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Review Article

# Thermodynamic Analysis and Performance Improvement in Biomass Power Plant: A Comprehensive Review

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## Abstract

Biomass power plants play a crucial role in the sustainable energy sector by converting organic materials such as agricultural residues, forest biomass, and dedicated energy crops into electricity and heat. Biomass power plants represent a viable and renewable energy solution that can contribute to transitioning to a low-carbon economy. Their ability to convert organic materials into electricity and heat, coupled with proper management of feedstocks and emissions, can provide a sustainable alternative to fossil fuel-based power generation. Biomass has appeared as one of the most encouraging renewable energy sources for the replacement of fossil fuels. An extensive study about the prospective of biomass to produce renewable energy in the world has been exhibited in this article. The biomass-driven combined heat and power plant demonstrates 67% and 12% efficiency improvement compared to the stand-alone biomass power plant. BFP-CCS performs best at the $H_2O/Mn_2O_3$ mass ratio of 1.6, the $H_2O/O_2$ molar ratio of 2.8, the $O_2$/biomass mass ratio of 0.22, and the fuel utilization factor of 0.65. The exergo-economic and exergo-environmental factors obtained are 51.5% and 0.0288% respectively at the favorable operating conditions. The round-trip efficiency of the process using R1233zd was 8.77%, which was slightly lower than that of the process using R245fa (8.84%). The net power output of the final CLC integrated configuration and conventional power plants are 492.19 kW and 273.12 kW respectively. A lot of energy can be recovered without low-temperature corrosion problems, and 7% of the total input energy can be saved. The maximum obtainable exergy efficiency was 42.03%, which was related to MSW (Municipal Solid Waste). The primary aim of this review is to furnish a thorough understanding of the thermodynamic complexities and potential improvements within biomass power plants. Through a critical analysis of current research and emerging technologies, this review aims to establish the groundwork for more effective and sustainable energy production from biomass, playing a crucial role in shaping a cleaner and more environmentally friendly future.

## Keywords

Sustainable Energy, Organic Materials, Agricultural Residues, Forest Biomass, Renewable Energy, Low-Carbon Economy, Fossil Fuel, Municipal Solid Waste

## 1. Introduction

In the year 2022, as highlighted by Hong Guo et al. [1], biomass energy stands as the world's fourth-largest energy source, trailing only behind coal, oil, and natural gas. A pivotal feature of biomass power generation is its ability to achieve nearly zero CO2 emissions throughout its life cycle. Positioned as a clean and renewable energy alternative, bio-

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mass energy holds immense potential in addressing energy shortages, fostering ecological improvements, and preserving the delicate balance of our ecosystems. Recognizing this, numerous countries and regions are actively promoting the use of biomass energy through legislative measures.

Among the various methods of biomass energy utilization, biomass power generation emerges as one of the most prevalent and effective approaches. The roots of global biomass power generation can be traced back to the 1970s during the global oil crisis when Denmark pioneered electricity generation using straw. Current projections from the International Energy Agency anticipate biomass energy to lead the ongoing surge in renewable energy growth, contributing to 40% of global energy consumption growth between 2018 and 2023.

Looking ahead, the forecast suggests that by 2040, renewable energy will encompass a significant share, ranging from 17% to 22% of primary energy, with biomass playing a pivotal role in meeting global power demand. Notably, the installed capacity of biomass power generation worldwide has witnessed a consistent upward trajectory since the early 21st century.

Since the 1970s, nations across the globe have been earnestly focusing on the development and utilization of biomass energy. Robust policies, both short-term and long-term, have been implemented to encourage research and utilization in this domain. In 2018, the International Energy Agency (IEA) shed light on biomass energy as an underestimated "giant" and underscored its significance in the upcoming five years. Recent data from the International Renewable Energy Agency (IRENA) [2] indicates a global biomass installed capacity exceeding 120 GW, as illustrated in Figure 1 showcasing the total global biomass installed capacity from 2012 to 2020.

This comprehensive review serves as a valuable resource for researchers, engineers, and policymakers committed to advancing biomass power generation and contributing to a more sustainable energy future. The primary goal is to offer a holistic understanding of the thermodynamic intricacies and potential enhancements in biomass power plants. By critically analyzing existing research and emerging technologies, this review aspires to lay the foundation for more efficient and sustainable energy production from biomass, contributing to a cleaner and greener future.

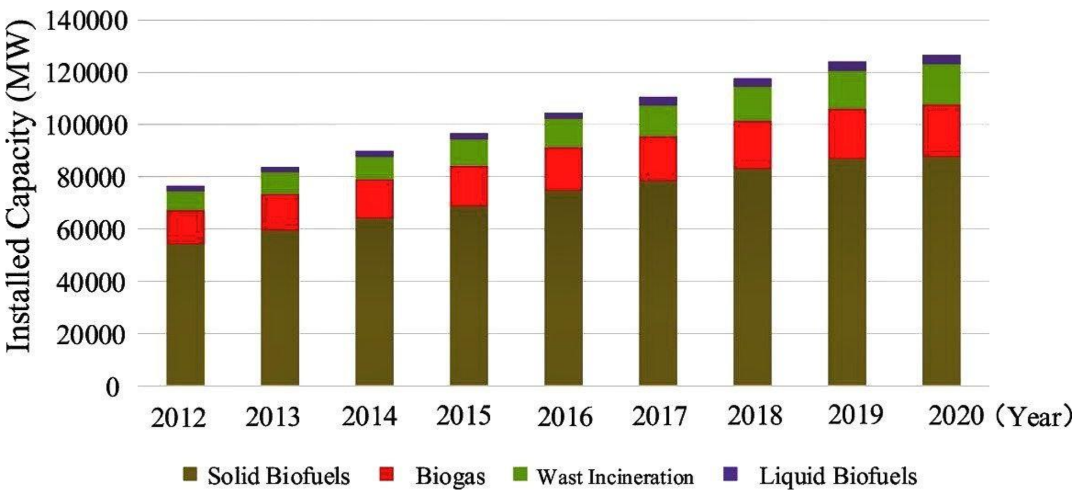


***Figure 1.*** *Total biomass installed capacity from 2012 to 2020 globally [2].*

## 2. Biomass Power Plant

The term biomass refers to living or recently dead organisms and any by-products of those organisms – plant or animal. In a strict sense, the term biomass encompasses all living things. In the context of biomass energy, refers to the crops, residues, and other forms of biological materials that can be used to substitute fossil fuels in energy production. Biomass has gained a lot of traction in recent years due to its ability for renewable electricity generation, green energy production, biofuels, and thermal energy. Plants, a form of living biomass, are the most common type of biomass that exists. Today, biomass power plants continue to evolve, with ongoing research and development efforts focused on improving efficiency, reducing emissions, and exploring new biomass conversion technologies. These plants play a crucial role in the renewable energy mix, providing a sustainable and carbon-neutral alternative to fossil fuel-based power generation [3].

### 2.1. Biomass-Driven Combined Heat and Power Plant

Fatemeh Lashgari et al., 2022 [4] unlike wind and solar energy, biomass is capable of providing stable and controllable energy output in an energy system at zero or even negative net emission rate. The combination of a gasification unit with a Brayton cycle is one of the traditional methods of utilizing biomass resources. This work presents a thorough (Energy, Exergy, Economic, Exergo-economic, and Environmental) analysis of a biomass-driven combined heat and power (CHP), via a gasified, with a compressed air energy storage (CAES) unit. The hybrid system is capable of multi-generating heat and power as well as contributing to load shifting and peak shaving for the electricity grid. With about 71% and 47% of total and electrical round-trip efficiencies, the proposed system demonstrates 67% and 12% efficiency improvement in comparison to the stand-alone biomass power plant. 348.4 MWh is the net produced power each day and 50% of this amount is generated during the on-peak period. Ultimate composition analyses of dry wood are shown in Table 1. Also, 6651.4 $m^3$ of domestic hot water is produced during the 24-hour operation of the system. The Levelized Cost of Electricity (LCOE) of the system is around 0.05 $/kWh with an average electricity price of 0.1 $/kWh elaborating the economic potentials of the system. The payback period and total profit of around 2 years and 181 M$ further prove the economic feasibility of the proposed system. Moreover, due to the obtained results from the environmental analysis, it is proved that the introduced system is capable of capturing 25,764 tons/year of $CO_2$ emission from the atmosphere.

Michela Costa et al., 2022 [5] present work, the technical, environmental, and economic impact of the entire biomass-to-energy supply chain is assessed concerning a real commercially available Combined Heat and Power (CHP) system, the CMD ECO20X based on biomass gasification, installed as operational demonstration in the Municipality of Laurino in the National Park of Cilento, Vallo di Diano, and Alburni (PNCVD) in Southern part of Italy. Several calculation tools previously developed by authors for the analysis of the performance of the various components of the ECO20X system are here employed to define the mass and energy fluxes that characterize its operations in a local supply chain where forest management residues (oak and beech trees) and olive pomade from oil mills in the area are exploited. Validation of the gasification model with the experimental result is shown in Table 2. The analysis aims to quantify the energy absorption necessary for the pre-treatment operations of the organic residue (shredding, briquetting, drying) which are essential for gasification, and how much they affect the production deriving from the biomass cogeneration process itself.

***Table 1.*** *Ultimate composition analyses of dry wood [4].*

| Element | Mass Fraction (wt. %) |
|---|---|
| C | 50 |
| N | 0 |
| H | 6 |
| S | 0 |
| O | 44 |

***Table 2.*** *Validation of gasification model with experimental results (considering wood chips as biomass feedstock with 20% moisture content at 800 ℃ gasification temperature) [4].*

| Composition | Model (%) | Experimental (%) |
|---|---|---|
| Carbon dioxide ($CO_2$) | 14.18 | 16.42 |
| Carbon monoxide (CO) | 19.39 | 23.04 |
| Hydrogen ($H_2$) | 18.73 | 15.23 |
| Methane ($CH_4$) | 0.59 | 1.58 |
| Nitrogen ($N_2$) | 47.11 | 42.31 |
| Oxygen ($O_2$) | 0 | 1.42 |

## 2.2. Novel Air-Cooled HGB Power Plant

Stefano Briolaa et al., 2019 [6] the biomass flow rate is controlled to maximize the net electric power or net thermodynamic efficiency of the plant with varying ambient air and geothermal fluid temperatures. In comparison to the first operating mode, the second enables a saving of the biomass used annually in the range of 28.3%–42.6%, corresponding to the maximum and minimum geothermal fluid temperature, respectively, with the resulting detrimental effect on the yearly produced electric energy in the range of 9%–23.6%. The present article proposes a novel air-cooled HGB power plant suitable for extreme environmental conditions, which can overcome the shortcomings described above. It has the following characteristics: a) the electricity generation takes place through the ORC turbine, avoiding the drawbacks of steam turbines, geothermal steam turbines, and thermal oils. In particular, the ORC turbine receives thermal power provided by the biomass heat source through the intermediate geothermal fluid; b) the control of the biomass mass flow rate is realized to maximize the plant energy performances at off-design conditions in the presence of the high fluctuations in the atmospheric air temperature and the large reduction of the geothermal source temperature during the entire operative plant life. In particular, the optimum values of the biomass mass flow rate are determined through an extensive.

## 2.3. Novel Biomass Fueled Power Plant

Linbo Yan et al., 2019 [7] that biomass-based power plants, especially those with carbon capture units, usually suffer the issue of low electric efficiency, which is averse to their commercial application. As one approach to solving this issue, a novel biomass-fueled power plant with carbon capture and sequestration (BFP-CCS) is proposed in this work. The BFP-CCS subunit models are first validated before the integrated model of BFP-CCS is built. Then, the BFPCCS characteristics are analyzed in terms of energy, exergy, and economics, and the optimum operation condition of BFP-CCS is determined. Based on this research, it is found that BFP-CCS performs best at the $H_2O/Mn_2O_3$ mass ratio of 1.6, the $H_2O/O_2$ molar ratio of 2.8, the $O_2$/biomass mass ratio of 0.22 and the fuel utilization factor of 0.65. The corresponding net efficiency, the life cycle $CO_2$ emission, and the leveled cost of electricity of BFP-CCS are 51.7%, \$0.0501 /kWh, and −0.591 kg/kWh, respectively. The biggest contributors to the energy and exergy losses are the steam turbine and the solid oxide fuel cell in BFP-CCS, respectively. The major implication of this study is that an efficient and economical BFP-CCS system is put forward, which is promising for $CO_2$ removal during power generation.

## 2.4. Oxy-Fuel Combustion Based on Circulating Fluidized Bed Power Plant

Yan Shi et al., 2020 [8] oxy-fuel combustion with circulating fluidized bed (CFB) is a promising technology applied in carbon capture and sequestration. In this work, a supercritical oxy-fuel combustion system based on CFB boiler firing coal, lignite and sawdust is established to evaluate the system's performance. Five primary units are arranged including an air separation unit, a CFB combustor considering the fuel combustion characteristics, a steam generation cycle, a simplified power island and a $CO_2$ purification and compression unit. After the validation, the influence of fuel types, oxygen concentration, flue gas recirculation forms and exhaust flue gas temperature on the system performance including adiabatic flame temperature, flue gas loss, net efficiency and exergy efficiency are evaluated. The results showed that compared to lignite and sawdust combustion, oxy-fuel combustion with coal has the highest net efficiency and exergy efficiency which is mainly because of the lower moisture and ash. However, the drying process will not significantly increase the net efficiency of sawdust combustion according to the electricity consumption of biomass drying. Also, a dry cycle is preferable in high moisture fuel combustion due to the better burnout performance and less recirculation fan work. To increase the net efficiency, reducing the exhaust flue gas temperature and increasing the combustion pressure are both effective.

## 2.5. Bottom Ash Discharged Biomass-Based Thermal Power Plant

Jong-Hwan Park et al., 2023 [9] this study aimed to determine the applicability of bottom ash (BA) discharged from a biomass-based thermal power plant as an agricultural soil conditioner. Figure 2 shows that the physicochemical and structural properties of BA used in this study were similar to those of wood-pellet-based biochar derived at 600 ℃. Additionally, XPS, FTIR, and SEM-EDS described the structural properties of BA well proving that BA has a stable carbon structure. It was confirmed that BA has beneficial agricultural functions, such as improved soil physical properties, water holding capacity and nutrient residence time, and $CO_2$ reduction. Toxicity tests were performed on five crops to evaluate the stability of BA; these results were similar to those of the control, without significant differences. The optimal BA treatment for Chinese cabbage cultivation was 100 kg/10a, which showed a yield index of 138 compared to that of the control. There was no significant difference in the physicochemical properties of the soil and the content of inorganic components in Chinese cabbage in the presence or absence of BA treatment. Overall, it is suggested that BA can be used as an effective soil-improving agent for the cultivation of crops on agricultural land as it has an excellent role in soil improvement and crop yield enhancement.

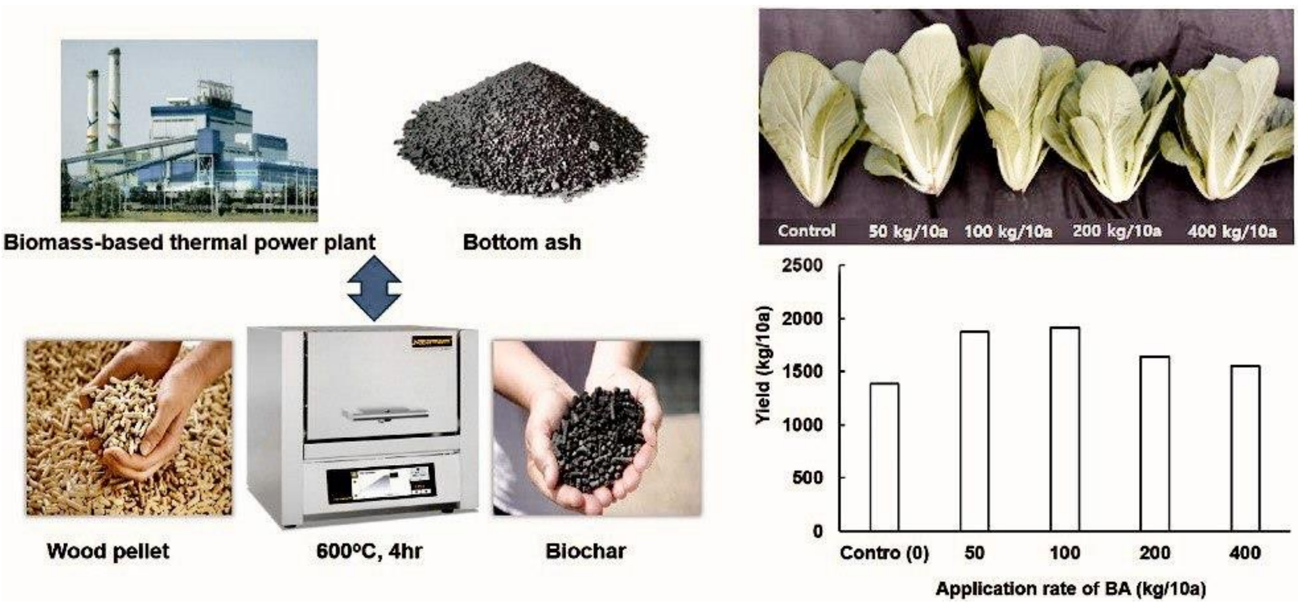


*Figure 2. Bottom ash discharged from biomass-based thermal power plants [9].*

### 2.6. Biomass-Based Combined Power and Cooling Plant

S. Chowdhury et al., 2023 [10] the paper report 6E analyses (energy, exergy, economic, environmental, exergo -economic, and exergo-environmental) of a biomass-based combined power and cooling plant that uses sawdust as its fuel, steam as its sole gasifying agent. The gasification model includes tar in the producer gas and yields maximum hydrogen content when the steam-to-biomass ratio (STBM) and reactor temperature are set to 2 and 800 ℃ respectively. The performance of the co-generation plant is assessed by varying different input parameters viz. air compressor pressure ratio (pr) and turbine inlet temperature (TIT). Simulation results show that the optimum performance is achieved when TIT is 1100 ℃ and pr is in the range of 6 to 8. The exergo-economic factor and exergo-environmental factor are evaluated by considering these optimized conditions. Exergy analysis suggests that the gasifier is subjected to maximum exergy destruction. From economic analysis, the computed effective price of electricity (EPOE) is 0.064 USD/kWh with the discounted payback period of the plant being 8.5 years. The exergo-economic and exergo-environmental factors obtained are 51.5% and 0.0288% respectively at the favorable operating conditions.

### 2.7. Wood-Fired Power Plant

Thomas Plankenbuhler et al., 2023 [11] fuel costs are the determining factor for the operational expenditure of solid biomass furnaces. Consequently, there is an incentive to shift towards cheaper feedstock like forest residues, composting residues, or waste wood. This comes at a price, namely challenging properties during combustion as well as fluctuating fuel properties due to inhomogeneities or varying manual mixing. Together, this poses challenges for an industrial furnace's control system. Currently relying on only a few static control loops for thermal load or air supply and distribution, furnaces struggle under rapidly changing fuel properties. Briefly: Traditional control systems are running reactively. In contrast to that, this work focuses on the development of a proactive control system for industrial furnaces and power plants. This contribution describes the approach and the methodology for such a system as well as the industrial implementation and obtained results from a 12+ month evaluation period at a 6 MW biomass plant. The first necessary step is to determine the relevant properties of incoming biomass fuels before the combustion itself. For this purpose, we captured fuel photographs of the utilized biomass feedstock of a 6 MW biomass power plant. Subsequently, using image processing techniques and a statistical/machine learning approach, we define a parameter for the current 'fuel quality'. Data from the plant's process control system is used to provide alternative furnace settings for the fuel stoking rate, grate speed, and the air supply concerning the fuel quality. Improved settings are derived by technical and operational considerations as well as combustion experiments in a full-scale environment. The final step is to manipulate the furnace's set points of the existing control loops automatically and continuously based on the controller's suggestion. During the 12+ month demonstration period including tests at deliberate extreme conditions and edge cases, a faster adaption to changing fuel properties and more stable operation can be observed.

### 2.8. Fluidized Bed Reactor Biomass Power Plant

Takayuki Uchino et al., 2023 [12] this study focused on a biomass power plant (Organic Rankine Cycle: ORC, 1 MWe) integrated with a thermochemical heat storage (TCS) system as a Carnot battery. In the TCS, a fluidized bed reactor using CaO/Ca $(OH)_2$/alumina particles was used, and steam was used as a fluidizing and reacting gas. The surplus electricity from variable renewable energy (VRE) is converted to heat and stored during the daytime, and the stored energy is utilized to generate power in the evening. In this study, there were three objectives. First, process performances were compared when R245fa or R1233zd was used as a working fluid of ORC, and influences of ORC parameters such as the turbine inlet temperature, superheat temperature, and the scale of the power generation, were evaluated. In addition, the effects of the fluidized bed volume and the reduction of biomass fuel combustion were also investigated. Second, the potential of the proposed process that can absorb the VRE fluctuation was evaluated by dynamic calculation. Third, the economics of the TCS system was evaluated. Results show that the round-trip efficiency of the process using R1233zd was 8.77%, which was slightly lower than that of the process using R245fa (8.84%). The increases in the turbine inlet temperature led to the increase in heat recovery from the outlet steam of the TCS reactor, meanwhile, the round-trip efficiency decreased. Figure 3 shows the efficiencies of the cases changing the superheat temperature (5 → 15 ℃) were slightly changed (<0.5%). To achieve high energy efficiencies, a large-scale biomass power plant and a small-fluidized bed volume were effective. It was found that the VRE fluctuation was mostly absorbed by the TCS with a fluidized bed and ORC process. In the economic evaluations, the leveled cost of storage regarding only the TCS system was 0.92–2.37 USD/kWhe when the charging electricity cost was 0.05 USD/kWhe. LCOS also decreases to 0.50–1.14 USD/kWhe if the electricity cost is free during daytime in the future and power output is two times in a day.

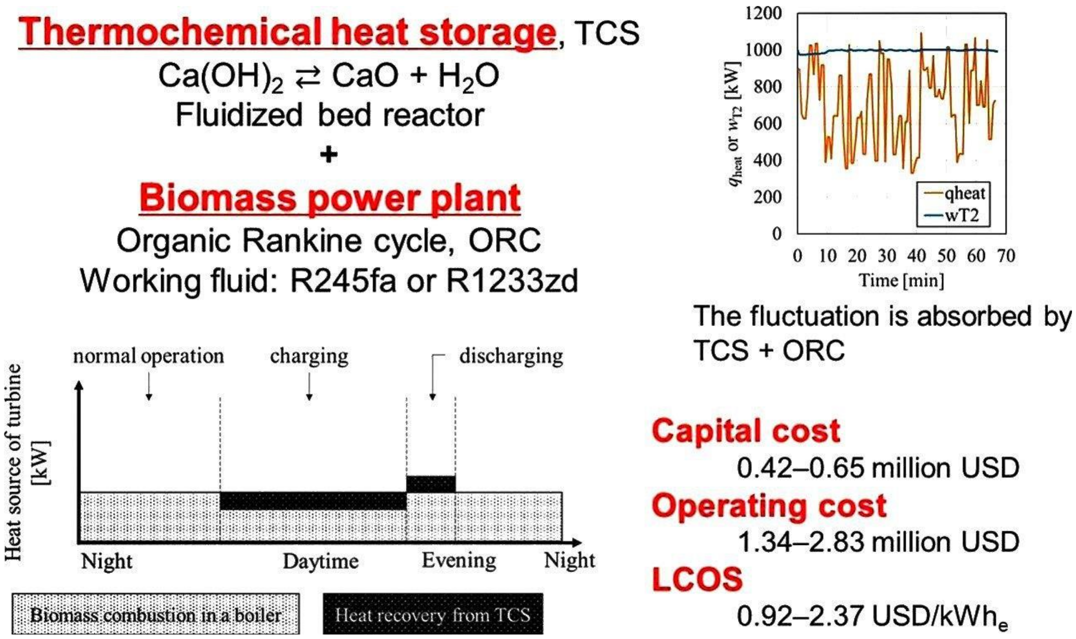


***Figure 3.*** *Thermochemical heat storage on a biomass power plant [12].*

## 2.9. Organic Rankine Cycled Biomass-Fired Power Plant

Shailesh Singh Sikarwar et al., 2020 [13] Global warming due to greenhouse emissions is the most annoying problem for sustaining life on Earth. Many researchers are contributing to the development of sustainable energy technologies. Chemical Looping Combustion (CLC) is a modernistic technology in which fuels produce heat and power without carbon emission. Agricultural biomass can be a potential substitute for fossil fuels for low-capacity energy generation. Further, CLC of biomass is a carbon-negative technology that can address the present greenhouse gas emission problem. In this study, a novel configuration of a CLC-based biomass power plant integrated with the Organic Rankine Cycle is proposed. The effects of key design parameters like oxygen carrier-to-biomass ratio, operating pressure of air/fuel reactors, and air reactor operating temperature are studied to improve the process energy and exergy efficiencies. Integration of waste heat recovery recuperates with the ORC cycle resulted in a further increase of power output by 49.93 kW. The performance of the proposed configuration is compared with conventional power plants to highlight its advantages. The net power output of the final CLC integrated configuration and conventional power plants are 492.19 kW and 273.12 kW respectively. Finally, the individual unit-wise exergy analysis is presented to identify the possible performance improvement options. Figure 4 shows the schematic process diagram of the CLC loop. Also, Figure 5 describes the schematic diagram of a conventional BFPP (Biomass-Fired Power Plant).

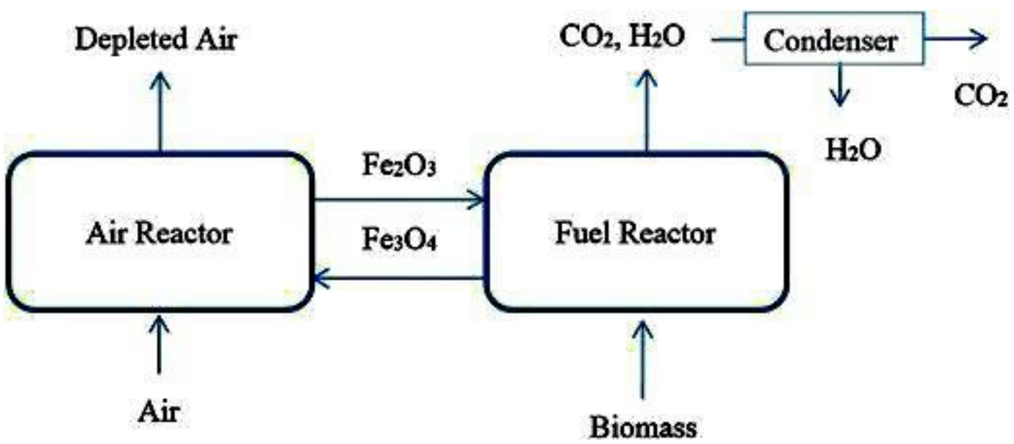


***Figure 4.*** *Schematic process diagram of CLC loop (chemical looping combustion) [13].*

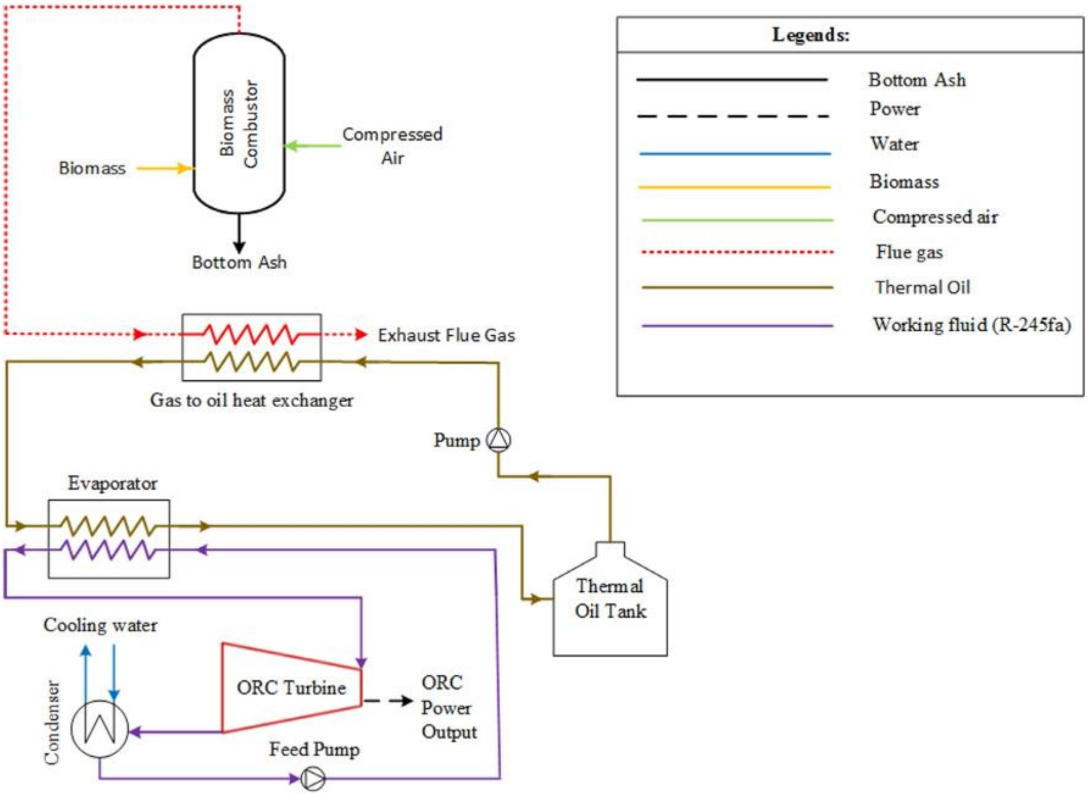


***Figure 5.*** *Schematic diagram of conventional BFPP (biomass fired power plant) [13].*

## 3. Performance Analysis and Improvement of Biomass Power Plant

### 3.1. Combustion Performance Analysis in a Biomass Power Plant

João Pedro Silva et al., 2021 [14] combustion air systems are an important aspect of the industrial boiler's performance, and they are being used increasingly to reduce emissions. Generally, improvements in boiler performance and emissions reduction can be achieved by modifying the air system. In the specific case of primary air, its temperature, distribution, and vibration of the grate significantly affect the conversion and mixing of biomass. Consequently, in this work, a comprehensive analysis of a biomass power plant operation, which is a result of an experimental campaign developed for 12 days is presented. In this regard, since the fuel has highly variable physical and chemical properties, disturbances causing an unsteady conversion process and corrosion risks were verified. Furthermore, the influence of the primary air distribution and the grate vibration cycles was evaluated through different tests. The grate vibration periods revealed that increasing the interval without vibrations results in a significant reduction of CO emissions. However, increasing this period may lead to some agglomeration problems in the grate. Concerning the primary air supply, in the three different sections of the grate, the supply of a more significant amount of air in the first two sections of the grate, in the central region of the grate, decreases the CO emissions. Additionally, the possibility of reducing the flue gas temperature using empirical correlations for a quick estimation of acid dew point during flue gas cooling for heat recovery to preheat the primary air was studied. The results revealed a large amount of energy that can be recovered without low-temperature corrosion problems, and 7% of the total input energy can be saved. Figure 6 shows the schematic diagram of the interaction of flue gases and water/steam. The main combustion parameters are present in Table 3. And, Table 4 details the flue gas emissions (on a volume basis) obtained during a mandatory measurement.

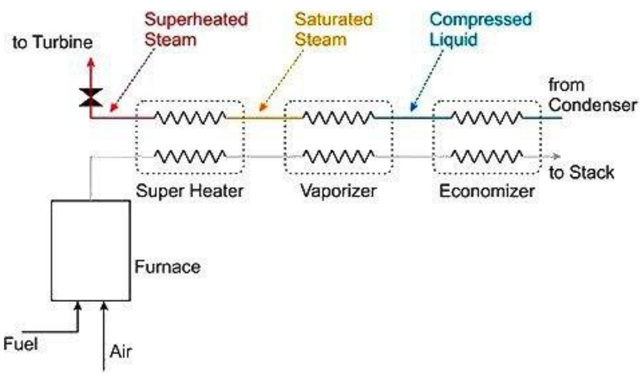


***Figure 6.*** *Schematic diagram of the interaction of flue gases and water/steam [14].*

***Table 3.*** *Nominal operating conditions [14].*

| Parameter | Value |
|---|---|
| Fuel flow rate (kg/h) | 12,200 |
| Primary air flow rate ($m^3$/h) | 33,150 |
| Secondary air flow rate ($m^3$/h) | 13,250 |
| Excess air (%) | 40 |

***Table 4.*** *Gaseous emissions and limit values [14].*

| Parameter | Emissions (mg/$m^3$) | Limit values (mg/$m^3$) |
|---|---|---|
| Particles | 25 | 150 |
| CO | 120 | 500 |
| $SO_2$ | 5 | 500 |
| $NO_x$ | 125 | 650 |

## 3.2. Economic and Environmental Analysis and Energy Efficiency of Electricity Generation from Biomass Resources

Imrul Reza Shishir et al., 2014 [15] biomass is always cost-effective in terms of energy conversion. Most importantly, resources, most of the time, are wastes. So, using biomass for energy conversion does not need any extra attention for resources. These resources also emit less carbon and sulfates in comparison to fossil fuels. As, such, these are environment-friendly sustainable sources of energy. In some cases, biofuel crops compete with food crops. But biomasses are part of the food corps. So, competition will never arise here. Biomass also absorbs carbon during its growth. So, carbon emission during energy conversion can be summed up as zero. The result of a study is shown in Figure 7 comparison between different sources of energy in terms of cost and carbon emission. This can also show the eligibility of biomass to be a sustainable energy source.

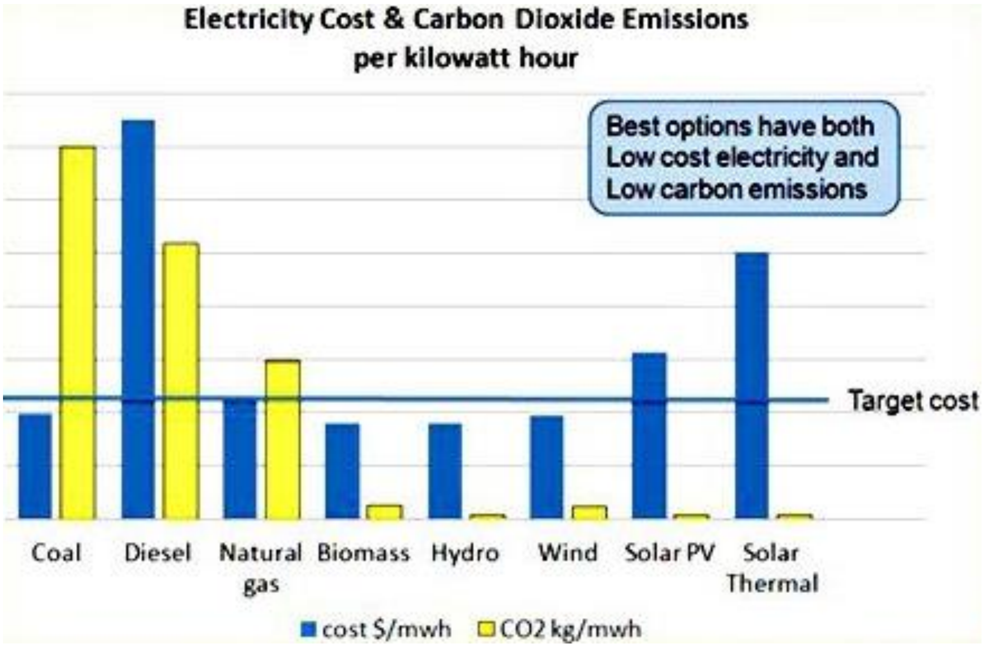


***Figure 7.*** *Comparison of efficient energy sources [15].*

## 3.3. Second Law Evaluation and Environmental Analysis of Biomass-Fired Power Plant

Tao Hai et al., 2023 [16] two novel configurations for hybridization of geothermal and biomass energies are proposed and analyzed in this paper. In the first system (named Configuration 1) geothermal heat is employed for feed water heating, while in the second one (named Configuration 2) the geothermal energy is employed for steam generation to be entered into the low-pressure steam turbine stage. The method of hybridization of geothermal and biomass resources in this paper is quite different than the schemes proposed in previous research. Another unique feature of the proposed hybrid configurations is the ability to utilize geothermal resources with various temperature levels. To assess the feasibility of proposed systems and to compare their performance, detailed simulation models are made based on the first and second laws. Also, the systems' performances are evaluated from the environmental perspective using three exergo-environmental factors. In addition, the optimal operating conditions of the systems are determined concerning the maximum exergy efficiency. For a wide range of practical operating conditions, it is found that the proposed Configuration 2 outperforms Configuration 1 due to the direct steam injection into the low-pressure turbine in the former. Under optimal operation, it yields 8.65% higher exergy efficiency as well as 12.5% lower environmental damage effectiveness compared to Configuration 1. Also, it is concluded that the gasification and combustion processes own more than 55% of overall exergy destruction in both systems.

### 3.4. Performance Analysis of Biomass-to-Energy System Based on Gasification and Pyrolysis

Tongyu Li et al., 2023 [17] a novel integrated biomass-to-energy system based on gasification and pyrolysis for efficient and sustainable energy production which is shown in Figure 8. The system combines the advantages of gasification and pyrolysis to convert different types of biomasses into electrical energy and hydrogen energy, respectively. The pyrolysis of woody biomass generates bio-oil and accompanying gas that is mixed with gasification-produced syngas to increase its heating value, thereby increasing power generation. The heat generated during gasification is used to provide thermal energy for pyrolysis, increasing the yield of pyrolysis products. The proposed system was thermodynamically and economically evaluated, and it was found that the system achieved high energy efficiency and economic benefits, greatly exceeding the energy utilization efficiency of conventional biomass power plants. The system also had excellent environmental performance with a lower $CO_2$ emission intensity than that of a coal-fired power plant. The effects of the pyrolysis temperature, gasification temperature, and turbine pressure ratio were explored in the novel system, and the results show that increasing the pyrolysis temperature appropriately is beneficial for increasing hydrogen production and power generation, while increasing the gasification temperature increases the hydrogen yield but decreases the system power generation. These results demonstrate that the proposed integrated biomass-to-energy system provides an efficient and sustainable approach to biomass energy utilization.

Haolin Liu et al., 2022 [18] in order to alleviate the impact of coal combustion on the environment, a scheme of biomass gasification in coal-fired ultra-supercritical power plant is proposed and simulated with Aspen plus. Simulation results show that the energy and exergy efficiencies of the coupled system have an increasing-decreasing tendency with the increase of the air/biomass ratio, reaching the maximum value when the air/biomass ratio is 1.6. The energy and exergy efficiencies of the coupled system decrease continuously with the increase of the excess air ratio. The coupled system has the highest energy and exergy efficiencies of 46.89% and 43.13%, which are 2.70% and 1.81% higher than those of an ultra-supercritical coal-fired system, respectively. Meanwhile, the coupled system has low $CO_2$, $SO_2$, and $NO_x$ emissions and thus many advantages in terms of environmental performance.

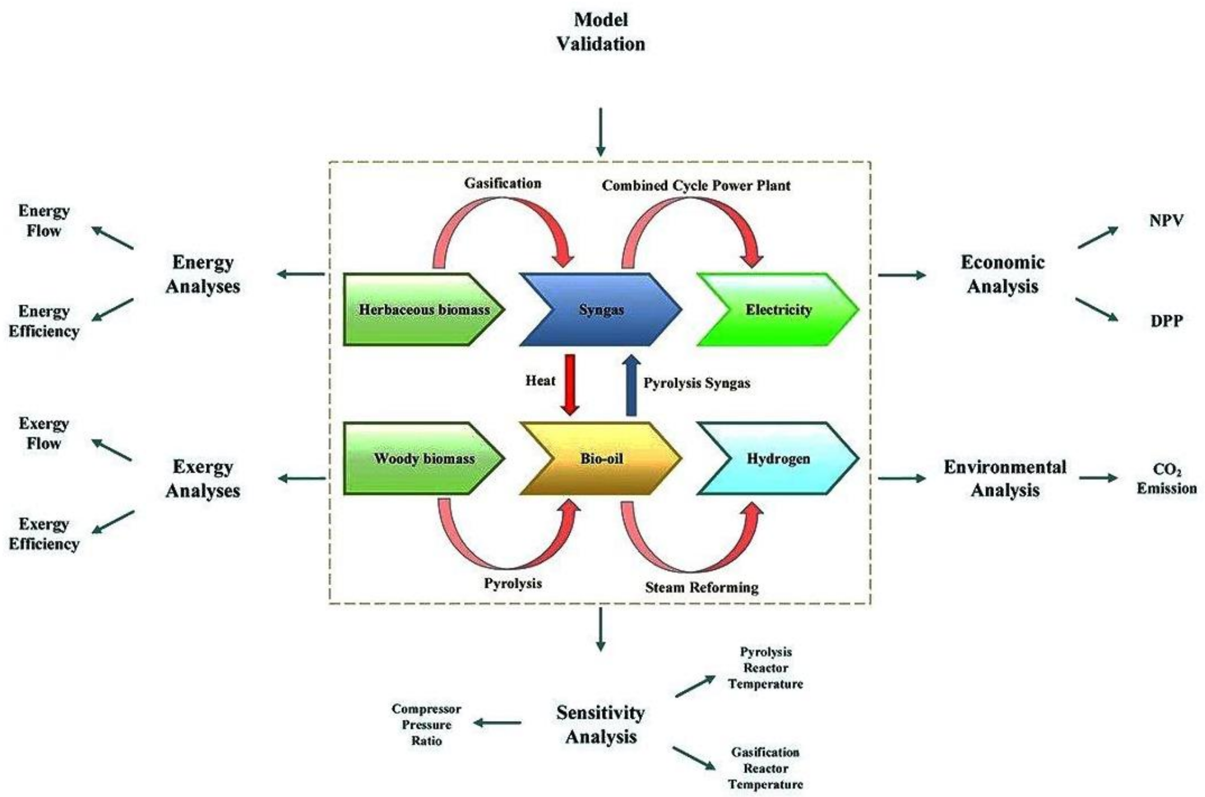


***Figure 8.*** *Gasification and pyrolysis process of biomass-to-energy [17].*

### 3.5. Energy, Exergy, Exergo-Economic, and Environmental Analyses of a Biomass-to-Energy

Fan He et al., 2022 [19] a novel biomass-driven heat and power cogeneration system comprising biomass gasification, a gas turbine, a Stirling engine, and a supercritical carbon dioxide cycle integrated with a domestic water heater was proposed in this work. Different biomass feedstocks (paper, wood, paddy husk, and municipal solid waste) were used in the gasified as the input fuel. The devised system was analyzed from energy, exergy, exergo-economic, and environmental viewpoints. Moreover, the effect of integrating the Stirling engine with the stand-alone CHP system is studied. Moreover, a detailed parametric analysis was performed to assess the effect of varying operating parameters on system efficiency. Finally, multi-objective optimization using a genetic algorithm in MATLAB software was performed to obtain the optimum operating points. According to the results, using municipal solid waste as the input biomass resulted in the highest exergy efficiency of 41.36% and the lowest $CO_2$ emission of 0.9021 t/MWh which is shown in Figure 9. Also, the system with the Stirling engine had a higher exergy efficiency and lower $CO_2$ emission than the system without the Stirling engine. According to the optimization results, the maximum obtainable exergy efficiency was 42.03%, which was related to MSW. Also, the minimum achievable $c_{p, tot}$ was 10.94$/GJ, attributable to the respective paddy husk. Figure 10 shows the comparison of energy and exergy efficiencies of different biomasses for the proposed system with and without SE.

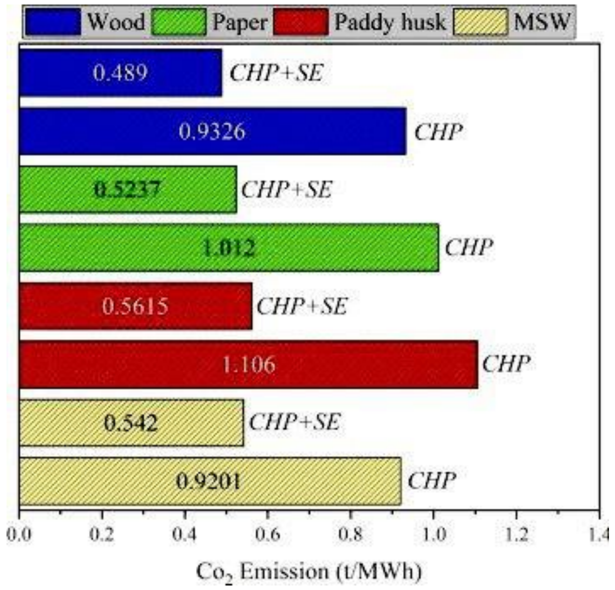


***Figure 9.*** *Comparison of $CO_2$ emission of different biomasses for the proposed system with and without SE [19].*

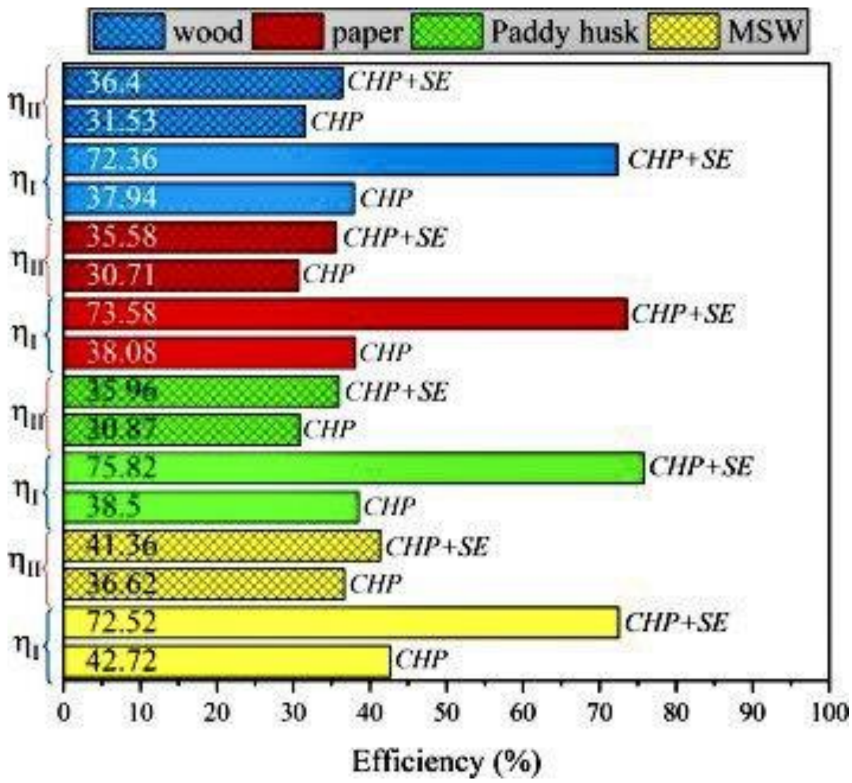


***Figure 10.*** *Comparison of energy and exergy efficiencies of different biomasses for the proposed system with and without SE [19].*

## 4. Summery

*Table 5. Various biomass power plant with their observation.*

| Biomass Power Plant | Reference | Methodology | Observation |
|---|---|---|---|
| Biomass-Driven Combined Heat and Power Plant | [4] | The combination of a gasification with a Brayton cycle by utilizing biomass resources. | The proposed system demonstrates 67% and 12% efficiency improvement in comparison to the stand-alone biomass power plant. |
| Novel Air-Cooled HGB Power Plant | [6] | The biomass flow rate is controlled to maximize the net electric power/thermodynamic efficiency of the plant with varying ambient air and geothermal fluid temperatures. | The resulting detrimental effect on the yearly produced electric energy in the range of 9%–23.6%. |
| Novel Biomass Fuelled Power Plant | [7] | A novel biomass-fuelled power plant with carbon capture and sequestration is proposed in this work. | It is found that BFP-CCS performs best at the $H_2O/Mn_2O_3$ mass ratio of 1.6, the $H_2O/O_2$ molar ratio of 2.8, the $O_2$/biomass mass ratio of 0.22, and the fuel utilization factor of 0.65. |
| Oxy-Fuel Combustion Based on Circulating Fluidized Bed Power Plant | [8] | A supercritical oxy-fuel combustion system based on a CFB boiler firing coal, lignite, and sawdust is established to evaluate the system's performance. | The results showed that compared to lignite and sawdust combustion, oxy-fuel combustion with coal has the highest net efficiency and exergy efficiency which is mainly because of the lower moisture and ash. |
| Bottom Ash Discharged Biomass-Based Thermal Power Plant | [9] | The applicability of bottom ash (BA) discharged from a biomass-based thermal power plant as an agricultural soil conditioner. | The optimal BA treatment for Chinese cabbage cultivation was 100 kg/10a, which showed a yield index of 138 compared to that of the control. |
| Biomass-Based Combined Power and Cooling Plant | [10] | Biomass-based combined power and cooling plant that uses sawdust as its fuel, and steam as its sole gasifying agent. | The exergo-economic and exergo-environmental factors obtained are 51.5% and 0.0288% respectively at the favourable operating conditions. |
| Wood-Fired Power Plant | [11] | Fuel costs determining factor for the operational expenditure of solid biomass furnaces. Consequently, there is an incentive to shift towards cheaper feedstock like forest residues, composting residues, or waste wood. | At deliberate extreme conditions and edge cases, a faster adaption to changing fuel properties and more stable operation can be observed |
| Fluidized Bed Reactor Biomass Power Plant | [12] | In this thermochemical heat storage (TCS) system, a fluidized bed reactor using CaO/Ca$(OH)_2$/alumina particles was used, and steam was used as a fluidizing and reacting gas. | Results show that the round-trip efficiency of the process using R1233zd was 8.77%, which was slightly lower than that of the process using R245fa (8.84%). |
| Organic Rankine Cycled Biomass-Fired Power Plant | [13] | A novel configuration of a CLC-based biomass power plant integrated with the Organic Rankine Cycle is proposed | The net power output of the final CLC integrated configuration and conventional power plants are 492.19 kW and 273.12 kW respectively |

*Table 6. Thermodynamics analysis and performance improvement of biomass power plant.*

| Performance Analysis and Improvement | Reference | Methodology | Observation |
|---|---|---|---|
| Combustion Performance Analysis | [14] | By modifying the air system, in the specific case of primary air, its temperature, distribution, and vibration of the grate significantly affect the conversion and mixing of biomass. | The results revealed a large amount of energy that can be recovered without low-temperature corrosion problems, and 7% of the total input energy can be saved. |
| Economic and Envi- | [15] | Resources emit less carbon and sulphates in | The result of the study is carbon emission |

| Performance Analysis and Improvement | Reference | Methodology | Observation |
|---|---|---|---|
| ronmental Analysis | | comparison to fossil fuels. | during energy conversion can be summed up as zero as its sources of energy in terms of cost and carbon emission. |
| Second Law Evaluation and Environmental Analysis | [16] | In the first system, geothermal heat is for feed water heating, while in the second one geothermal energy is for steam generation to be entered into the low-pressure steam turbine stage | Under optimal operation, it yields 8.65% higher exergy efficiency as well as 12.5% lower environmental damage effectiveness compared to Configuration 1. Also, the gasification and combustion processes own more than 55% of overall exergy destruction in both systems. |
| Performance Analysis of Biomass-To-Energy System Based on Gasification and Pyrolysis | [17] | The pyrolysis of woody biomass generates bio-oil and accompanying gas that is mixed with gasification-produced syngas to increase its heating value, thereby increasing power generation. | The proposed integrated biomass-to-energy system provides an efficient and sustainable approach to biomass energy utilization. |
| Energy, Exergy, Exergo-economic, and Environmental Analyses of a Biomass-To-Energy | [19] | Different biomass feedstocks (paper, wood, paddy husk, and municipal solid waste) were used in the gasifier as the input fuel. | The maximum obtainable exergy efficiency was 42.03%, which was related to MSW. Also, the minimum achievable $c_{p,tot}$ was 10.94 $/GJ, attributable to the respective paddy husk |

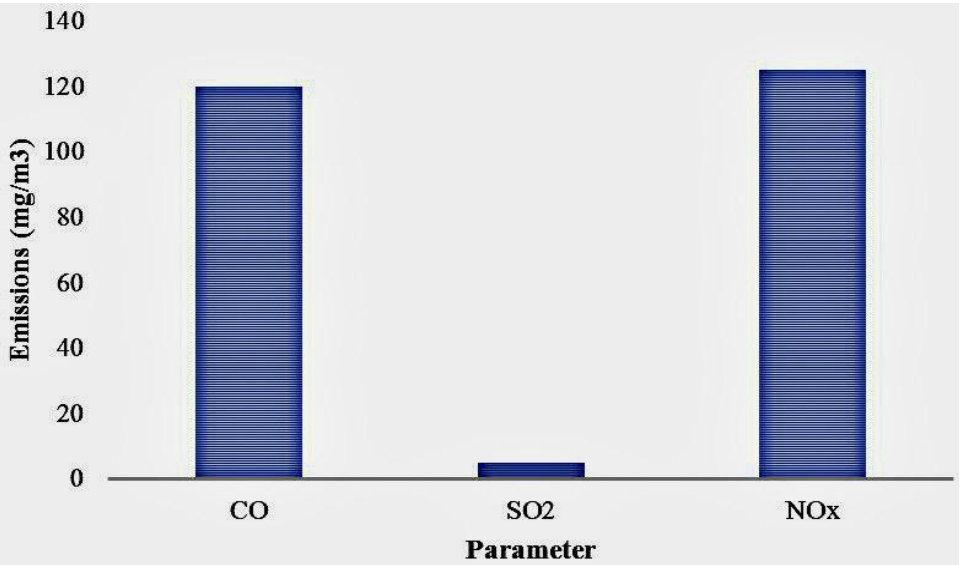


***Figure 11.*** *Gaseous emission of the biomass power plant.*

## 5. Conclusion

Biomass power plants are likely to continue playing an important role in the renewable energy sector. Biomass power plants may adopt advanced conversion technologies to improve efficiency and reduce emissions. These could include gasification, pyrolysis, and anaerobic digestion, which offer higher energy conversion rates and more flexibility in utilizing different types of biomass feedstock. Biomass power plants could explore innovative ways to source feedstock sustainably. This might involve using agricultural residues, dedicated energy crops, or even algae biomass as feedstock, which could help reduce competition with food production and minimize the carbon footprint of the biomass supply chain. The major conclusion can be drawn in the following way.

1) The biomass-driven combined heat and power plant demonstrates 67% and 12% efficiency improvement compared to the stand-alone biomass power plant.
2) The resulting detrimental effect on the yearly produced electric energy in the range of 9%–23.6%.
3) BFP-CCS performs best at the $H_2O/Mn_2O_3$ mass ratio of

1.6, the $H_2O/O_2$ molar ratio of 2.8, the $O_2$/biomass mass ratio of 0.22, and the fuel utilization factor of 0.65.
4) The exergo-economic and exergo-environmental factors obtained are 51.5% and 0.0288% respectively at the favorable operating conditions.
5) The round-trip efficiency of the process using R1233zd was 8.77%, which was slightly lower than that of the process using R245fa (8.84%).
6) The net power output of the final CLC integrated configuration and conventional power plants are 492.19 kW and 273.12 kW respectively.
7) A large amount of energy can be recovered without low-temperature corrosion problems, and 7% of the total input energy can be saved.
8) The maximum obtainable exergy efficiency was 42.03%, which was related to MSW (Municipal Solid Waste).

# Abbreviations

$CO_2$: Carbon Dioxide
IEA: International Energy Agency
IRENA: International Renewable Energy Agency
$SO_2$: Sulfur Dioxide
CHP: Combined Heat and Power
CAES: Compressed Air Energy Storage
LCOE: Levelized Cost of Electricity
CO: Carbon Monoxide
$H_2$: Hydrogen
$CH_4$: Methane
$N_2$: Nitrogen
$O_2$: Oxygen
BFP-CCS: Biomass Fueled Power Plant with Carbon Capture and Sequestration
CFB: Circulating Fluidized Bed
BA: Bottom Ash
STBM: Steam-To-Biomass Ratio
TIT: Turbine Inlet Temperature
EPOE: Effective Price of Electricity
TCS: Thermochemical Heat Storage
VRE: Variable Renewable Energy
CLC: Chemical Looping Combustion
BFPP: Biomass-Fired Power Plant

# Conflicts of Interest

The authors declare no conflicts of interest.

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