Investigation on the Efficacy of Using Biomass Agricultural Residue as Alternate Fuel for Binary-Fuel Cogeneration Power Plant

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***Abstract*— The ensuing research is focused on assessing the efficacy of converting existing fossil fuel thermal power plants to biomass power units. The study is conducted to analyze the performance and economic feasibility of a binary fuel Cogeneration power plant using biomass agricultural residue as an alternate fuel. The plant is designed to operate on both coal and biomass residue, and the performance of the plant has been evaluated by comparing the efficiencies on both fuels. The economic feasibility is evaluated by analyzing the reduction in fuel cost reduction achieved by using biomass residue as an alternate fuel. The performance analysis reveals that the isentropic efficiency (on a component performance basis) of the power plant is increased by 2% when biomass agricultural residue is used instead of coal. The economic analysis reveals that the use of biomass agricultural residue as an alternate fuel can result in a fuel cost reduction of 2 PKR/kWh as compared to coal. This reduction in fuel cost is attributed to the lower cost of biomass residue compared to coal as well as the availability of biomass residue as a renewable and abundant source of fuel. Therefore, initial priming of plant on fossil fuel may be necessary before switching power production to alternate fuel.**

Keywords—Biomass fuels, Agricultural residues, Binary fuel Cogeneration power plant, Efficiency enhancement, Economic analysis, Performance analysis

I. INTRODUCTION

Urbanization and technological progress are causing the world's energy needs to increase on a daily basis[1]. Experts are working hard to develop new and more sustainable energy generation and utilization methods[2][3].As technology advances, power plants are being used for different purposes, such as producing both electricity and heat. This is commonly referred to as Cogeneration[4]. Conventional power plants typically use 35% of available fuel energy, with the remaining 65% being released into the environment as waste. On the other hand, the regeneration cycle re-purposes 65% of the wasted energy for usable thermal applications such as in the sugar industry, cement industry, steel industry, etc.[5]–[8].The Russian Federation also uses Cogeneration sources with an installed capacity of 25 MW or more to supply electricity with a specific reference fuel consumption of 309.8 goe/kWh[9]. Fossil fuels, namely oil, coal, and natural gas, are the primary energy sources that fulfill around 80% of the world's annual energy demands, as Coal contributes 23.3%, oil accounts for 35.7%, and gas makes up 20.3% of the global energy requirements[10]. Non-renewable energy resources are depleting rapidly, with estimates suggesting a complete disappearance over the next 40-50 years.[11]–[13].The global community is progressively moving towards renewable energy sources, such as solar, wind, biomass, and others. This shift has become increasingly popular as a means to reduce dependence on non-renewable energy while promoting a more sustainable future[14].

According to the Intergovernmental Panel on Climate Change (IPCC), increased emissions from fossil fuels will lead to a temperature increase of 1.4 to 5.8 °C from the year 1990 to 2100[15], [16]. The contribution of biomass in the energy sector for industrialized and developed countries accounts for around 9-14%, from which 75% of global usage of it happens in developing countries, while 25% takes place in industrialized countries[17][18]. The net calorific values of biomass can range from 18.5 to 20 MJ/kg, the variation is dependent on the moisture content, which can be from 5% to 60%[19]. Biomass resources have the potential to meet the energy demands of countries with rich resources in Asia and Africa. However, developing a proper mechanism to utilize agro-residues, which make up the majority of available biomass resources, still poses a challenge in some countries such as Pakistan[20]. Wheat straws can be utilized for electricity production, similar to other forms of biomass. One notable environmental benefit of using wheat straw as a fuel source is its capacity for producing low levels of ash. Compared to coal, which has an ash content of around 15%, wheat straw produces only approximately 3% ash by weight. This makes it a more sustainable and ecologically sensible option for electricity generation[21]–[23].

II. METHODOLOGY AND MATERIALS

The methodology for this research paper is based on a five-step approach starting from selection of biomass fuel, selection powerplant, thermochemistry of combustion, performance analysis and finally economic analysis for cost of power production. The details methodology for each phase is presented in Fig. 1.

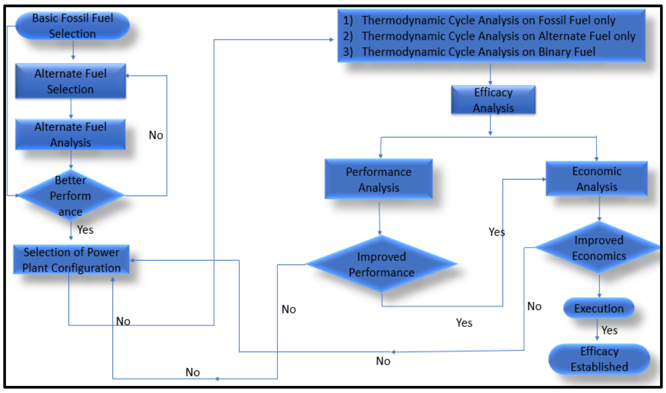

Fig. 1. Methodology

A. *Basic fuel and alternate fuel selection and fuel analysis*

Bituminous coal was selected as the basic fuel and wheat straw as an alternate fuel. Proximate and ultimate analyses have been carried out for basic fuel as well as an alternate fuel. Proximate analysis is carried out in a laboratory and ultimate analysis has been developed by, mathematical model. The characteristics of basic fuel as well as alternate fuel are compared in Table 1.

TABLE I. Comparison B/W Basic Fuel And Alternate Fuel Characteristics

Basic fuel (Coal)		
Component (Dry Basis)	**Value**	**Unit**
Ash	14.08	%
Volatile matter	26.75	%
Fixed Carbon	59.17	%
Total Carbon	71.60	%
Sulfur	0.60	%
Nitrogen	1.76	%
Oxygen	8.40	%
Hydrogen	3.92	%
HHV	27.34	MJ/kg
LHV	26.77	MJ/kg
Alternate fuel (Wheat Straw)		
Component (Dry Basis)	**Value**	**unit**
Ash	3.61	%
Volatile matter	87.68	%
Fixed Carbon	12.32	%
Total Carbon	49.99	%
Sulfur	0.08	%
Nitrogen	0.15	%
Oxygen	43.92	%
Hydrogen	5.86	%
HHV	19.19	MJ/kg
LHV	17.91	MJ/kg

B. *Plant selection & specifications*

To ensure the success of a project, it is necessary to choose the right power plant that meets the specific requirements of the project, such as energy demand, fuel availability, and environmental regulations. The selection process involves evaluating different types of power plants, such as coal-fired, natural gas-fired, nuclear, or renewable energy sources, to determine the most appropriate technology for the project. The specification process requires defining the technical specifications of the power plant, such as capacity, efficiency, and reliability, and ensuring compliance with relevant standards and regulations. A 120 MW simple cycle sub-critical binary fuel Cogeneration power plant with the following salient features, operating parameters, and plant process sequence has been selected[24]. The plant salient features include two turbines having a capacity of 60 MW each, two shell and tube type low pressure heaters, two de-aerators, three forward feedwater pumps, three superheaters, and a subcritical boiler.

The success of a power plant project depends on the effectiveness of the selection and specification methodology, which must be based on sound engineering principles, cost-effectiveness, and environmental sustainability. The plant schematics with operating parameters is shown in Fig.2.

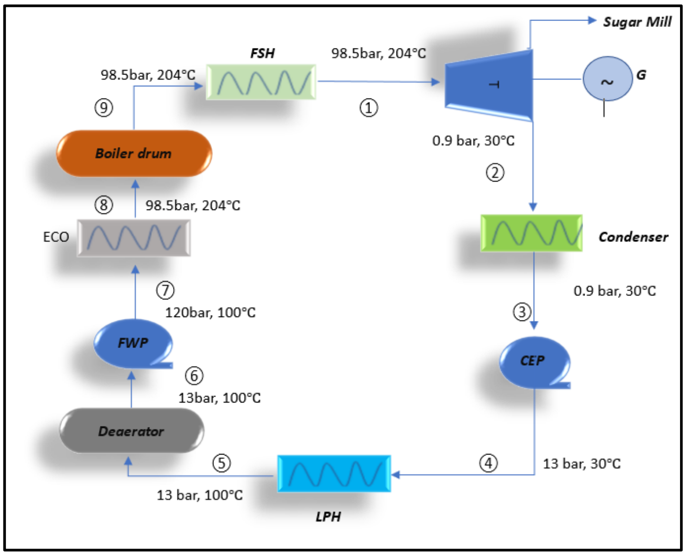

Fig. 2. Plant Schematics

C. *Thermodynamic analysis of basic and alternate fuel:*

It involves the application of thermodynamics principles to evaluate the performance of the power plant and its components. The first step in the thermodynamic analysis of the power plant is to define the system boundaries and identify the thermodynamic properties of the working fluid. The operating temperature and pressure range of the power plant is also determined. Thermodynamic analysis also involves the evaluation of the various components of the power plant, such as the boiler, turbine, heat exchangers, and condenser. Another important aspect of the thermodynamic analysis is the evaluation of the impact of operating parameters, such as temperature, pressure, and mass flow rate, on the performance of the power plant.

D. *Performance analysis:*

The performance analysis involves the study and evaluation of various parameters that affect the overall efficiency and productivity of a power plant. The performance analysis typically includes the calculation and analysis of energy consumption, heat transfer, power generation efficiency, and emissions. The results of the performance analysis can provide valuable insights into the operational performance of the power plant and help identify areas for improvement. This methodology is widely used in the power generation industry and is an essential tool for ensuring optimal performance and efficiency of power plants.

E. *Economic analysis:*

Economic analysis is a critical aspect that seeks to address economic issues. It involves the application of economic theories, principles, and concepts to analyze various economic phenomena. In conducting economic analysis, several methodologies can be employed, including quantitative, qualitative, and mixed-method approaches. Quantitative analysis involves the use of mathematical and statistical techniques to measure and quantify economic variables, while qualitative analysis seeks to understand the underlying reasons behind observed economic phenomena. Mixed-method approaches combine both quantitative and qualitative methods to provide a comprehensive understanding of economic issues.

III. MATHEMATICAL FORMULATION

A. *Fuel analysis*

This section describes the fuel source, the fuel type, and any pre-treatment processes that were applied to the fuel before use. The key fuel properties that were measured, such as calorific value, density, viscosity, ash content, moisture content, and elemental composition. Generalized combustion Equations (1-3) based on a mathematical model for basic fuel and alternate for stoichiometric reaction, lean reaction with 20% excess air with complete combustion, and lean reaction with 20% excess air with incomplete combustion have been developed.

$$\mathrm{X_C(C) + X_{H2}(H_2) + X_S(S) + X_{O2}(O_2) + X_{N2}(N_2) + XO_2 + YN_2 \rightarrow aCO_2 + bH_2O + cSO_2 + dN_2} \quad (1)$$

$$\mathrm{X_C(C) + X_{H2}(H_2) + X_S(S) + X_{O2}(O_2) + X_{N2}(N_2) + UO_2 + VN_2 \rightarrow aCO_2 + bH_2O + cSO_2 + eN_2 + fO_2} \quad (2)$$

$$\mathrm{X_C(C) + X_{H2}(H_2) + X_S(S) + X_{O2}(O_2) + X_{N2}(N_2) + UO_2 + VN_2 \rightarrow gCO_2 + hCO + bH_2O + cSO_2 + eN_2 + iO_2} \quad (3)$$

In eq (1), the X_C, X_{H2}, X_S, XO_2, and XN_2 are the molar fraction of carbon, hydrogen, sulfur, oxygen, and nitrogen in fuel, while X and Y are the numbers of moles of oxygen and nitrogen in the air per mole of fuel, whereas a, b, c, d are the number of moles of carbon dioxide, water, sulfur dioxide and nitrogen in flue gas for stoichiometric reaction.

In eq (2) U and V are the numbers of moles of oxygen and nitrogen in air and e and f are the number of moles of nitrogen and oxygen in flue gas for 20% excess air with complete combustion reaction.

In eq (3) U and V are the numbers of moles of oxygen and nitrogen in air and g, h, and i are the number of moles of carbon dioxide, carbon monoxide, and oxygen in flue gas for 20% excess air with incomplete combustion reaction.

1) *Net heat added to the system*

When a chemical reaction takes place in a boiler or gas turbine, heat will be added to the system, The net heat added to the system which is measured negative because heat is rejected in combustion it can be calculated as below.

$$Q_{f,PR} = \sum_P (nMh)_P - \sum_R (nMh)_R \quad (4)$$

The general equation for the calculation of enthalpies of products and reactants constituents is as follows.

$$\overline{\Delta h_{component}} = \bar{h}_{component}(\mathrm{T_P} - \mathrm{T_{ref}}) \quad (5)$$

where T_P and T_R are operating and reference temperatures.

2) *Adiabatic flame temperature*

It is determined by considering the reactants' thermodynamic properties, such as their heat of formation, specific heat, molecular weight, and the stoichiometry of the reaction. Adiabatic flame temperature plays a significant role in the design and optimization of combustion systems, as it influences the efficiency, emissions, and safety of the process. It can be calculated as.

$$\mathrm{T_P} = \mathrm{T_R} + \left(\frac{-\mathrm{Q_{f,PR}}}{\sum_{\mathrm{P}} \mathrm{np}\overline{\mathrm{Cp}}} \right) \quad (6)$$

The general equation for the calculation of specific heat at a constant pressure of individual components is as follows.

$$\bar{C}_{P,component} = a + bT + cT^2 + dT^3 \quad (7)$$

$$\mathrm{T} = \frac{\mathrm{T_R} + \mathrm{T_{max}}}{2} \quad (8)$$

where a, b, c, and d are empirical values that are given in Table A-2 by Cengel[25].

B. *Thermodynamic analysis*

The analysis determines the optimal operating conditions that maximize efficiency and minimize losses. The results of such analyses can provide valuable insights for improving the performance of power systems, which are widely used in power generation and industrial processes. It includes the calculations of the enthalpy of the condenser, enthalpies, and work done by the condensate extraction pump and feed water pump, and turbine work.

1) *Net work and thermodynamic efficiency*

Net work output can be calculated by the following formula.

$$\Delta \mathrm{W_{net}} = \mathrm{W_T} - \mathrm{W_P} \quad (9)$$

Where *W_T and W_P* are turbine and pump works and can be calculated by the following formulas.

$$\mathrm{W_T} = \dot{m}_s(\mathrm{h}_{in} - \mathrm{h}_{out}) \quad (10)$$

$$W_P = v\left(p_{discharge} - p_{suction}\right) \quad (11)$$

$$\eta_{\mathrm{th}} = \frac{\Delta \mathrm{W_{net}}}{\mathrm{Q_{add}}} \times 100 \quad (12)$$

$$\mathrm{Q_{add}} = \dot{m}_w(\mathrm{h}_{out} - \mathrm{h}_{in}) \quad (13)$$

2) *Boiler efficiency and fuel consumption*

Improving boiler efficiency can have a significant impact on the overall performance and profitability of a power plant, making it an important area of research and development for the energy industry. To calculate the Boiler efficiency, we use the following formula.

$$\eta_{\mathrm{boiler}} = \frac{\dot{m_w}(h_{main\,steam} - h_{feedwater})}{\dot{m_{fuel}} \times \mathrm{GCV}} \times 100\% \quad (14)$$

Where GCV is the gross calorific value of fuel.

C. *Economic analysis*

Comprehensive performance analysis may include various factors such as Plant load factor, utility factor, Maximum & Actual annual power output, Plant operating factor, Annual plant capacity factor, Plant use factor, rate of fuel burned, Gross station HR, Station net power output, Net station HR, Gross station efficiency, Total fuel consumption in a year and Total fuel consumption cost in a year. The results of the performance analysis can be used to optimize the plant's operations, reduce energy waste, and improve overall efficiency, thereby contributing to sustainability and cost-effectiveness. To calculate the Gross station HR, we use the following formula.

$$\text{gross station HR} = \frac{\text{rate of fuel burned}\times\text{LHV}_{\text{fuel}}}{\text{gross power}} \tag{15}$$

IV. RESULTS

The research aimed to investigate the feasibility of using biomass agricultural residue as an alternate fuel for binary fuel Cogeneration power plants. The study was conducted using a mathematical model.

A. *Thermochemistry of Basic Fuel (Bituminous Coal)*

Combustion equations for each reaction are presented below.

$$5.96(\mathrm{C}) + 1.96(\mathrm{H_2}) + 0.01875(\mathrm{S}) + 0.2625(\mathrm{O_2}) + 0.0628(\mathrm{N_2}) + 6.704\mathrm{O_2} + 25.20\mathrm{N_2} \rightarrow 5.96\mathrm{CO_2} + 1.96\mathrm{H_2O} + 0.01875\mathrm{SO_2} + 25.262\mathrm{N_2} \tag{16}$$

$$5.96(\mathrm{C}) + 1.96(\mathrm{H_2}) + 0.01875(\mathrm{S}) + 0.2625(\mathrm{O_2}) + 0.0628(\mathrm{N_2}) + 8.04\mathrm{O_2} + 30.31\mathrm{N_2} \rightarrow 5.96\mathrm{CO_2} + 1.96\mathrm{H_2O} + 0.018\mathrm{SO_2} + 30.94\mathrm{N_2} + 1.336\mathrm{O_2} \tag{17}$$

$$5.96(\mathrm{C}) + 1.96(\mathrm{H_2}) + 0.01875(\mathrm{S}) + 0.2625(\mathrm{O_2}) + 0.0628(\mathrm{N_2}) + 8.04\mathrm{O_2} + 30.31\mathrm{N_2} \rightarrow 5.3694\mathrm{CO_2} + 0.5966\mathrm{CO} + 1.96\mathrm{H_2O} + 0.018\mathrm{SO_2} + 30.94\mathrm{N_2} + 1.6368\mathrm{O_2} \tag{18}$$

1) *Combustion temperature for stoichiometric reaction*

$$\sum_R (nMh) = 241054.50\ kJ/kmol$$
$$\textstyle\sum_P (nMh) = -2260429.12\ kJ/kmol$$
$$Q_{f,PR} = -2501483.63\ kJ/kmol$$
$$\textstyle\sum_P np\overline{Cp} = 1131.86\ \ kJ/kmol.K$$
$$T_P = 2508.07\ K$$

2) *Combustion temperature for lean reaction with 20% excess air with complete combustion*

$$\textstyle\sum_R (nMh) = 263821.98\ kJ/kmol\ ($$
$$\textstyle\sum_P (nMh) = -2113191.70\ kJ/kmol$$
$$Q_{f,PR} = -2377013.68\ kJ/kmol$$
$$\textstyle\sum_P np\overline{Cp} = 1355.43\ kJ/kmol.K$$
$$T_P = 2051.69\ K$$

3) *Combustion temperature for lean reaction with 20% excess air with incomplete combustion*

$$\textstyle\sum_R nMh = 263821.98\ kJ/kmol$$
$$\textstyle\sum_P nMh = -1934018.73\ kJ/kmol$$
$$Q_{f,PR} = -2197840.71\ kJ/kmol$$
$$\textstyle\sum_P np,\overline{Cp} = 1356.29\ \ kJ/kmol.K$$
$$T_P = 1918.48\ K$$

B. *Thermochemistry of Alternate Fuel (Biomass Residue)*

Combustion equations for each reaction are presented below.

$$4.16(\mathrm{C}) + 2.93(\mathrm{H_2}) + 0.0025(\mathrm{S}) + 1.3725(\mathrm{O_2}) + 0.0053571(\mathrm{N_2}) + 4.26\mathrm{O_2} + 16.02\mathrm{N_2} \rightarrow 4.16\mathrm{CO_2} + 2.93\mathrm{H_2O} + 0.0025\mathrm{SO_2} + 16.026\mathrm{N_2} \tag{19}$$

$$4.16(\mathrm{C}) + 2.93(\mathrm{H_2}) + 0.0025(\mathrm{S}) + 1.3725(\mathrm{O_2}) + 0.0053571(\mathrm{N_2}) + 5.11\mathrm{O_2} + 19.22\mathrm{N_2} \rightarrow 4.16\mathrm{CO_2} + 2.93\mathrm{H_2O} + 0.0025\mathrm{SO_2} + 19.23\mathrm{N_2} + 0.85\mathrm{O_2} \tag{20}$$

$$4.16(\mathrm{C}) + 2.93(\mathrm{H_2}) + 0.0025(\mathrm{S}) + 1.3725(\mathrm{O_2}) + 0.0053571(\mathrm{N_2}) + 5.11\mathrm{O_2} + 19.22\mathrm{N_2} \rightarrow 3.744\mathrm{CO_2} + 0.416\mathrm{CO} + 2.93\mathrm{H_2O} + 0.00253\mathrm{SO_2} + 19.23\mathrm{N_2} + 1.06\mathrm{O_2} \tag{21}$$

1) *Combustion temperature for stoichiometric reaction*

$$\textstyle\sum_R (nMh) = 170709.944\ kJ/kmol$$
$$\textstyle\sum_P (nMh) = -1948892.428\ kJ/kmol$$
$$Q_{f,PR} = -2119602.372\ kJ/kmol$$
$$\textstyle\sum_P np\overline{Cp} = 799.80\ \ kJ/kmol.K$$
$$T_P = 2948\ K$$

2) *Combustion temperature for lean reaction with 20% excess air with complete combustion*

$$\textstyle\sum_R (nMh) = 183591.69\ kJ/kmol$$
$$\textstyle\sum_P (nMh) = -1885420.64\ kJ/kmol$$
$$Q_{f,PR} = --2069012.34\ kJ/kmol$$
$$\textstyle\sum_P np\overline{Cp} = 929.29\ \ kJ/kmol.K$$
$$T_P = 2524\ K$$

3) *Combustion temperature for lean reaction with 20% excess air with incomplete combustion*

$$\textstyle\sum_R (nMh) = 183591.69\ kJ/kmol$$
$$\textstyle\sum_P (nMh) = -1763845.42\ kJ/kmol$$
$$Q_{f,PR} = -1947437.11\ kJ/kmol$$
$$\textstyle\sum_P np\overline{Cp} = 929.850\ \ kJ/kmol.K$$
$$T_P = 2392\ K$$

C. *Thermodynamic analysis*

Thermodynamic analysis is an important aspect of this study. It involves the application of thermodynamics principles to evaluate the performance of the power plant and its components. The first step in the thermodynamic analysis of the power plant is to define the system boundaries and identify the thermodynamic properties of the working fluid. The operating temperature and pressure range of the power plant is also determined. Thermodynamic analysis also involves the evaluation of the various components of the power plant, such as the boiler, turbine, heat exchangers, and condenser. Another important aspect of the thermodynamic analysis is the evaluation of the impact of operating parameters, such as temperature, pressure, and mass flow rate, on the performance of the power plant. The overall results are presented below.

TABLE II. THERMODYNAMIC ANALYSIS

Component	Value
W_T	97.7 MW
W_P	1.7196 MW
ΔW_{net}	47.99 MW

η_{th}	30.23 %
Work ratio	0.98
Steam rate	0.075
η_{boiler}	41.8 %
Basic fuel consumption	50 ton/h
Alternate fuel consumption	71.3 ton/h

D. Plant Economics

The economic analysis is a critical aspect that seeks to address economic issues. It involves the application of economic theories, principles, and concepts to analyze various economic phenomena. In conducting economic analysis, several methodologies can be employed, including quantitative, qualitative, and mixed-method approaches. Quantitative analysis involves the use of mathematical and statistical techniques to measure and quantify economic variables, while qualitative analysis seeks to understand the underlying reasons behind observed economic phenomena. Mixed-method approaches combine both quantitative and qualitative methods to provide a comprehensive understanding of economic issues. The overall analysis is presented below.

TABLE III. PLANT ECONOMICS ANALYSIS

Component	Value	Unit
Rated capacity	86400	MWh
W_T	97.7	MW
$t_{crushing}$	2880	hrs.
$t_{non\text{-}crushing}$	5040	hrs.
$P_{Crushing}$	255686.4	MWh
$P_{non\text{-}Crushing}$	542001.6	MWh
$t_{in\text{-}service}$	7920	hrs.
t_{total}	8640	hrs.
PLF	0.825	--
Utility factor	0.74	--
P_{annual} (max)	1036800	MWh
P_{annual} (actual)	797688	MWh
POF	0.916	--
PCF	0.796	--
PUF	0.839	--
Rate of coal burned	100000	lbm/hr.
Rate of alternate fuel burned	142600	lbm/hr.
Gross station HR	9582.13	btu/kWh
P_{Net}	88.8	MW
η_{gross} (coal)	35.56	%
η_{gross} (wheat straw)	37.28	%
Fuel cost(coal)	14.10	PKR/kWh
Fuel cost(wheat straw)	12.25	PKR/kWh

V. CONCLUSIONS

A. Conclusions

The study conducted on the binary fuel Cogeneration power plant using biomass agricultural residue as alternate fuel has revealed promising results. The results show that the gross efficiency of the power plant has increased 2% in switching from fossil fuel (coal) to biomass fuel (wheat straw) as alternate fuel. The increase in efficiency can be attributed to the higher calorific value of biomass residue and lower ash content, which in turn has better combustion characteristics. In addition to this, the economic analysis of the study has also revealed that the use of agriculture residue as an alternate fuel has reduced the fuel cost by 2 PKR/kWh. This reduction in fuel cost is not only economically beneficial but also sustainable in the long run.

The study concludes that the use of biomass agricultural residue as an alternate fuel in a binary fuel Cogeneration power plant is a viable option, which can significantly improve the efficiency and economic feasibility of power generation. Therefore, the adoption of biomass residue as an alternate fuel can be a sustainable solution to meet the growing energy demands of the world while minimizing the negative environmental impacts of power generation.

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