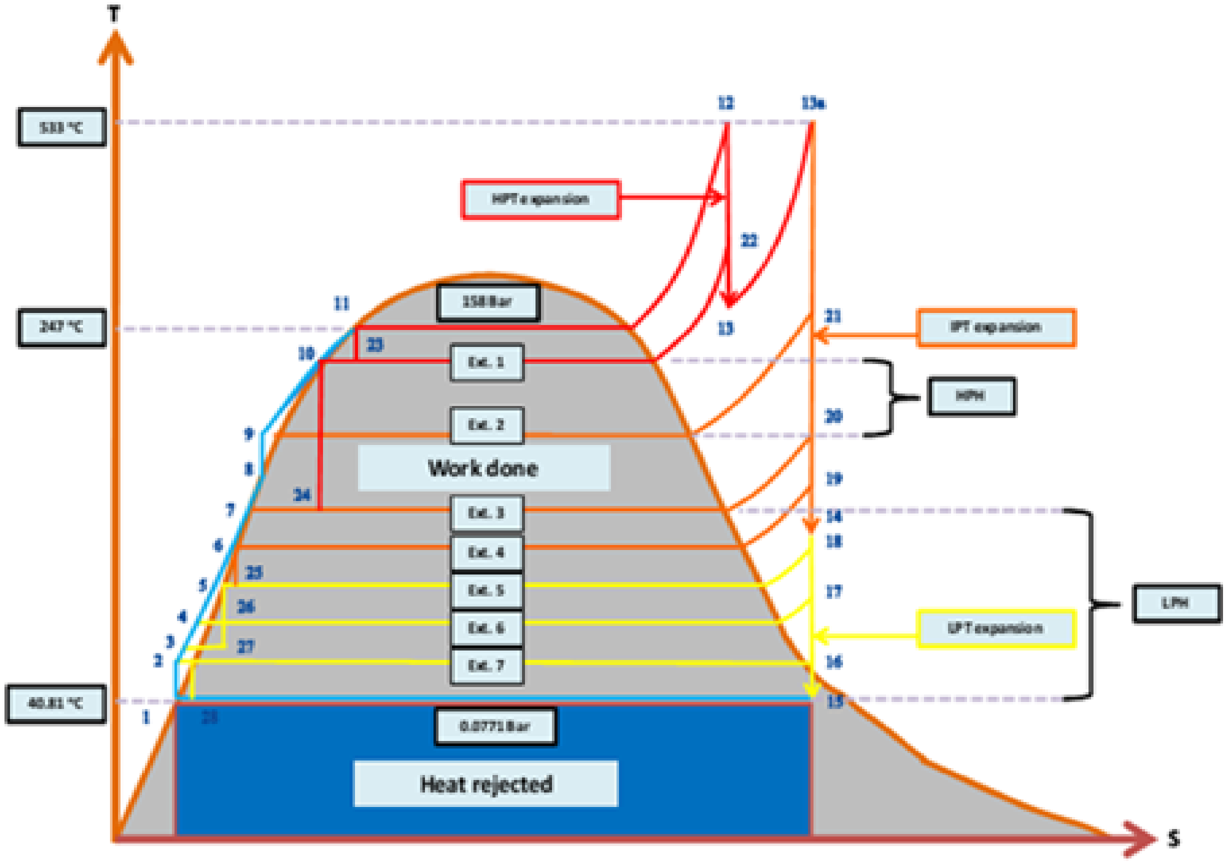

Figure 2.T-s diagrams of Thailand's coal-fired power plant [26].

The selected coal-fired power plant from Thailand (Thai's-PP) is located in Northern Thailand. It was designed for 300 MW gross power generation capacity. This plant has operated in environment temperature (T_o) and pressure (P_o) around 32.17°C and 101.3 kPa, respectively [27].

Table 1. Thermodynamic properties of Thai's Power Plant.

Point	T (°C)	P (Bar)	m (kg/s)	h (kJ/kg)	s (kJ/kg.K)
1	41.000	0.076	168.772	169.623	0.579
2	41.500	13.870	168.772	175.020	0.592
3	60.500	13.370	168.772	253.273	0.838
4	101.300	12.870	168.772	424.651	1.322
5	101.600	12.870	198.182	425.917	1.325
6	125.300	12.370	198.182	526.351	1.585
7	150.800	11.870	198.182	635.632	1.849
8	179.500	9.906	237.222	760.846	2.134
9	183.000	194.500	237.222	785.723	2.144
10	207.100	193.500	237.222	884.419	2.397
11	247.000	192.500	237.222	1071.210	2.766
12	533.925	158.173	237.222	3397.150	6.436
13	336.973	40.560	216.571	3059.000	6.523
13a	533.895	38.219	216.571	3525.290	7.213
14	271.290	4.635	189.316	3006.280	7.392
15	40.810	0.077	162.633	2363.380	7.567
16	62.000	0.217	6.139	2494.670	7.525
17	117.600	1.122	12.620	2710.480	7.400
18	193.300	2.462	7.924	2854.880	7.377
19	265.800	5.087	8.866	2993.500	7.326
20	355.500	9.906	9.819	3170.050	7.320
21	423.000	16.760	8.570	3303.690	7.290
22	335.000	39.660	20.651	3053.700	6.525
23	211.300	39.660	20.651	903.570	2.433
24	188.600	16.760	29.221	801.193	2.222
25	130.700	5.087	8.866	549.371	1.642
26	106.900	2.462	16.790	448.303	1.384
27	102.900	1.122	29.410	431.405	1.339
28	61.900	0.217	6.139	259.134	0.855
29	31.242	0.038	8500.000	130.926	0.454
30	41.198	0.066	8500.000	172.541	0.588

Figure 1 depicts the scheme of Thai-PP. The main components consist of a high-pressure turbine (HPT), intermediate pressure turbine (IPT), low-pressure turbine (LPT), boiler (B), high-pressure heater (HPH), low-pressure heater (LPH), condenser (C) and pumps (P). **Figure 2** shows the temperature and entropy condition that was required by the plant to be operated. Furthermore, Thai's PP operated a single re-heat system and condensing steam turbine to improve the overall efficiency of the plant. The input and output values of each plant component could be established using the measured and calculated thermodynamic properties, as shown in **Table 1**.

Table 1 shows the important analysis data, which covers temperature, pressure, mass flow rate, enthalpy, and entropy in each stream. Enthalpy and entropy are determined by using CATT3 software, whereas energy and exergy streams are calculated using MS. Excel Sheet. Then, low heating value (LHV) and high heating value (HHV) can be determined using coal properties compositions, which are presented in **Table 2**.

Table 2. As received basis of lignite coal properties in Thailand's Power Plant [28].

No	Content	Unit	Max. load
1	Carbon	% wt	0.2723
2	Hydrogen	% wt	0.0162
3	Oxygen	% wt	0.0708
4	Nitrogen	% wt	0.0106
5	Sulphur	% wt	0.0276
6	Ash	% wt	0.2855
7	Moisture	% wt	0.3173
8	LHV	MJ/kg	9.587
9	HHV / Chemical Exergy	MJ/kg	10.745
10	Fuel flow rate	Ton/h	270.483

Table 2 provides lignite coal properties that are used at maximum load conditions on Thai's PP. The carbon content of lignite is lower than ash and moisture content. These coal data properties were provided by Helios, M.P. et al. [27-28].

ENERGY ANALYSIS

According to the first law of thermodynamics, energy analysis of a steam power plant generally considers the heat transfer process, the work of the turbine and pump, and the fuel energy as indicators to find the overall thermal efficiency and energy balance. Thus, the power output of the steam turbine, W_t, is calculated as:

$$\dot{W}_t = \dot{m}_s\left(h_{s,in} - h_{s,out}\right) \quad (1)$$

Where h is known as enthalpy and subscript $_{s,in}$ and $_{s,out}$ represents inlet and outlet steam conditions. Then, the power consumption of the boiler feed pump (transport water), $_w$, from the inlet site ($_{w,in}$) to the outlet site ($_{w,out}$), can be calculated using the equation as follow:

$$\dot{W}_p = \dot{m}_w \frac{\left(h_{w,in} - h_{w,out}\right)}{\eta_p} \quad (2)$$

From equations 1 and 2 above, the net electrical power output is given by:

$$\dot{W}_{net} = \sum \dot{W}_t - \dot{W}_p \quad (3)$$

The lower heating value (LHV) and high heating value (HHV) of lignite coal can be determined by the following [29-30].

$$\text{LHV} = 33.9\text{C} + 117\left(H - \frac{O}{8}\right) + 10.5\text{S} - 2.5\text{w} \quad (4)$$

$$\text{HHV} = \text{LHV} + 2.5(9\text{H} + w) \quad (5)$$

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

$$\dot{Q}_b = \dot{m}_{coal} \times LHV \quad (6)$$

Finally, the overall thermal efficiency of the power plant can be calculated as:

$$\eta_{En} = \frac{\dot{W}_{net}}{\dot{Q}_b} \quad (7)$$

The energy balance of a control volume system becomes

$$\sum_{in}\left(\dot{E} + \dot{Q}_b\right) = \sum_{out}\left(\dot{E} + \dot{W}_{net}\right) \quad (8)$$

Then, the ratio of energy loss shows how much energy loss was contributed by each component, and it can be determined by:

$$R_{En_L} = \frac{En_{L,i}}{\sum En_j} \quad (9)$$

EXERGY ANALYSIS

Based on the second law of thermodynamics, the equation of exergy balance can be derived by combining the energy equation and entropy equation. The entropy balance of a control volume system is given as follows:

$$\left[\sum_i^n \dot{s}_i + \sum_i^n \frac{\dot{Q}}{T} + \dot{s}_{gen}\right] = \left[\sum_o^t \dot{s}_o + \sum_o^t \frac{\dot{Q}}{T}\right] \quad (10)$$

The exergy balance of a control volume system becomes

$$\left[\sum_i^n \dot{E}x_i + \sum_i^n 1 - \left(\frac{T}{T_k}\right)Q_k\right] = \left[\sum_o^t \dot{E}x_o + \dot{W} + \dot{E}x_D\right] \quad (11)$$

The exergy rate of a stream is obtained from

$$\dot{E}x = \dot{m}(e_x) \quad (12)$$

$$\dot{m}(e_x) = \dot{m}(e_x^{tm} + e_x^{ch}) \quad (13)$$

Referring to equation 13, specific exergy is divided into two parts, which e_x^{tm} is the exergy of thermo-mechanical process and e_x^{ch} is the exergy of the chemical process, called chemical exergy. In this case, the chemical exergy value is assumed to be similar to HHV, which is considered as the maximum energy that can be extracted from the fuel. Then, the exergy of the thermo-mechanical process is given by:

$$e_x^{tm} = (h - h_o) - T_o(s - s_o) \quad (14)$$

Equation 14 is also applied to explain the exergy destruction rate in each component, such as the boiler, turbine, heater, condenser, and pump, whereas the total exergy destruction rate of each component (described in **Figure 1**) can be determined as a sum of exergy destruction components rates:

The overall exergy efficiency of the system is given by

$$\dot{E}x_{D,total} = \sum \dot{E}x_{D,i} \quad (15)$$

Beside the ratio of energy loss, the ratio of exergy destruction shows how much exergy destruction was contributed by each component, and it can also be determined from:

$$\psi_{Ex} = \frac{\dot{W}_{net}}{\dot{m}_{coal} \times e_x^{ch}} = 1 - \frac{\sum \dot{E}x_D}{\dot{m}_{coal} \times e_x^{ch}} \quad (16)$$

$$R_{Ex_D} = \frac{\dot{E}x_{D,i}}{\sum \dot{E}x_D} \quad (17)$$

In supporting energy and exergy analysis, some equations applied in this case study are provided in **Appendix 1**; **Table 3**. The equations represent five major components of Thai's PP, which cover equations for exergy destruction and exergy efficiency.

EXTERNALITIES COST RATE ANALYSIS

The externalities cost rate of Thai's PP is calculated based on the price of fuel (coal) supplied in that plant, around 15 $/tonne. The externalities' cost rate is required to consider cost allocation in order to improve another device performance and identify which device contributes the highest externalities cost rate. Equations 18 and 19 are provided to calculate the energy externalities cost rate based on energy loss and exergy destruction, respectively.

$$\dot{C}_{En_{L,i}} = \left(c_{En,L} \times \dot{E}n_{L,i} \times t_{op}\right) \quad (18)$$

$$\dot{C}_{Ex_{D,i}} = \left(c_{Ex,f} \times \dot{E}x_{D,i} \times t_{op}\right) \quad (19)$$

Where c is the specific cost, $\dot{C}$ represents cost rate, and t_{op} is the operating time of the plant.

ASSUMPTIONS

In conducting energy, exergy, and externalities cost rate analyses, some assumptions were required to help with the calculation. The assumptions to analyse this plant are described below:

1. The power plant cycle operates at a steady state or open system, and the operating time of the plant was assumed to be 8640 hours/year.
2. No stray heat transfer from any components to their surroundings
3. Kinetic and potential energy effects can be neglected
4. Wasted energy from flue gas, blowdown, and ash was neglected
5. Reference environment condition follows the temperature and pressure condition of Thai's PP.
6. Certain components such as boiler stop valves, fuel oil pumps, coolers, induced draught and forced draught fans, and pressure drops along pipelines were assumed negligible.
7. The value of chemical exergy is almost similar to the high heating value (HHV).

RESULTS AND DISCUSSION

Based on the first and second law thermodynamics, both efficiencies of the cycle are identified to be around 35.60 % and 31.76 %, respectively. This value Another result of this study is concluded in some tables and figures in this section.

Table 3 shows the energy and exergy efficiency of each component in the Thai's-PP. The efficiency values were achieved by using equations 7 and 16. As source and sink of energy conversion, the boiler and condenser are discussed deeply in this section. Energy and exergy efficiencies in Boiler are identified at 90.62 % and 42.27%, respectively. Low exergy efficiency in the boiler caused a high-temperature gap between the combustion chamber and environmental conditions, which influenced the value of entropy in the process.

Table 3. Energy and exergy efficiency Thai's-PP component at maximum load.

Components		Energy η_{En} (%)	Exergy ψ_{Ex} (%)
Boiler		90.62	42.27
Turbine	HPT	86.77	80.45
	IPT	87.84	79.64
	LPT	87.35	80.95
Pumps	CEP	100.00	26.92
	BFP	100.00	88.86
Rejected Heat		98.99	52.15
HPH	1	99.97	98.34
	2	99.94	91.40
Deaerator		99.99	96.63
LPH	1	98.85	58.00
	2	99.86	79.39
	3	99.94	94.88
	4	99.99	96.36
Remained Heat		1.01	47.85

Further, a misunderstanding of condenser efficiency is explained. The condenser is categorized as a heat transfer device, and its function is to absorb the amount of heat from the stream and transfers it to the outside system. The waste heat of the condenser is not used for another purpose like the heat exchanger did. Based on that reason, the efficiency of the condenser is separated. The condenser energy efficiency represents by rejected heat and remained heat in the stream. Based on heat rejection, the condenser energy efficiency is around 98.99%, while based on heat remaining is about 1.01%. This value accounts from the remaining heat of the stream in it. Later, the exergy efficiency of the condenser is higher than boiler because of its smaller entropy change and temperature gap in the process.

Table 4. Energy and exergy ratio Thai's-PP component at maximum load.

Components		Energy REn,L (%)	Exergy REx,D (%)
Boiler		14.57	84.60
Turbine	HPT	2.29	3.08
	IPT	2.84	4.42
	LPT	3.07	4.20
Pumps	CEP	0	0.12
	BFP	0	0.12
Rejected Heat		76.24	1.81
HPH	1	0.03	0.71
	2	0.02	0.18
Deaerator		0.00	0.18
LPH	1	0.11	0.12
	2	0.03	0.27
	3	0.01	0.10
	4	0.00	0.11
Condenser		1,29	0.95

Then, the energy and exergy loss ratio of all components calculated by equations 9 and 17 are presented in **Table 4**. The energy or exergy loss ratio informs how significant energy loss and exergy destruction occur in each component. The smaller energy and exergy ratio, the higher energy and exergy efficiency can be achieved.

Details of energy and exergy balance on Thai-PP were clearly shown in **Figure 3** and **4**, respectively. According to the energy analysis in **Figure 3**, the rejected heat process of the condenser has contributed a significant value of energy loss of around 353.73 MW or around 49.11% of the total energy input. Then, it was followed by the boiler and turbines. The heaters and deaerator loss are less than 0.1 %. Different from energy analysis, exergy analysis identified that the highest exergy destruction occurs in the boiler around 57.713% and turbines around 0.08%, respectively as shown in Figure 4. Later, exergy destruction in the condenser is accounted only 5.21 MW or 0.006% of the total exergy input. It describes that energy analysis only investigates the quantity of energy process; meanwhile, exergy analysis evaluates energy from the quantity and quality side.

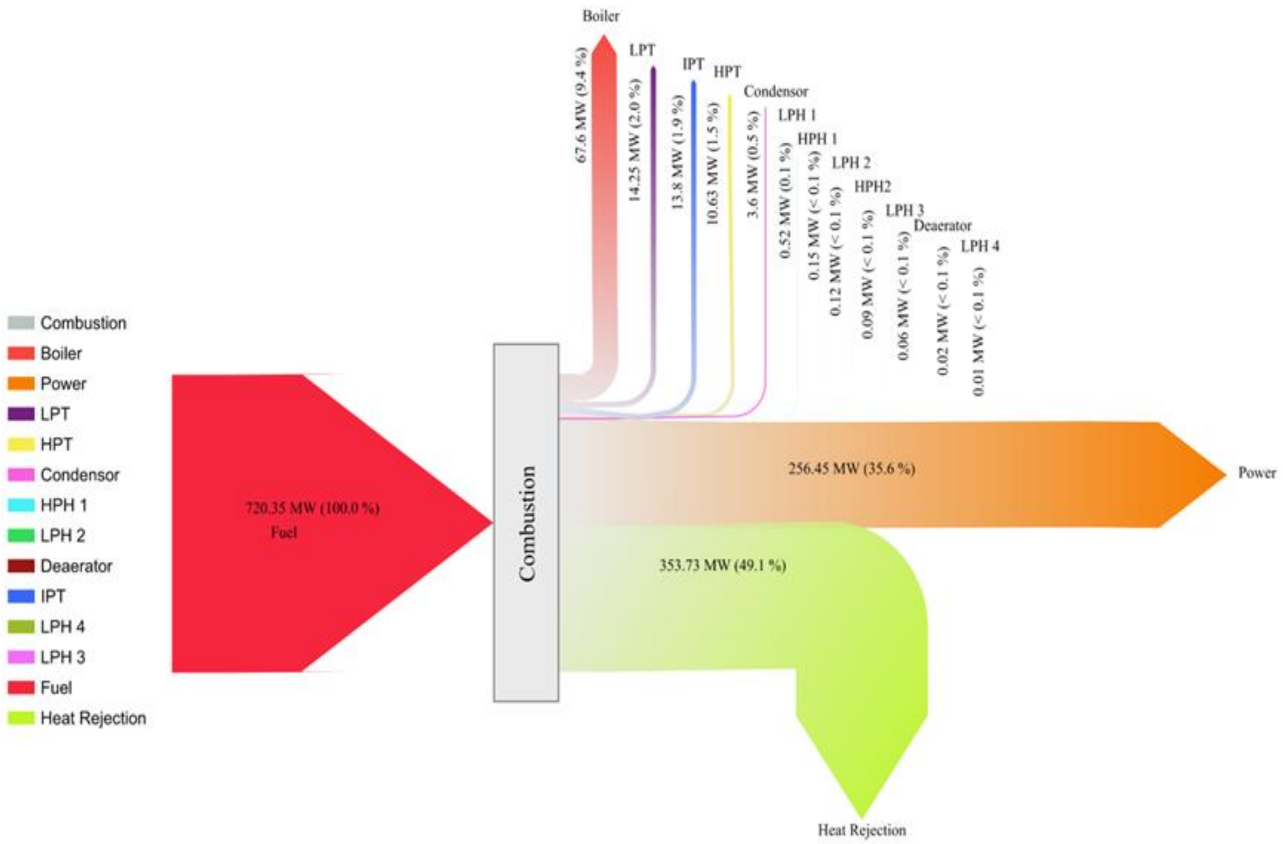

Figure 3. Energy balance of Thai's PP at maximum load

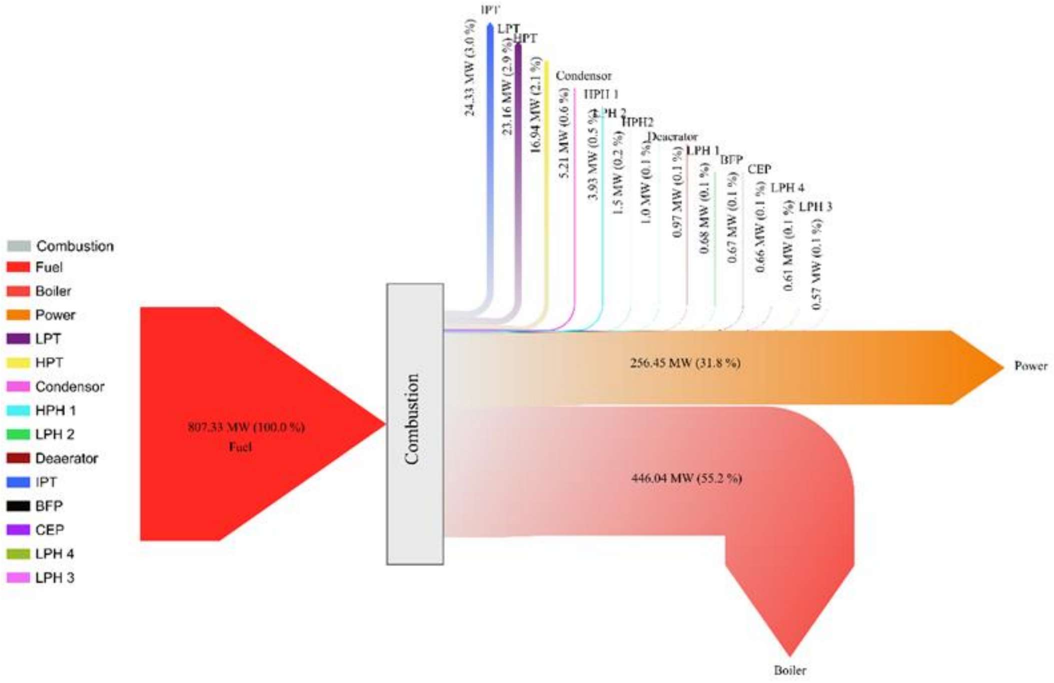

Figure 4. Exergy balance of Thai's PP at maximum load

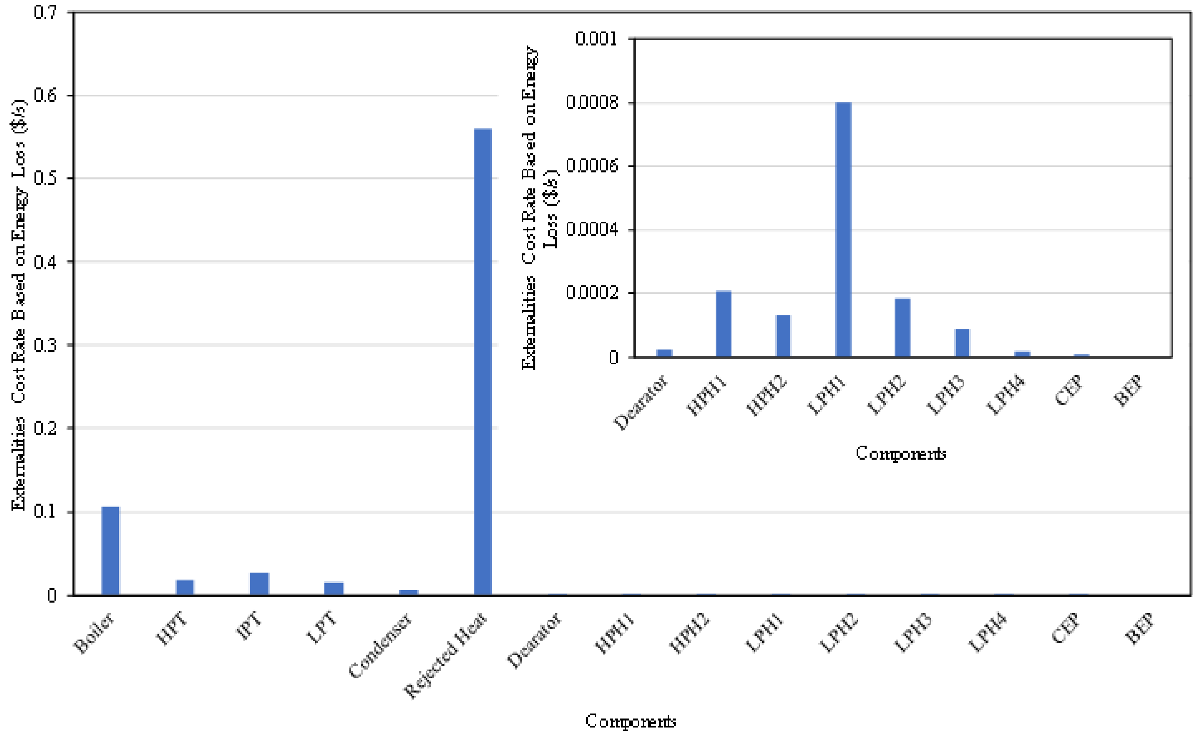

Figure 5. Externalities cost rate distribution of Thai's PP based on energy loss.

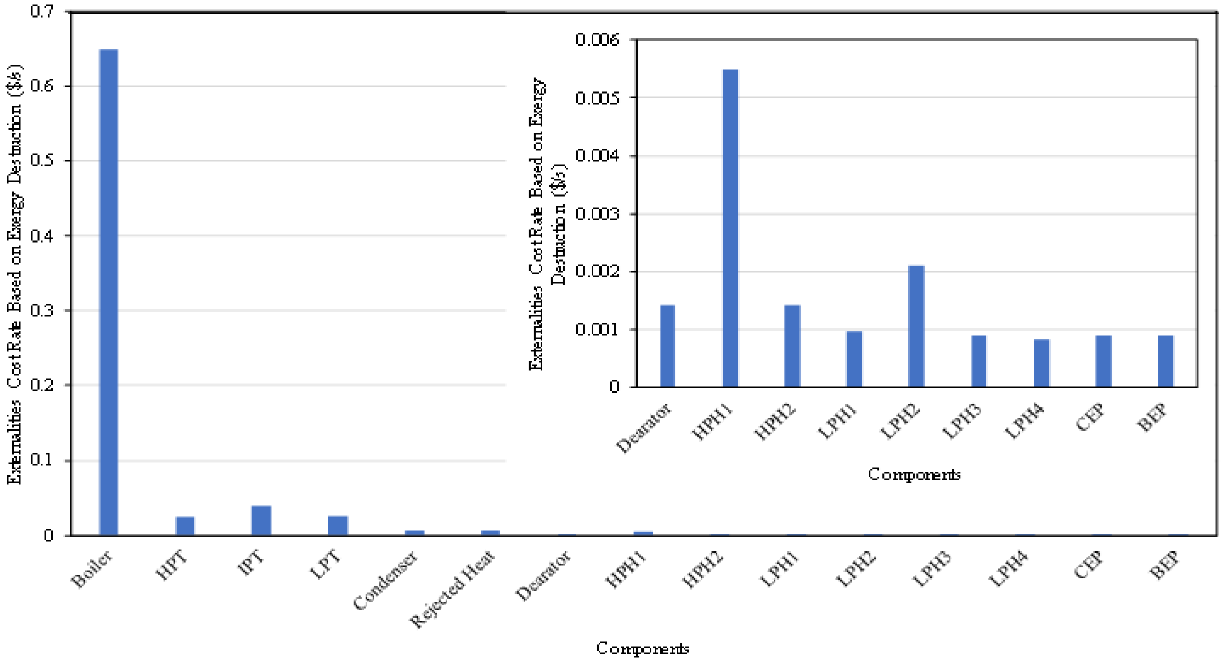

Figure 6. Externalities cost rate distribution of Thai's PP based on exergy destruction

Figures 5 and **6** represent the Energy externalities cost rate based on the first and second law of thermodynamics, which calculate based on equations 18 and 19. **Figure 5** shows that the externalities cost rate is based on energy loss in Thai's PP caused by the heat rejection process at the condenser, at which the rate was about 0.57 $/s. Then, figure 6 shows that the externalities cost rate of exergy destruction identifies at the boiler. The rate was about 0.64 $/s. Nevertheless, it can be concluded that the externalities cost rate using the second law of thermodynamics is more reasonable than the first law in terms of quantity and quality of energy in each stream.

Later, the saving cost is an important part of this analysis. Saving cost is the amount of allocated money that can be achieved for another purpose from reutilised energy in the plant. It could be estimated by multiplying both externalities' costs with the operating time of the plant in a year, as given in the previous section. Hence, Thai's PP has potential cost saving based on energy loss of around 22.39 million $/year, whereas around 23.95 million $/year based on exergy destruction.

CONCLUSION

Three types of analysis focused on the first and second law of thermodynamics. It identified where the largest energy loss and exergy destruction occur technically in the system. It also analysed contribution of energy loss and exergy destruction in terms of currency rates, and calculated potential cost saving by converting energy loss and exergy destruction in terms of cost.

In a Thai's PP, the energy loss at the condenser was the highest among the major units of the power plants. Rejected heat that was contributed by condensers in that plant reached 49.11% at full load condition and was followed by the boiler, turbine, etc. Furthermore, the boiler was identified as the highest exergy destruction producer, which had around 57.73% of total exergy input into the system, followed by turbines, heaters, etc. In addition, the energy and exergy efficiency of Thai's PP was identified to be around 35.60% and 31.76%, respectively.

The externalities cost rate based on energy loss and exergy destruction was conducted to identify which component should be improved. The externalities cost of heat rejection of the plant took place at the condenser, which contributed around 76.63% of the total externalities cost based on energy loss. As known, the heat rejection is a compulsory process in energy analysis, so it cannot avoid in the thermodynamics cycle of the plant. However, externalities cost analysis of energy losses identified that the boiler was the component essential to be paid attention. Further, the externalities cost of exergy destruction was also agreed that the boiler is required to be improved due to its contribution of around 84.96% of the externalities cost of exergy destruction. Since exergy analysis considered more on quantity and quality of energy, it suggested boiler and turbine required to be improved. By improving boiler and turbine components, Thai's PP has a potential cost saving of around 21.2 million $/year which reduces 88.44% of the externalities cost of exergy destruction.

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Author Contributions

The main contributor of this research is M.P. Helios and A. Andini; the other authors are supporting contributors to this work.

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NOMENCLATURES

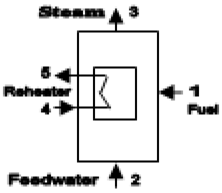
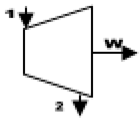
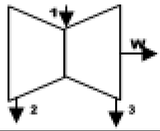
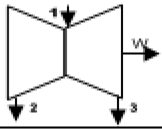
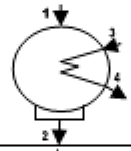
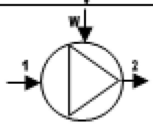
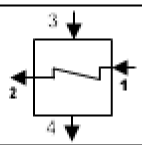
Symbol	Description	Unit
$\dot{E}x$	Exergy	(kW)
$\dot{e}_x$	Specific exergy	(kJ/kg)
$\dot{E}_{x_D}$	Exergy destruction	(kW)
$\dot{E}_{x_L}$	Exergy loss	(kW)
$\dot{E}$	Energy rate	(kW)
$\dot{E}_{n_L}$	Energy loss	(kW)
$\dot{m}$	Mass flow rate	(kg/s)
h	Enthalpy	(kJ/kg)
s	Entropy	(kJ/kg.K)
$\dot{e}_x^{ch}$	Chemical exergy	(kJ/kg)
$\dot{e}_x^{tm}$	Thermo-mechanical exergy	(kJ/kg)
T	Temperature	(℃)
$\dot{Q}$	Heat rate	(MW)
$\dot{W}$	Power output	(MW)
η	Energy efficiency	(%)
ψ	Exergy efficiency	(%)
Σ	Summation	
c	Specific cost	($/GJ)
$\dot{c}$	Cost rate	($/s)
t	Operating time	(s)
C	Carbon fraction	(%)
H	Hidrogen fraction	(%)
O	Oxygen fraction	(%)
S	Sulphur fraction	(%)
N	Nitrogen fraction	(%)
w	Moisture fraction	(%)
LHV	Low heating value	(kJ/kg)
HHV	High heating value	(kJ/kg)
R	Ratio	

Subscript

w	Water
s	Steam
in, out	Input and output stream
1, 2	1 and 2 stream
net	Net
th	Thermal
En, f	Fuel, based on energy content
Ex, f	Fuel, based on exergy content
i, k	Represent components
o	Environment reference
tot	Total
en	Energy
ex	Exergy
v	Vapour
op	Operating

Appendix

Appendix 1. Exergy equations of Thailand's coal-fired power plants.

No.	Components	Scheme	Exergy destruction	Exergy efficiency
1	Boiler		$Ex_{D,B} = Ex_1 + Ex_2 + Ex_4 - Ex_3 - Ex_5$	$\psi_{Ex,B} = \frac{(Ex_3 - Ex_2) + (Ex_5 - Ex_4)}{(Ex_1)}$
2	HP Turbine		$Ex_{D,HPT} = Ex_1 - Ex_2 - W$	$\psi_{Ex,HPT} = W/(Ex_1 - Ex_2)$
	IP Turbine		$Ex_{D,IPT} = Ex_1 - Ex_2 - Ex_3 - W$	$\psi_{Ex,IPT} = W/(Ex_1 - Ex_2 - Ex_3)$
	LP Turbine		$Ex_{D,IPT} = Ex_1 - Ex_2 - Ex_3 - W$	$\psi_{Ex,IPT} = W/(Ex_1 - Ex_2 - Ex_3)$
3	Condenser		$Ex_{D,C} = Ex_1 + Ex_3 - Ex_2 - Ex_4$	$\psi_{Ex,C} = (\dot{E}x_4 - \dot{E}x_3)/(\dot{E}x_1 - \dot{E}x_2)$
4	Pump		$Ex_{D,P} = Ex_1 + W - Ex_2$	$\psi_{Ex,P} = (Ex_2 - Ex_1)/W$
5	Heater		$\psi_{Ex,H} = (Ex_1 - Ex_2)/(Ex_3 - Ex_4)$	$\psi_{Ex,H} = (Ex_1 - Ex_2)/(Ex_3 - Ex_4)$