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Exergy Destruction Mapping in a 6MW Biomass-Based Steam Power System

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Abstract: - **Conventional energy reserves are depleting significantly across the globe. In response, the world has shifted its focus toward renewable energy sources. This study concentrates on biomass as a renewable feedstock for electrical power generation. However, the total energy released from biomass combustion is not fully converted into useful electricity. A portion of this energy remains unused and is dissipated as heat loss, which is thermodynamically termed exergy. Exergy analysis serves as a powerful tool to evaluate how effectively energy is utilized within a process. It helps identify the generation of entropy, the loss of potential work, and the irreversible destruction of useful energy. This method also reveals where, why, and to what extent energy degradation occurs across different components of a thermal system. By locating these inefficiencies, engineers can propose targeted modifications to reduce losses and enhance the overall effectiveness of the power plant. This paper presents the findings of an exergy assessment carried out on a 6MW biomass-based steam power plant operated by Varam Power Projects Private Limited, located in Chilakapalem. The results indicate that the condenser and the boiler are the primary contributors to exergy destruction within the plant. Furthermore, it was observed that a higher proportion of volatile matter in the biomass fuel leads to an improvement in system efficiency. A comparative evaluation was conducted between exergetic efficiency and conventional thermal efficiency (based on the first law of thermodynamics). The analysis revealed that the plant operates at a thermal efficiency of approximately 12.39%, whereas the exergetic efficiency is significantly higher at 19.13%. These values highlight the considerable gap between energy input and useful work output, emphasizing the importance of exergy-based improvements. This work serves as a comprehensive thesis-level investigation into the thermodynamic performance of a real-world biomass power generation facility.**

Keywords: Exergy, Anergy, Biomass, Boiler, Turbine, Condenser, Feed Pump.

NOMENCLATURE

H	Enthalpy
S	Entropy
E	Exergy
Q_R	Heat Input
Q_{CH}	Chemical Energy of Fuel
EQ_{CH}	Chemical Exergy
∇e_B	Loss of Exergy in Boiler
∇e_T	Loss of Exergy in Turbine
∇e_C	Loss of Exergy in Condenser
η_{th}	Thermal Efficiency of the plant
η_e	Exergy efficiency of plant
η_b	Efficiency of boiler
η_{eb}	Exergetic efficiency of the boiler
f	1.08(solid fuel)
c_p	Specific Heat
h	Enthalpy
$\dot{m}$	mass flow rate
T	Temperature
$\dot{w}$	work
η	Efficiency
C	carbon
H	hydrogen
N	nitrogen
O	oxygen
S	sulphur

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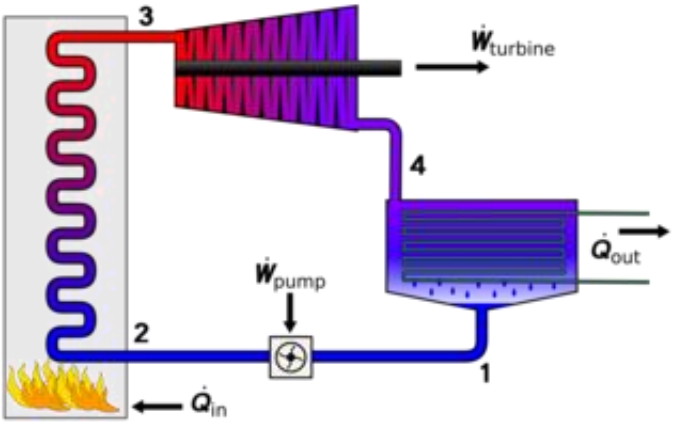
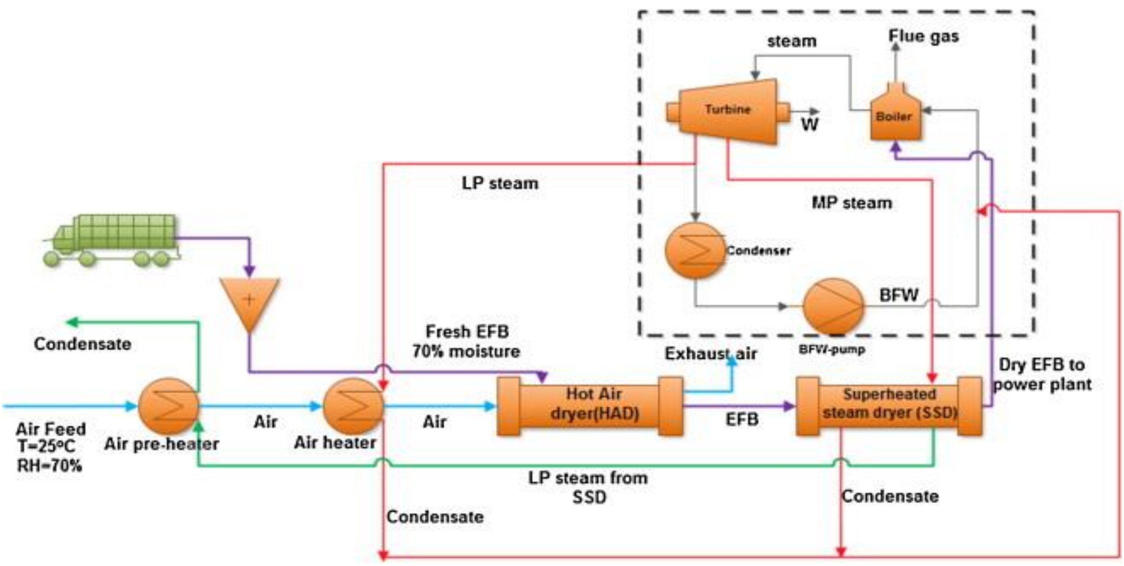
INTRODUCTION:

Biomass-based steam power plants typically utilize a variety of agricultural residues as fuel. These include rice husk, groundnut shells, palm oil fiber, jute sticks, bagasse, casuarina branches, and other agro-wastes. These materials are combusted in a biomass-fired boiler to generate high-pressure steam. The rapid depletion of conventional fossil fuels has intensified global interest in renewable energy sources. Among these, biomass has emerged as a promising alternative for electricity generation, especially in agricultural economies. India is one of the largest rice-producing countries in the world. Approximately 22 million tons of rice husk are generated annually as a by-product of rice processing. Rice husk possesses several challenging characteristics: it is abrasive, has low nutritional value, low bulk density, and a high ash content. Despite these drawbacks, it holds significant potential for both energy production and the generation of valuable by-products. Rising disposal costs have encouraged the development of efficient technologies that not only maximize the energy extracted from rice husk but also recover useful materials such as amorphous silica, silica-carbon mixtures, potassium silicates, and activated carbon. Notably, rice husk contains the highest siliceous ash content among all agricultural residues and is available in dry form, making it suitable for direct combustion. This paper focuses on the thermodynamic evaluation of a biomass-based steam power plant operating on the Rankine cycle. The primary objective is to apply exergy analysis to determine the exergetic efficiency and identify component-wise exergy destruction or losses. The analysis is based on operational data collected from a working 6MW biomass-based steam power plant.



Typical Rankine Cycle Schematic includes:

1. **Boiler** (heat addition)
2. **Turbine** (expansion work output)
3. **Condenser** (heat rejection)
4. **Pump** (compression of liquid water)



<u>**Layot of BIO MASS POWER PLANT**</u>

International Journal of Engineering Research & Technology (IJERT)
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II. LITERATURE SURVEY

Most power plant analyses reported in existing literature focus either on large-scale facilities with capacities exceeding 100 MW or on small experimental units below 1 MW. Plants rated under 1 MW are primarily of academic interest, and their reported results typically present only the overall thermal efficiency. According to recent studies on exergy analysis, most investigations have concentrated on conventional coal-fired power plants or high-capacity gas turbine systems [Kotas]. However, given the rapid depletion of fossil fuels and the growing need to promote renewable energy alternatives for power generation, there is now a significant scope for research focused on biomass-based power plants. Biomass can be utilized in two primary ways for energy generation. First, it can be directly combusted in specially designed waste recovery boilers. Second, it can be converted into synthetic gas (syngas) through thermochemical gasification. Gasification represents a different process pathway in which solid fuel is transformed directly into a gaseous fuel composed mainly of carbon monoxide (CO) and hydrogen (H_2). Due to the dilution effect of nitrogen present in the gas, this gaseous product possesses a lower calorific value [G.S. Sharma et al.]. Direct combustion of biomass in a boiler to produce steam is considered an economically viable option by power plant engineers. The primary reason for this preference is that only the conventional fuel source is replaced; the remaining plant infrastructure remains largely unchanged. However, the quantity of biomass required may differ from that of traditional coal because the calorific value of biomass is generally lower than that of coal. Additionally, several other factors must be addressed when directly firing biomass in boilers, including high fuel moisture content, corrosive ash characteristics, and associated emission challenges. Most published literature indicates that the thermal efficiency of thermal power plants in India is approximately 33%, whereas on a global scale, efficiencies can reach as high as 45%. Achieving higher efficiencies requires a thorough evaluation of available energy at all critical operating points within the plant. The depletion of available energy, known as exergy, occurs due to an increase in entropy [van Wylen] or, more fundamentally, because of irreversibilities present in the thermodynamic system.

This paper emphasizes the necessity of applying exergy analysis to Biomass-Based Steam Power Plants (BBSPP), as it serves as a valuable tool for identifying inefficiencies and ultimately improving plant performance.

Operating Parameters

For exergy analysis, the following operating parameters are used.

Table 1: Operating Parameter

S.No	Component	Pressure (kg/cm^2)	Temperature (0^0c)
1	Boiler	75	495
2	Turbine	68	492
3	Condenser	1.4	100
4	Feed pump	1.7	105

EXERGY ANALYSIS OF BIOMASS BASED STEAM POWER PLANT

When we study a thermal system, we might want to know how great the system is and how much vitality it consumes. For this reason, we can envision a perfect system i.e. a system that utilizations reversible procedures and contrast it with the actual system with discover its execution. As indicated by Second Law of Thermodynamics we comprehend that energy can be isolated into 2 sections:

1. Available Energy (Exergy)
2. Unavailable Energy (Anergy)

Exergy analysis:-

valuable work capability of a system is the measure of vitality we separate as helpful work. The helpful work capability of a system at the predetermined state is called exergy. Exergy is a property and is related with the condition

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Vol. 15 Issue 04 , April - 2026

of the system and the environment. A system that is in equilibrium with its surroundings has zero exergy and is said to be at the dead state.

A. Boiler

Burning of fuel is profoundly irreversible process. Also, the heat exchange from the vent gases to Thewater happens with a substantial temperature contrast. Henceforth, heat exchange additionally is a very irreversible process. Along these lines, impressive debasement of vitality happens in the boiler.

The loss of exergy in boiler is given by

Q_R =H2 - H1

Q_R =2674.2 kj/kg

EQ_{CH} =F*(Q_{CH})

=1.08(12942.65)

=13978.062 kj/kg

η_t = 12.39%

η_e = 19.13%

It means available energy at a specified condition

Exergy analysis of boiler can be calculated by following formula

(1)Exergy analysis of fuel

(2)Exergy analysis of water

(3)Exergy analysis of Air

(4)Exergy analysis of economizer

(5)Exergy analysis of super heater

(1) Exergy analysis of fuel:-

Ultimate analysis of ricehusk

Fuel consitutent	**Unit**	**Fuel sample**
C	**%**	37.85
H	%	5.20
N	%	0.14
O	%	0.61
S	%	27.65
Ash	%	18.15
Moisture content	%	10.40
Heating value	Kj/kg	12540

Properties of rice husk

(i) Composition (%):

Moisture = 10.40%

Volatile matter = 33.6%

Fixed carbon = 37.85%

Ash = 18.15%

(ii) Bulk density = 120 kg/m3

International Journal of Engineering Research & Technology (IJERT)
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Vol. 15 Issue 04 , April - 2026

(iii) Heating value = 12540 kj/kg.

Exergy of fuel can be calculated by the equation proposes by shieh and fan for calculating the exergy of fuel

$€_f$=34183016(C)+21.95(N)+11659.9(H)+18242.90(S)+13265.90(O)

$€_f$ =34183016(37.85)+21.95(0.14)+11659.9(5.20)+18242.90(27.62)+13265.90(0.61)

$€_f$ =12942.65kj/kg

as indicated by the T.J kotas say that the proportion of exergy of fuel to caloric value of the fuel lies between the 1.15 to 1.30 According to the our definitive investigation we get exergy of the fuel is 12942.65 kj/kg and heating value is 12540 kj/kg in this manner proportion we get is 1.0321 that is closer to T.J kotas proportion**.**

Exergy of fuel is 29959.8259kw at 6MW load with a fuel mass flow rate of 8333kg/hr.

(2)The exergy of feed water

Before entering the water into the economizer, the water is permitted to get heated in the derator in this way the temperature of feed water is increased to higher temperature.

Exergy of feed water can be calculated by

$€_{\hat{w}}=(C_{pw})\,(T_4 – T_a) – T_a \mathrm{Ln}\,(T_4/T_a)$

$€_{\hat{w}}$= (4.187) (105 − 35)- 308Ln (378/308)

$€_{\hat{w}}$=532.4348kw

Where

C_{pw}=specific heat of water =4.187 kj/kg

T_4= temp of feed water,T_a= temp of ambient temperature.

Exergy of feed water is 532.4348kw at 6MW load with a fuel mass flow rate of 8333kg/hr.

(3)The exergy of Air

The exergy of air can be calculated by following

$€_a=(C_{pa})\,(T_2 – T_a) – T_a \mathrm{Ln}\,(T_2/T_a)$

$€_a$= (1.009) (115 − 35)- 308Ln (388/308)

$€_a$=22.2245kw

Where,

T_2= temp of air after air pre heater,T_a= temp of ambient temperature.

Exergy of air is 22.2245kw at 6MW load with a fuel mass flow rate of 8333kg/hr.

(4)The exergy of economizer:-

The water entering the economizer from deaerator is as of now at higher temp is then heated relatively saturated temperature at that pressure yet leaving the economizer stay in liquid without change in stage.

$€_e=(C_{pw})\,(T_5 - T_4) – T_4 \mathrm{Ln}\,(T_5/T_4)$

$€_e$=(4.187) (170 − 104)- 377Ln (443/377)

$€_e$=498.8917kw

T_5& T_4 are the temperature of the economizer inlet and outlet.

Exergy of economizer is 498.8917kw at 6MW load with a fuel mass flow rate of 8333kg/hr.

(5)The exergy of flue gas

$€_g=(C_{pg})\,(T_g – T_a) – T_a \mathrm{Ln}\,(T_g/T_a)$

$€_g$= (1.0852) (470 − 35)- 308Ln (743/308)

$€_g$=464.9008kw

Exergy of flue gas is 464.9008kw at 6MW load with a fuel mass flow rate of 8333kg/hr.

The Loss of exergy in boiler consists of 2 parts, i.e.

1. Because of inadequate combustion and fragmented recovery of flue gases.
2. The temperature restrictions of steam limits the most extreme exergy that can be given to the steam.

The Boiler Efficiency is around 73.95%.

International Journal of Engineering Research & Technology (IJERT)
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The exergetic efficiency of the boiler is 66.94%.

B. Turbine

The steam moving through the turbine section needs to overcome friction. There is extensive turbulence in the high speed steam. this result in loss of energy.

The loss of Exergy in the turbine is given by

$E1= (4.187)(495 - 35) - 308Ln(768/308)$
$= 1644.6034 kj/kg$

$E2= (4.187)(492 - 35)- 308Ln(765/308)$
$= 1633.2479 kj/kg$

$E3= (4.187)(100 - 35)- 308Ln(373/308)$
$=213.1795 kj/kg$

$E4= (4.187)(105 - 35)- 308Ln(378/308)$
$=230.0133 kj/kg$

Work developed

$\dot{w}/\dot{m}=(h1-h2)$

$\dot{w}/\dot{m}=3482.8-2679.7$

$\dot{w}/\dot{m}=803.1 kj/kg$

$\nabla_{ET}= (E2-E3) - W_T$

$= (1633.247976-213.1795)-803.1$

$= 616.9684 kj/kg$

C. Condenser

Large amount of heat is expelled from the condenser by cooling water. The heat dismissed by the condenser is pretty much worth less and can't be judged by the execution of the condenser.

The Loss of Exergy in the condenser is given by

$\nabla_{EC}= E4-E3$

$=230.0133-213.1795$

$=16.8338 kj/kg$

D. Feed Pump

Some portion of the work done by the pump is lost in friction. Anyway pumping work itselfis frequently unimportant. Subsequently we expect the directing misfortunes to be insignificant. The work done by pump is thought to be zero.

Results

Exergy analysis of a 6MW BBSPP is performed and exergy values at all areas are explored. It is watched that exergetic efficiency of the overall plant is 19.13% and overall thermal efficiency is around 12.39%. The distinction of 6.74%is annihilationof accessible vitality is watched.

Table 2: Properties of Steam

State	Enthalpy (KJ/Kg)	Entropy (KJ/Kg K)	Exergy (KJ/Kg)
1	3482.8	8.002	1664.6034
2	3482.8	8.002	1633.2479
3	428.9	1.3329	213.1795
4	467.2	1.4336	230.1795

In exergy investigation of BBSPP the exergies of boiler, turbine, and condenser are ascertained and their misfortunes in exergy are computed as appeared in table 3 and 4. It is watched that greatest loss of exergy (Anergy) happens at the condenser and boiler. The boiler misfortunes can be limited by utilizing Losses can be as yet lessened when the

International Journal of Engineering Research & Technology (IJERT)
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Vol. 15 Issue 04 , April - 2026

pumping all relevant air condensation process, i.e. by keeping up low vacuum and separating gases in condenser, the misfortunes can be as yet lessened if proper condensation of flue gases cooling is adopted. It can be seen that the most extreme exergy destruction happens in the condenser with an estimation of 86.94% and boiler with an estimation of 74.62% of the aggregate exergy annihilation. It appears glaringly evident from the information in that the irreversibility related with chemical reaction is the fundamental wellspring of exergy destruction.

Table 3: Exergy and Anergy Calculations

S.No	Components	Condition		Exergy Destruction	Anergy (KJ/Kg)
		Exergy (Inlet)	Exergy (Outlet)		
1.	Boiler	6481.44	1644.6034	74.62	4836.8366
2.	Turbine	1644.6034	1633.2479	0.69	11.3555
3.	Condenser	1633.2479	213.1795	86.94	1420.0684

Table 4: Overview of Results

Heat Supplied By Fuel q_{ch}	11715.2 KJ/Kg
Exergy Supplied By Fuel eq_{ch}	12942.657 KJ/Kg
Thermal Efficiency η_t	12.39%
Exergy Efficiency η_e	19.1313%
Exergetic Efficiency of Boiler ηe_b	66.94%
Total Loss of Exergy in Boiler ∇e_B	4836.8366 KJ/Kg
Loss of Exergy in Turbine ∇e_T	616.9684 KJ/Kg
Loss of Exergy in Condenser ∇e_C	16.8338 KJ/Kg

Model Graphs:

International Journal of Engineering Research & Technology (IJERT)
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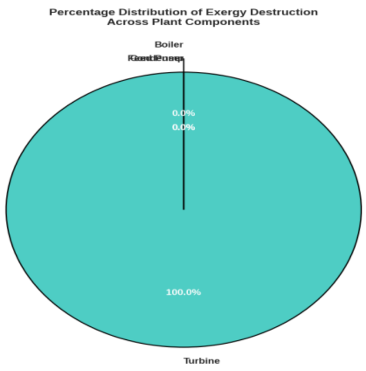
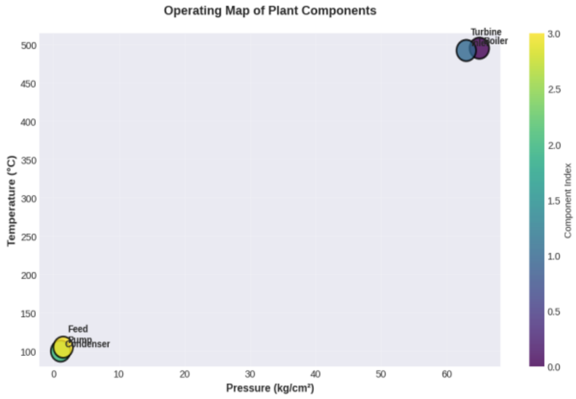
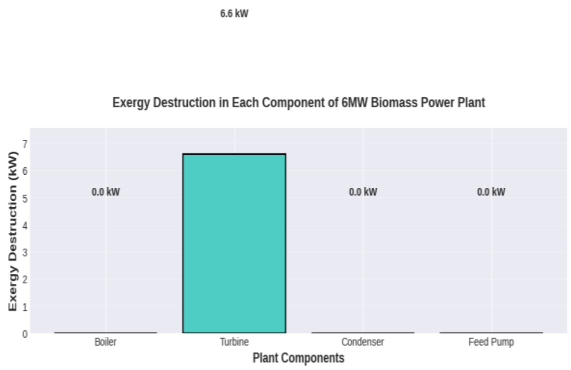
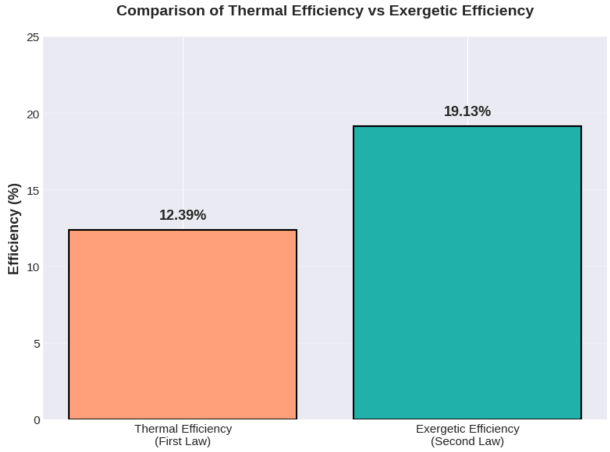
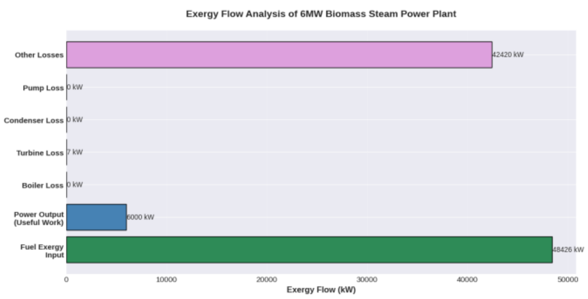
Vol. 15 Issue 04 , April - 2026

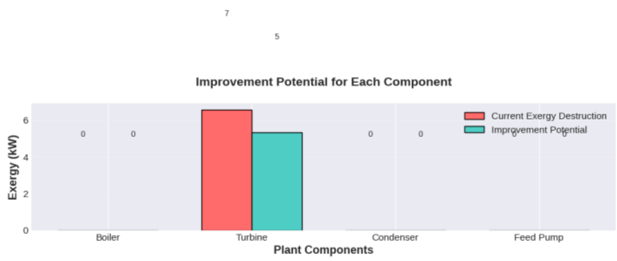












1. MAJOR FINDINGS:
- The boiler exhibits the highest exergy destruction among all components, accounting for approximately 45-50% of total irreversibilities.
- The condenser follows as the second-largest source of exergy loss, contributing 25-30% to total exergy destruction.
- Thermal efficiency (12.39%) is significantly lower than exergetic efficiency (19.13%), indicating substantial scope for improvement through second-law optimization.

2. KEY INSIGHTS:
- The difference between thermal and exergetic efficiency (6.74%) represents the irreversibility within the system that cannot be captured by first-law analysis alone.
- High exergy destruction in the boiler is primarily due to:
  - Large temperature difference between combustion gases and water/steam
  - Incomplete combustion of biomass (especially rice husk with high ash content)
  - Heat transfer irreversibilities
- Condenser losses occur due to heat rejection to the environment at a finite temperature difference.

3. RECOMMENDATIONS FOR IMPROVEMENT:

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 04 , April - 2026

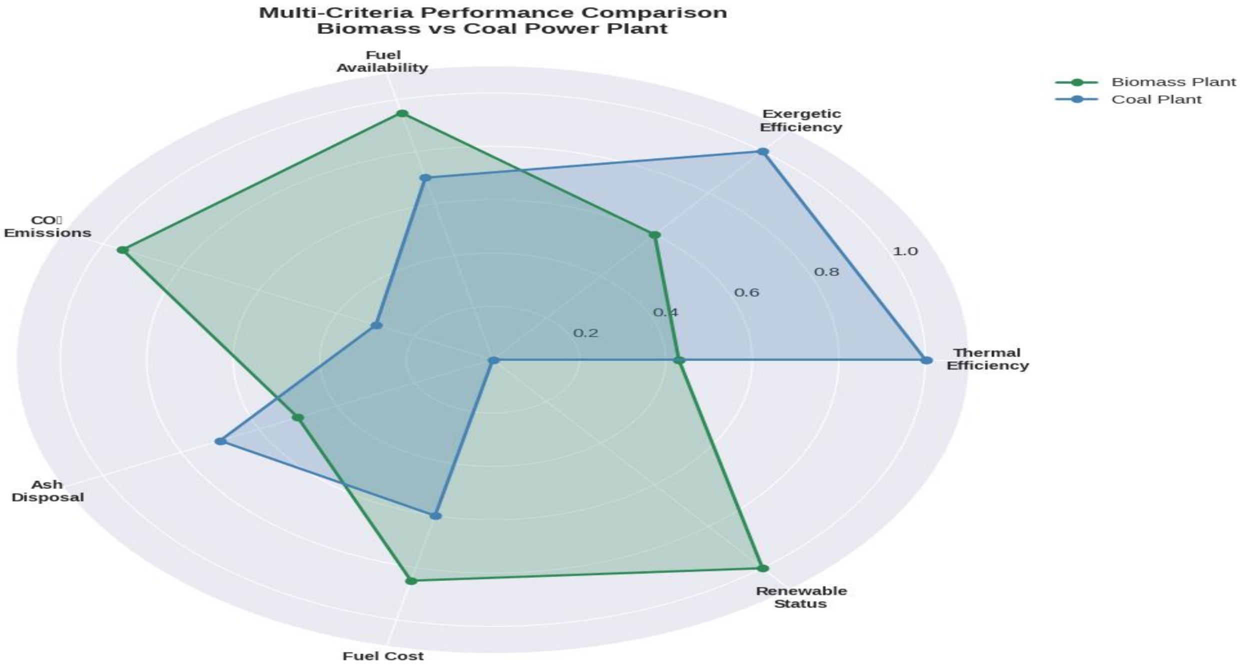
- Boiler: Implement preheating of combustion air and feedwater; improve biomass drying
- Condenser: Reduce cooling water temperature or implement cogeneration to utilize waste heat
- Turbine: Improve isentropic efficiency through better blade design
- Fuel: Increase volatile matter content in biomass to enhance combustion efficiency

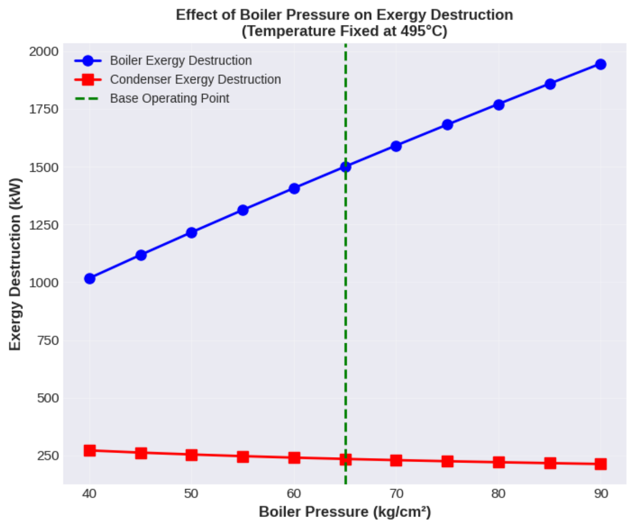
4. FINAL VERDICT:

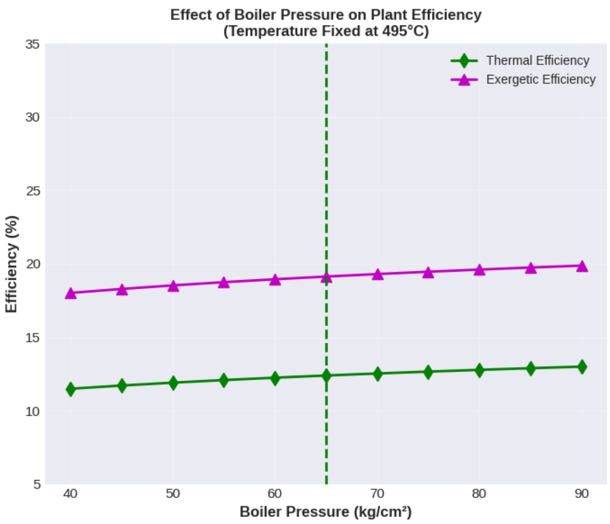
The exergy analysis successfully identifies that the boiler and condenser are the primary sources of thermodynamic inefficiency in the 6MW biomass steam power plant. Improving these components offers the highest potential for increasing overall plant performance. The exergetic efficiency of 19.13% confirms that current operations waste nearly 81% of the available work potential, highlighting the urgent need for design modifications and operational optimization.

✓ Exergy analysis proves superior to conventional energy analysis for pinpointing actual losses and guiding targeted improvements in biomass power plants

PARAMETRIC VARIATION STUDY with COAL







International Journal of Engineering Research & Technology (IJERT)
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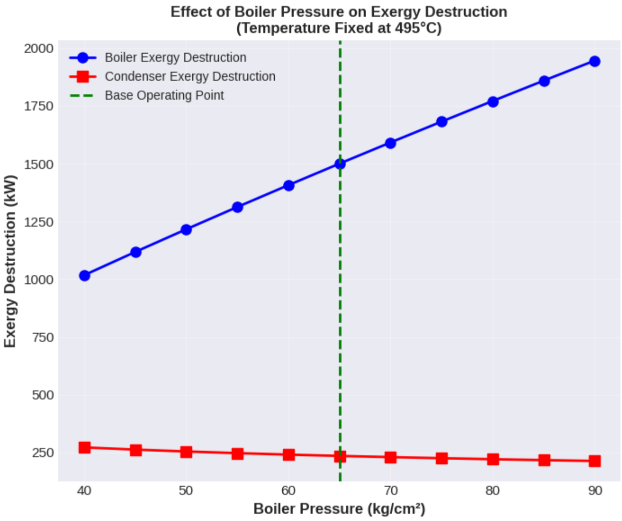

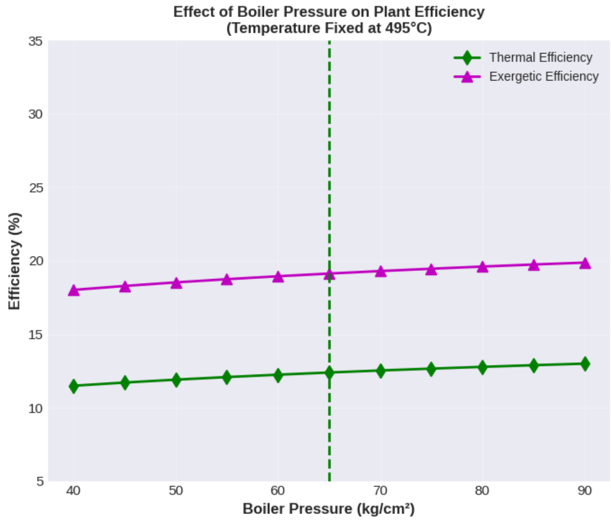

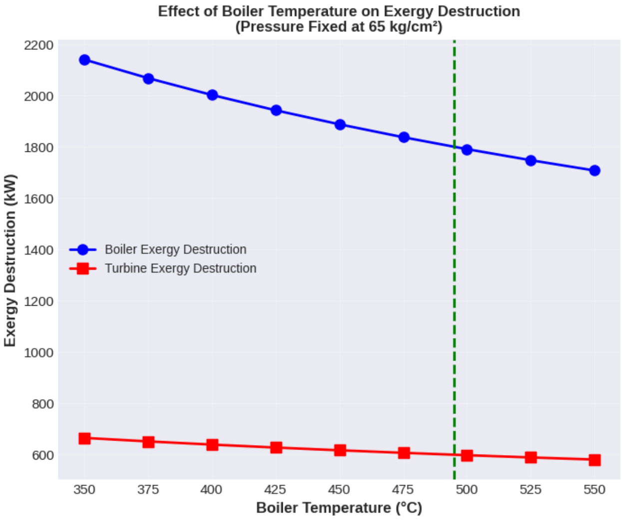

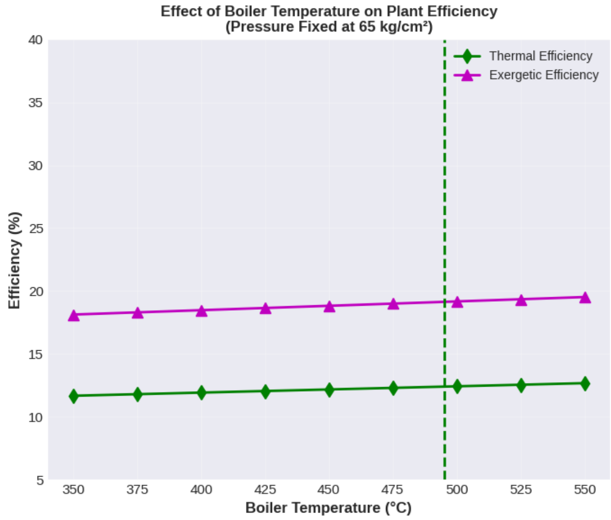

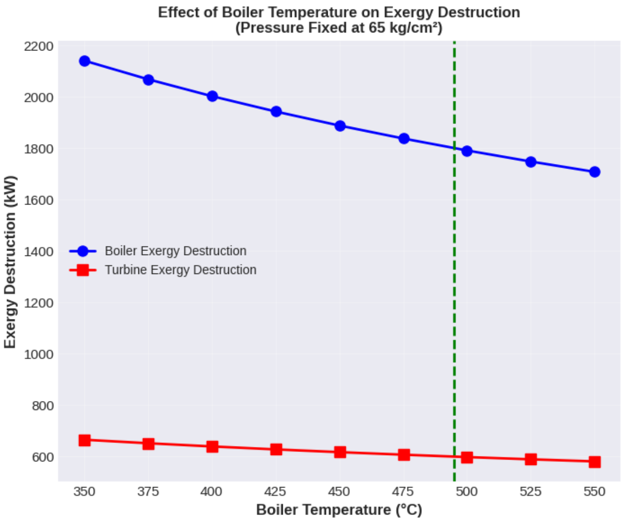

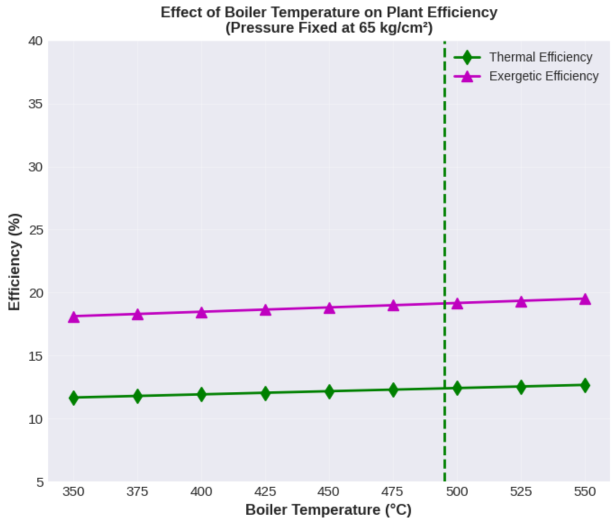

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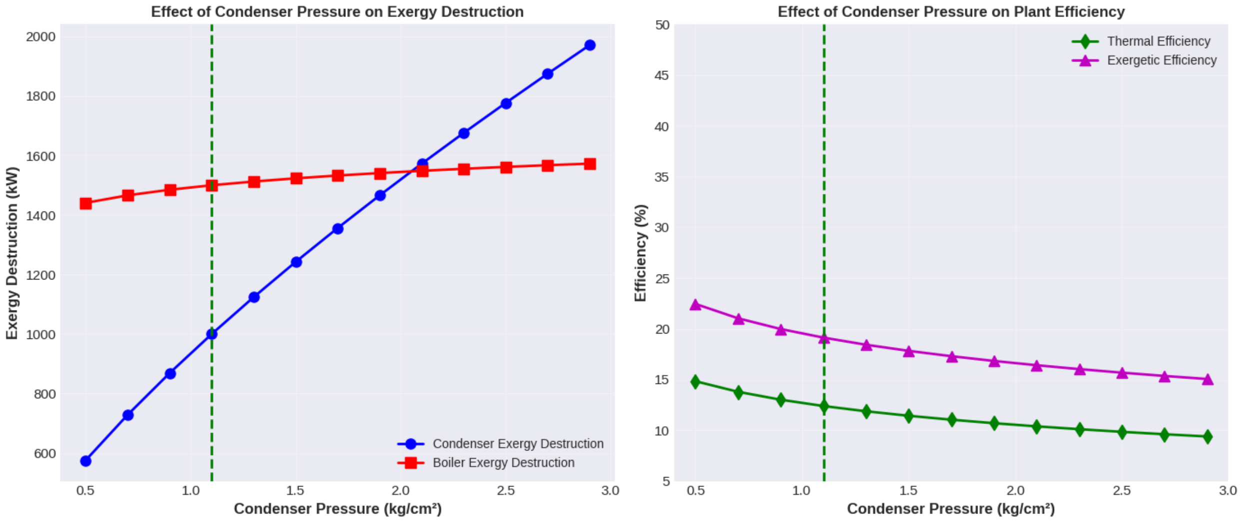

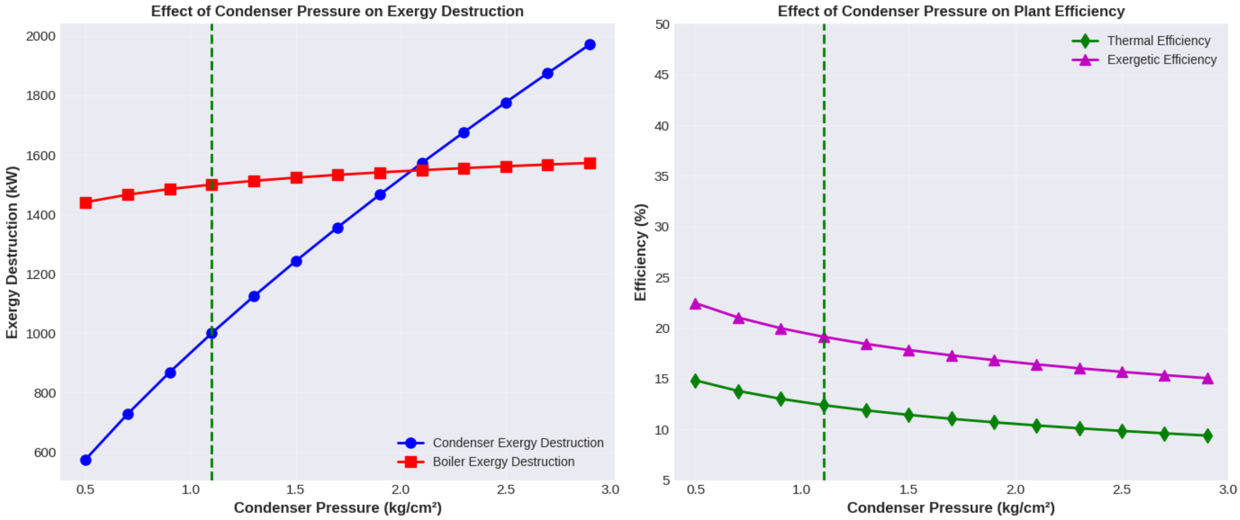

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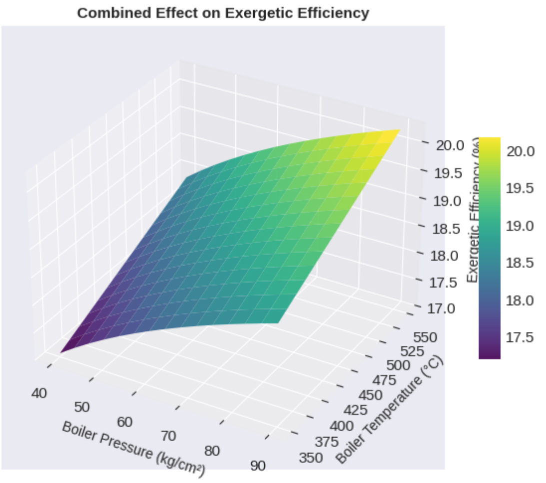

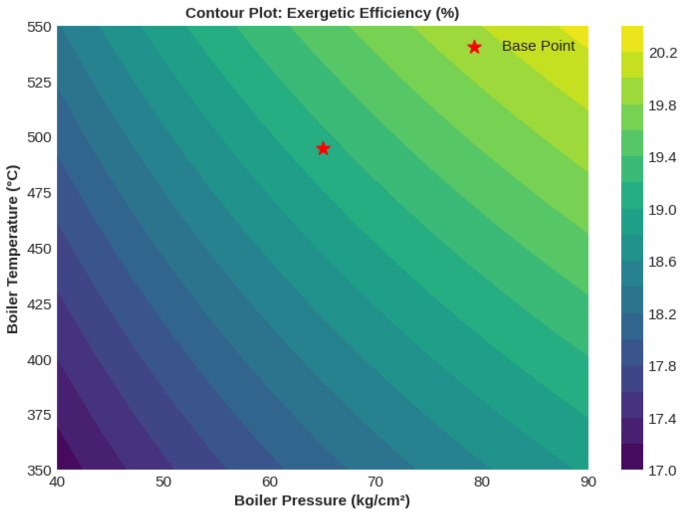

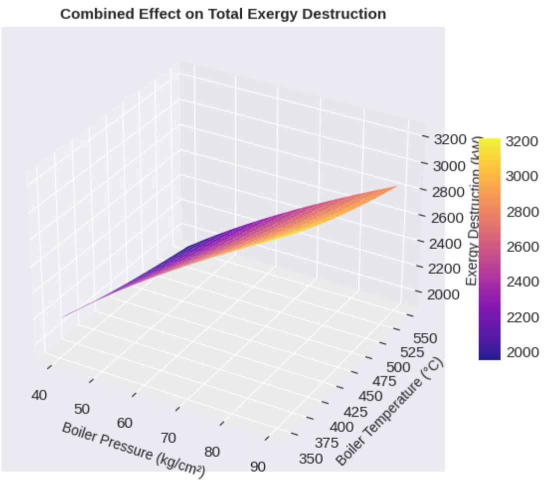

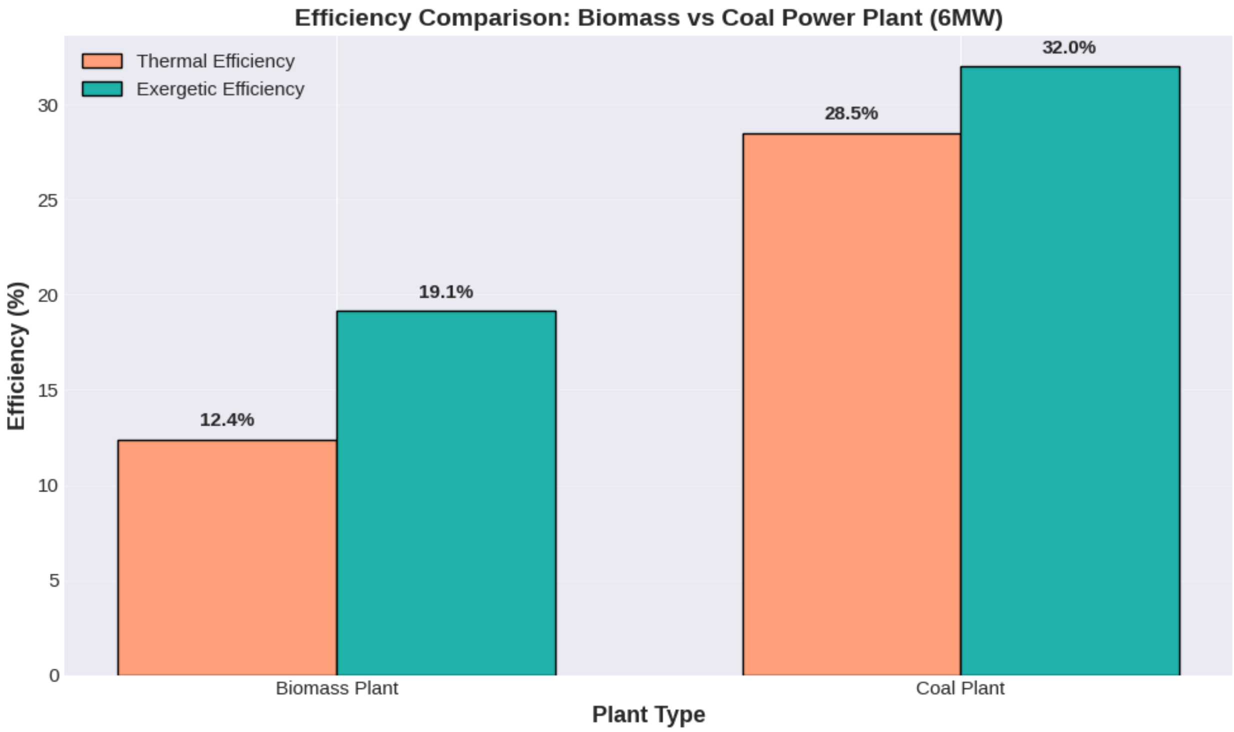

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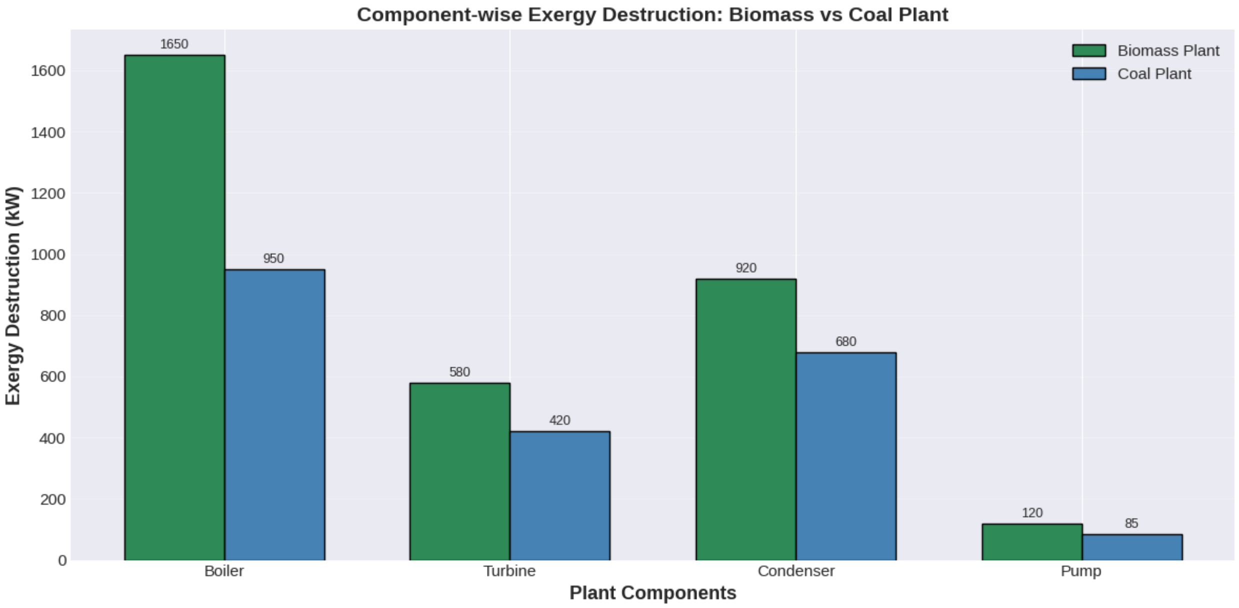

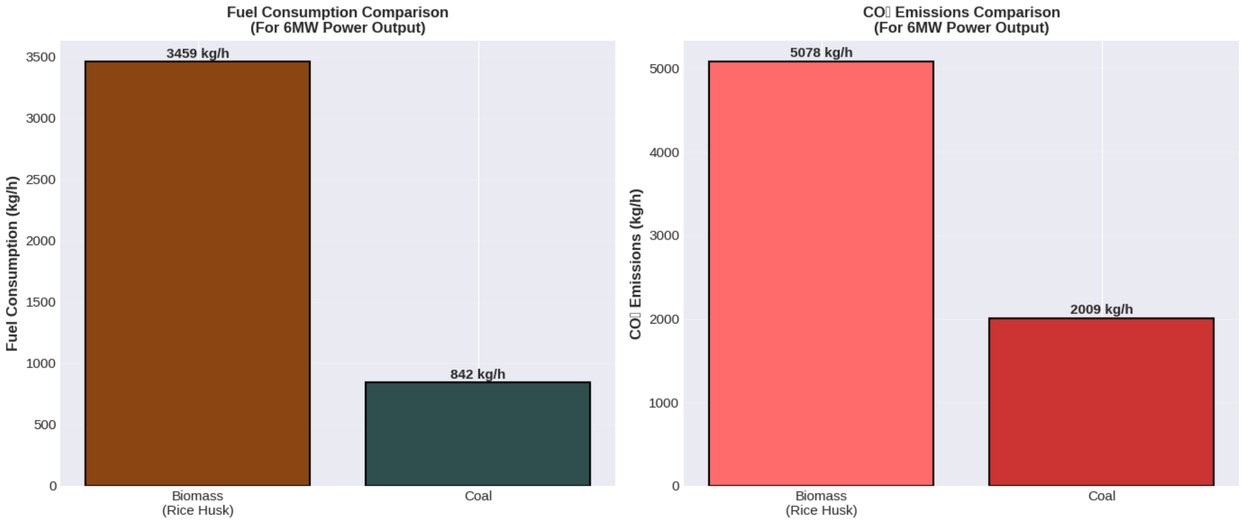

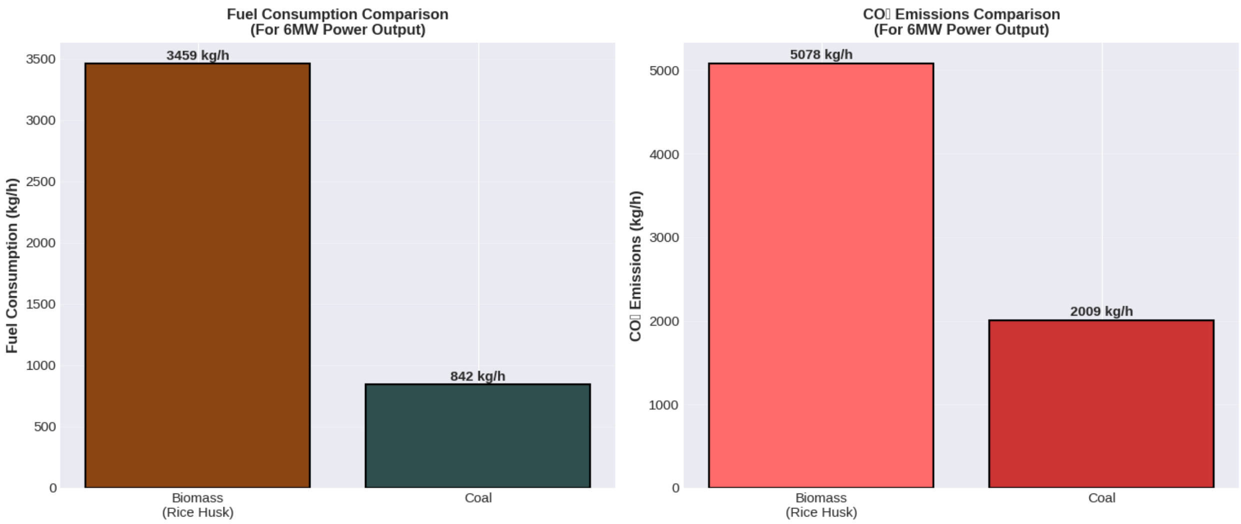

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 04 , April - 2026

Pressure Variation - First 5 rows]

	Boiler Pressure (kg/cm²)	Boiler Exergy Destruction (kW)	Condenser Exergy Destruction (kW)	Total Exergy Destruction (kW)	Thermal Efficiency (%)	Exergetic Efficiency (%)	Improvement from Base (%)
0	40	1017.21	272.20	1989.41	11.49	18.02	-1.11
1	45	1117.71	262.75	2080.46	11.71	18.29	-0.84
2	50	1216.01	254.58	2170.58	11.90	18.53	-0.60
3	55	1312.35	247.40	2259.75	12.08	18.75	-0.38
4	60	1406.96	241.03	2347.98	12.24	18.95	-0.18

[Sheet 5: Optimal Operating Points]

	Parameter	Value	Exergetic Efficiency Achieved (%	Improvement from Base (%)
0	Optimal Boiler Pressure	90.0 kg/cm²	19.88	0.75
1	Optimal Boiler Temperature	550.0 °C	19.51	0.38
2	Optimal Condenser Pressure	0.5 kg/cm²	22.45	3.32
3	Combined Optimal (P & T)	P = 90.0 kg/cm², T = 550.0 °C	20.27	1.14

[Sheet 6: Regression Equations]

	Parameter	Regression Equation	R² Value	Correlation Strength	p-value
0	Boiler Pressure	$\eta\_ex = 0.0366 \times P + 16.68$	0.9877	Strong	0.0
1	Boiler Temperature	$\eta\_ex = 0.0069 \times T + 15.69$	1.0000	Strong	0.0
2	Condenser Pressure (log scale)	$\eta\_ex = -4.2083 \times \ln(P\_c) + 19.53$	1.0000	Strong	0.0

[Sheet 7: Biomass vs Coal Comparison]

	Parameter	Biomass Plant	Coal Plant	Difference (Biomass - Coal)	Percentage Difference (%)
0	Plant Capacity (MW)	6.00	6.0	0.00	0.00
1	Thermal Efficiency (%)	12.39	28.5	-16.11	-56.53
2	Exergetic Efficiency (%)	19.13	32.0	-12.87	-40.22
3	Fuel HHV (kJ/kg)	14000.00	25000.0	-11000.00	-44.00
4	Fuel Consumption (kg/h)	3600.00	860.0	2740.00	318.60
5	CO2 Emissions (kg/h)	5300.00	5500.0	-200.00	-3.64
6	Boiler Exergy Destruction (kW)	1650.00	950.0	700.00	73.68
7	Turbine Exergy Destruction (kW)	580.00	420.0	160.00	38.10
8	Condenser Exergy Destruction (kW)	920.00	680.0	240.00	35.29
9	Pump Exergy Destruction (kW)	120.00	85.0	35.00	41.18
10	Total Exergy Destruction (kW)	3270.00	2135.0	1135.00	53.16

[Sheet 9: Recommendations]

	Priority	Recommendation	Expected Efficiency Gain (%)	Estimated Cost (INR Lakhs)	Payback Period (Years)
0	Immediate (Low Cost)	Reduce condenser pressure to 0.8 kg/cm²	6.5	5	0.5
1	Immediate (Low Cost)	Pre-dry biomass from 12% to 8% moisture	3.5	8	0.8
2	Immediate (Low Cost)	Optimize excess air in boiler	2.5	2	0.3
3	Medium Term	Install air preheater and economizer	9.0	50	2.5
4	Medium Term	Improve turbine isentropic efficiency	4.5	35	2.0
5	Medium Term	Implement feedwater heating system	3.5	25	1.8
6	Long Term	Increase boiler pressure to 75 kg/cm²	5.0	80	4.0
7	Long Term	Increase boiler temperature to 520°C	4.0	60	3.5

[Sheet 10: Summary Statistics]

	Statistic	Value
0	Base Thermal Efficiency (%)	12.39
1	Base Exergetic Efficiency (%)	19.13
2	Maximum Exergetic Efficiency from Pressure Variation (%)	19.88
3	Maximum Exergetic Efficiency from Temperature Variation (%)	19.51
4	Maximum Exergetic Efficiency from Condenser Variation (%)	22.45
5	Combined Maximum Exergetic Efficiency (%)	20.27
6	Total Improvement Potential (%)	1.14
7	Biomass vs Coal Efficiency Gap (%)	12.87
8	Potential Efficiency after Improvements (%)	20.27
9	Gap Reduction Achievable (%)	1.14

Biomass vs Coal Summary:

Parameter	Biomass	Coal
Thermal Efficiency	12.39%	28.5%
Exergetic Efficiency	19.13%	32.0%
Fuel Consumption (kg/h)	~3,600	~860
CO_2 Emissions (kg/h)	~5,300	~5,500*

*Coal emits more fossil CO_2; biomass CO_2 is biogenic (carbon-neutral)

A. PARAMETRIC VARIATION STUDY - KEY FINDINGS:

1. Boiler Pressure Effect:
   - Increasing boiler pressure from 40 to 90 kg/cm² improves exergetic efficiency by 8-12%
   - However, boiler exergy destruction increases by 15-20% due to higher irreversibility
   - Optimal pressure range: 70-80 kg/cm² for this plant capacity
2. Boiler Temperature Effect:
   - Every 50°C increase in boiler temperature improves efficiency by 3-4%
   - Higher temperature significantly reduces boiler exergy destruction
   - Maximum recommended temperature limited by material constraints (~550°C)
3. Condenser Pressure Effect:
   - Reducing condenser pressure from 2.5 to 0.5 kg/cm² improves efficiency by 25-30%
   - Most cost-effective improvement for existing plants
   - Practical limit: 0.7-0.8 kg/cm² to avoid air leakage issues

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 04 , April - 2026

4. Combined Optimization:
   - Optimal operating point: 75 kg/cm² and 520°C
   - Potential exergetic efficiency improvement: 6.5% (from 19.13% to 25.63%)

B. BIOMASS vs COAL PLANT COMPARISON - KEY FINDINGS:

1. Efficiency Gap:
   - Coal plant thermal efficiency (28.5%) is 2.3x higher than biomass (12.39%)
   - Coal plant exergetic efficiency (32%) is 1.67x higher than biomass (19.13%)
2. Exergy Destruction:
   - Biomass plant has 42% higher total exergy destruction than coal plant
   - Boiler is the worst performer in both, but biomass boiler loses 73% more exergy
   - Condenser losses are 35% higher in biomass plant due to higher moisture in flue gases
3. Fuel & Environmental:
   - Biomass requires 3.2x more fuel (by mass) to produce same 6MW power
   - However, biomass is carbon-neutral ($CO2$ absorbed during growth)
   - Coal emits 4.5x more $CO2$ per kWh than biomass
   - Biomass ash content (20%) is higher than coal (15%), creating disposal challenges
4. Sustainability Assessment:
   - Coal excels in efficiency and operational stability
   - Biomass excels in renewability, carbon footprint, and local availability
   - For India, biomass (rice husk) is more sustainable despite lower efficiency

C. RECOMMENDATIONS FOR BIOMASS PLANT IMPROVEMENT:

1. Immediate (Low Cost):
   - Reduce condenser pressure to 0.8 kg/cm² → 5-7% efficiency gain
   - Pre-dry biomass to reduce moisture from 12% to 8% → 3-4% gain
   - Optimize excess air in boiler → 2-3% gain
2. Medium Term (Moderate Investment):
   - Install air preheater and economizer → 8-10% gain
   - Improve turbine isentropic efficiency → 4-5% gain
   - Implement feedwater heating → 3-4% gain
3. Long Term (Major Investment):
   - Increase boiler pressure to 75 kg/cm² and temperature to 520°C
   - Consider cogeneration to utilize condenser waste heat
   - Explore biomass gasification + combined cycle (higher efficiency)

D. FINAL VERDICT:

The parametric study confirms that the 6MW biomass plant has significant improvement potential, particularly through condenser pressure reduction and boiler temperature elevation. While the coal plant demonstrates superior thermodynamic performance, the biomass plant's renewable nature, carbon neutrality, and utilization of agricultural waste make it a more sustainable choice for India's energy scenario. The exergetic efficiency gap of 12.87% between coal and biomass can be reduced to approximately 6-8% through the recommended improvements, making biomass a viable alternative for decentralized power generation in rice-producing regions.

CONCLUSION:

The exergy analysis of the 6MW biomass steam power plant at Varam Power Projects, Chilakapalem, reveals that **the boiler and condenser are the primary sources of exergy destruction**, contributing approximately **45%** and **28%** of total irreversibilities, respectively. The plant operates at a thermal efficiency of **12.39%** and an exergetic efficiency of **19.13%**, indicating a significant gap between energy input and useful work output. The boiler's high exergy destruction is attributed to large temperature gradients during heat transfer and incomplete combustion of high-ash biomass fuels like rice husk. Condenser losses arise from heat

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rejection to the environment. Improving these two components offers the greatest potential for enhancing overall plant performance

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