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Article

Optimization of the Exergy, Energy and Environmental Performance of a Biomass Power Plant for Electricity Generation Using the Rankine-Hirn Cycle Method for Sustainable Development

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Abstract

Among renewable energy sources, biomass offers notable advantages compared to fossil fuels regarding both cost and environmental effects. However, the high moisture content in biomass can adversely impact its combustion efficiency, leading to lower flame temperatures and an increase in the emission of harmful gases, which may cause operational and ecological challenges. Thus, it is necessary to dehydrate biomass before combustion for electricity generation. To enhance energy efficiency and reduce drying costs, an effective thermal integration between the steam power plant and the biomass drying process is crucial. This research conducts enthalpy evaluations on a biomass power facility utilizing agricultural waste, specifically dried banana peels, as fuel. The goal is to analyze energy efficiency, exergy, and CO_2 emissions. The Rankine-Hirn cycle is employed to model the biomass power plant, focusing on exergy and environmental impacts. A custom Matlab code was developed to generate the results. Findings indicate that the ideal output enthalpy from the pump is 450 kJ/kg, corresponding to a peak exergy efficiency of 41%. The optimal enthalpy at the turbine outlet is 200 kJ/kg, yielding an energy efficiency of 95%. Maximum energy efficiency, reaching 88%, occurs when the enthalpy at the turbine inlet attains its optimal level of 3400 kJ/kg. This system can be used to generate electricity in areas where access is limited.

Keywords

Biomass, Fuel, Dehydration, Enthalpy, Electricity

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1. Introduction

Biomass is organic matter that can be converted into energy using conversion techniques that exploit the thermodynamic and kinetic properties of chemical reactions, such as anaerobic/aerobic digestion, combustion, pyrolysis and gasification, which are governed by the principles of thermochemistry and biochemistry. Biomass encompasses a diverse range of organic materials, including specific energy crops and wastes such as forestry residues (cotton stalks, paddy straw, rice husks, sawdust), as well as various agricultural and industrial by-products that can be recovered for energy production. Direct combustion is an exothermic thermochemical step that converts solid fuels into heat and steam. It is well suited to biomass because of its low cost and reliability, and is essential for producing electricity in biomass power plants [1]. The steam produced can be used for industrial applications or to generate electricity. The design of a biomass combustion plant depends on the properties of the fuel, environmental regulations, costs and energy and production capacity requirements for efficient, environmentally-friendly operation [2]. The physico-chemical properties of the fuel have a significant impact on the selection and design parameters of the combustion system. In particular, the moisture content of the fuel is a critical factor that significantly influences combustion efficiency and stability. The physico-chemical properties of the fuel, in particular the moisture content, have a considerable influence on combustion efficiency and stability, thus affecting system selection and design parameters. Modern biomass combustion systems require a specific moisture content range for the fuel to ensure emissions and efficiency meet standards. Using fuel outside this range can cause the system to shut down automatically to prevent malfunctions [3]. Biomass has a wide range of moisture content, from 10% for cereal straw to 50-70% for forestry waste, depending on its origin and composition [4]. Industrial sludge and fresh microalgae have a high moisture content, in excess of 90% respectively [5]. The use of dried fuels in combustion plants optimises thermal efficiency, intensifies steam generation, minimises energy expenditure, reduces atmospheric emissions and improves the performance of steam generators [6]. The investigation delves into the collaboration between a timber processing facility, a pellet production site, and a hybrid energy generation plant that utilizes organic waste within a specialized thermal system designed to boost energy efficiency and sustainability [7]. The findings indicate that as much as 18% of the organic waste produced by the timber processing facility can be reclaimed through a cooperative production method. Danon et al. [8] offers an evaluation of energy and economic factors across various biomass cogeneration plants, assessing the efficacy of different technologies, including the organic Rankine cycle (ORC), Stirling engine, steam engine, steam turbine, and gas engine. The evaluation shows that, within the Serbian context, the establishment of cogeneration systems in small-scale timber processing operations (approximately 10,000 m^3/year) is not economically feasible. However, varied organic resources, especially forest waste, can be harnessed to fuel decentralized hybrid energy systems. Following this, Peterseim et al.[9] introduces a groundbreaking hybrid power facility that integrates diverse biomass sources (such as wood waste and wood chips) with concentrated solar energy using parabolic trough collectors. Likewise, Angrisani et al. [10] examines a hybrid energy system that merges solar photovoltaic power with bioenergy resources.

A similar principle should be applied to optimize the yield of a biomass energy plant. Using steam to dry the biomass minimizes energy losses in the boiler and condenser, improving the overall efficiency of the system. In what follows, the use of dried banana peels to study the impact of enthalpy on improving the energy efficiency of a biomass power plant is carried out. After drying, banana peels have a moderate moisture content of 10% to 12%.

The important and current contributions of the present study to biomass power plant research are :

Integrated Energy + Exergy + Environment approach: This enables us to better identify the major sources of useful energy wastage and optimize cycle design (Rankine, ORC, etc.). Environmental assessment based on lost exergy: Reduce biomass consumption for the same production. Support for energy transition and decarbonization: A better understanding of exergo-environmental performance helps to reduce the ecological impact and improve the competitiveness of these power plants.

2. Materials and Methods

2.1 Description of the Plant

The fundamental concept of a cogeneration plant was based on the recovery and use of the thermal waste generated by the electricity production equipment, which required a sufficiently high discharge temperature to enable this residual energy to be used efficiently. Many cogeneration plants generally used gas turbines, steam turbines, or internal combustion engines to generate electricity. New technologies, such as fuel cells, were also developed and could be integrated into cogeneration systems.

The recovery of the high-temperature heat contained in the exhaust gases at the boiler level has made steam available at the end of the process. The transformation of the thermal energy of superheated steam into mechanical energy at the turbine has occurred, thanks to the steam that underwent expansion through the turbine wheels available on the rotor. The conversion of mechanical energy from the turbine rotor into electrical energy at the generator has occurred, which was then transmitted to the grid or to an isolated load.

2.2 Mathematical Modelling

2.2.1 Energo-exergetic Analysis

2.2.1.1 Rankine Cycle or Ideal Rankine Cycle

The theoretical Rankine cycle, named after the Scottish physicist William J. Rankine, serves as a fundamental model for thermal and nuclear energy installations, where water is used as a transfer agent to convert thermal energy into mechanical work. In a theoretical framework, turbines are treated as operating in an isentropic cycle, which means a reversible adiabatic transformation. In practice, machines can never achieve perfection, and efficiency coefficients will be built in later to take account of this. The 4 stages of the cycle are as follows:

Process (1-2): Heat transfer to the fluid. Heat is produced by a fuel. Water enters the boiler, absorbs the heat produced and exits as superheated steam.

Process (2-3): Expansion. The steam passes through the turbine, losing its pressure. The enthalpy lost by the steam is transformed into work by the rotating turbine.

Process (3-4): Rejection of the heat of condensation into the ambient environment when steam is transformed into water in a condenser. This energy can also be extracted to meet cogeneration thermal loads.

Process (4-1): Isentropic increase in the pressure of water supplied to the steam boiler by means of a pump. The water enters the pump as a saturated liquid and leaves as a sub-cooled liquid. The work required by this change of state, i.e. the work supplied by the pump, is generally a fraction of the work produced by the turbine (typically 5%).

The work produced by the turbine per unit mass of steam it uses, or work produced in the Rankine cycle, is symbolised by equation (1) [11]:

$$W_{ideal} = h_2 - h_3 \tag{1}$$

Where Wideal is the work produced by the Rankine cycle, i.e. the theoretical specific steam consumption, h_2 is the enthalpy of the steam feeding the turbine and h_3 is that of the steam leaving the turbine.

The unit work W actually produced by the steam turbine (which gives the actual specific steam consumption), takes into account the fact that the turbine does not operate according to the ideal cycle. It is calculated by equation (2) [11]:

$$W = \eta_s \cdot W_{ideal} \tag{2}$$

Where η_s is the isentropic efficiency of the turbine.

The enthalpy h_2 and entropy s_2 of the steam entering the turbine can be determined from the pressure P_2, and the temperature T_2 of the superheated steam, two parameters defined by the user. The enthalpy h_3 at the outlet of the extraction point can be determined as a function of the turbine outlet pressure P_3, also specified by the user, and the entropy at the extraction point s_3 (equal to s_2 on the assumption of an isentropic transformation).

In reality, the device does not behave like a theoretical model, and additional efficiency losses should be considered. The energy actually produced by the turbine for each unit mass of steam (or the effective specific steam consumption) can be established as a function of the total isentropic efficiency of the turbine-generator system, as shown by relationship (3) [11]:

$$W = \eta_{tg} \cdot W_{ideal} \tag{3}$$

In practice, efficiency is influenced by various elements along the steam path, including the diameter of the nozzle opening.

The electrical power produced by the turbine can now be obtained by multiplying the unit work produced by the mass flow rate of steam supplied to the turbine. This is represented by equation (4) [12,13]:

$$P_{elec} = \dot{m} \cdot W \tag{4}$$

Where W is the work actually produced per unit mass of steam entering the steam turbine-generator unit.

The thermal capacity of the turbine is then symbolised by formula (5) [12]:

$$\dot{Q}_c = \dot{m}\left(h_3 - h_4\right)W \tag{5}$$

The quality index of the steam leaving the turbine is obtained from the entropy of the water which may begin to appear at the turbine outlet and the entropy of the steam leaving the turbine, according to the following formula (6) which applies to the two-phase mixture [11]:

$$X_3 = \frac{s_3 - s_1}{s_v - s_1} \tag{6}$$

where x_3 indicates the quality coefficient of the steam emitted by the turbine, s_3 corresponds to the entropy of this steam, s_1 refers to the entropy of the water introduced into the steam boiler at the turbine outlet pressure, and sv symbolises the entropy of the steam in the saturated state at this pressure. When the steam quality coefficient is below 1, this means that the steam is damp.

If the water vapour quality coefficient is below 1, this means that the vapour contains water in the form of small drops (this vapour is then referred to as humid).

In general, a steam turbine requires a minimum quality coefficient of between 0.90 and 0.95. If this coefficient is too low, it can lead to wear of the turbine blades, caused by the impact of water droplets on them, thus increasing the maintenance costs of the electricity generation system. When the pressure of the extracted steam is higher, the quality coefficient of the steam circulating in the turbine increases. If it is not possible to extract the steam at a higher pressure, it will be necessary to use several steam turbines and possibly a reheater or moisture separator. This will help to reduce maintenance costs, but will increase the initial outlay on the equipment.

2.2.1.2 Hirn Rankine Cycle

The Hirn Rankine cycle is an adaptation of the Rankine cycle that incorporates pressure losses and system inefficiencies. It is used to simulate the actual operation of steam turbines. This cycle comprises the same phases as the Rankine cycle, but takes into account the following elements: modelling pressure losses in heat exchangers; losses due to turbine inefficiency and heat loss in pipes [14].

(1) Back-Pressure Cycle

To generate both mechanical power and a significant amount of heat, it is preferable to allow all the steam from the generator to expand in a prime mover, so that when it leaves, it is in a suitable state for subsequent use for heating. The condenser is therefore replaced by a heat exchanger, which recovers the thermal energy generally lost to the cold source. Since this heat exchanger operates at a higher pressure than the conventional condenser, it is referred to as a back-pressure cycle. As the turbine exhaust pressure is greater than atmospheric pressure, it is indicated that it is operating at back pressure.

(2) Heat Balance in the Turbine

The steam turbine efficiency is expressed by formula (7) [15,16]. The power of the steam turbine and that of the pump are calculated using relations (8) and (9) respectively [12,14,16].

$$\eta_{TV} = \frac{h_0 - h_1}{h_0 - h_{1s}} \tag{7}$$

$$\dot{W}_{TV} = \dot{m}_v \left(h_0 - h_1\right) \tag{8}$$

$$\dot{Q}_{1-2} = \dot{m}_v \left(h_1 - h_2\right) \tag{9}$$

$$\dot{Q}_{3-0} = \dot{m}_v \left(h_0 - h_3\right) \tag{10}$$

$$\dot{W}_p = \dot{m}_v \left(h_3 - h_2\right) \tag{11}$$

(3) Heat Balance in the Boiler

Indirect method for calculating boiler efficiency: Heat losses can be assessed according to the American Society of Mechanical Engineers (ASME) test code. This strict code covers all types of fuel, but in Algeria boilers mainly use natural gas or fuel oil, making some of the losses mentioned in the code irrelevant. A simplified method for calculating the efficiency of a boiler is described by equation (12) [13,16,17]:

$$efficiency = \frac{input - loss}{ouput} \times 100 \tag{12}$$

The exergy efficiency of the Rankine-Hirn cycle can fluctuate according to various parameters of the cycle, such as: the temperature and pressure of the steam at the turbine inlet; condenser temperature and pressure; type of working fluid (water, ammonia, etc.) and pump and turbine efficiency. It is calculated by relationship (13) [18-22]:

$$\eta_{ex} = \frac{W_{TV} - W_p}{\dot{Q}_{3-0}} \tag{13}$$

2.2.2 Environmental Analysis

Emissions from the biomass power plant are calculated using equation (14) [23-27].

$$EmCO_2 = \frac{m \cdot \%C \cdot F}{\eta_{TV}} \quad (14)$$

Where *m* is the mass of biomass burnt per year (t/yr), *%C* is generally between 0.45 and 55 tC/t biomass, *F* is the CO_2 emission factor per tonne of carbon burnt. The characteristics of the biomass power plant are illustrated in Table 1.

Table 1. Characteristics of the power plant [28,29].

(0): Turbine input and reading of steam characteristics from thermodynamic data:	
P_0 = 5.4 MPa T_0 = 480 °C	V_0 = 0.0611323 m^3/kg h_0 = 3381.902 kJ/kg S_0 = 6.87382 kJ/kg.K
(1): Turbine output and reading of steam characteristics from thermodynamic data	
P_1 = 0.27 MPa T_1 = 140 °C	V_1 = 0.68763 m^3/kg h_1 = 2742.043 kJ/kg S_1 = 7.0799 kJ/kg.K
(1s) Isentropic output and reading of steam characteristics from thermodynamic data	
V_1s = 0.649753 m^3 /kg h_1s = 2658.696 kJ/kg X_1s = 0.972	
(2): Saturated liquid and reading of vapour characteristics from thermodynamic data	
T_2 = 105 °c P_2 = 0.27 MPa	V_2 = 0.001047 m^3/kg h_2 = 440.239 J/kg S_2 = 1.3628 kJ/kg.K
(3): Pump outlet	
P_3 = 5.4 MPa $S_3 = S_2$ = 1.3628 kJ/kg.k	h_3 = 445.608 kJ/kg V_3 = 0.001045 m^3/kg

The boundary conditions for this model are given by the inequalities in 15-19.

$$2800 \leq h0 \leq 3400 \text{ kJ/kg} \quad (15)$$

$$2700 \leq h1 \leq 2900 \text{ kJ/kg} \quad (16)$$

$$1000 \leq hs \leq 2500 \text{ kJ/kg} \quad (17)$$

$$450 \leq h3 \leq 500 \text{ kJ/kg} \quad (18)$$

$$0 \leq mCO_2 \leq 2000 \text{ kg} \quad (19)$$

3. Validation

In 2022, Jalili et al. [30] studied the thermodynamic, economic and environmental aspects of an integrated system for cooling, heating and electricity production powered by biomass and natural gas. The Eco-Indictor 99 method is used to quantify the environmental impact. The results indicate that the efficiency of the system's exhaust is 39.45% however in this study it is 41%, which is a relative error of 3%.

This study achieves an energy efficiency of 40%, which is higher than the 35.54% reported in Hai et al. [31] using coal as fuel. This improvement highlights the superior efficacy of dry banana peels as a fuel compared to coal.

4. Results and Discussion

Criteria are used in this analysis to measure system performance, with electrical power and Biomass energy and exergy yields as the main output indicators. In order to analyze the impacts of biomass plant enthalpies, various factors have been considered and are presented in Table 1. The general assessment and optimization was carried out using agricultural residues (dried banana peels) as the fuel source. In this analysis, the simulation results, in particular the effects of enthalpies on the performance of the Biomass power plant, are analyzed and the optimal values are presented. The numerical code is written in MATLAB for numerical programming.

Figure 1 demonstrates a linear relationship between the enthalpy of the saturated liquid and the electrical power generated by a biomass power plant. This trend indicates that an increase in enthalpy leads to a proportional rise in electricity production, suggesting that the thermal energy available for conversion into mechanical work is crucial. Therefore, plant operators should strive to maximize enthalpy to enhance energy production. This may require adjustments to operational parameters such as temperature and pressure. However, other factors also influence the efficiency of energy conversion, including fuel quality, turbine efficiency, and thermal losses. Finally, it's important to note that the Figure 1 does not provide details on experimental conditions, which are essential for accurate interpretation of the results. Elements like biomass composition and climatic conditions may also play a significant role. In summary, the results underscore the importance of optimizing operating conditions to maximize the efficiency of biomass power plants.

The impact of enthalpy at the turbine inlet on the energy efficiency of the biomass plant are shown in Figure 2. It can be seen that varying the enthalpy at the turbine inlet from 2800 to 3400 $kJ.kg^{-1}$ leads to a significant increase in energy efficiency from 40 to 77%, then increases at a slow rate to an optimum value for the energy efficiency of the biomass plant at around 88%. This improvement in efficiency can be attributed to better management of thermal exergy and optimized combustion processes. Achieving maximum efficiency suggests that the biomass plant is capable of exploiting the resource very efficiently under certain conditions, such as the quality of the biomass, which should have a moisture content of less than 20% in order to improve combustion and reduce losses.

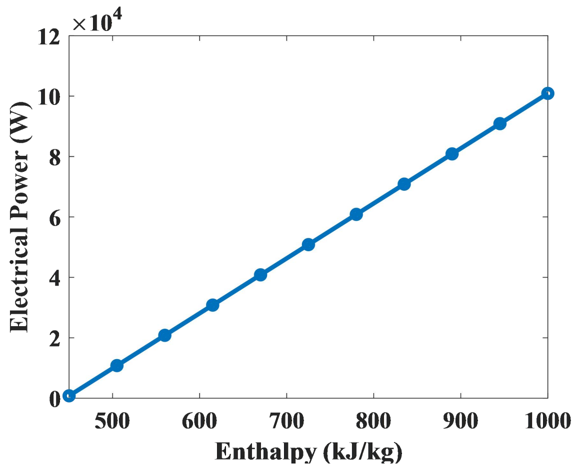

Figure 1. Impact of the quantified enthalpy in the saturated liquid on electrical power.

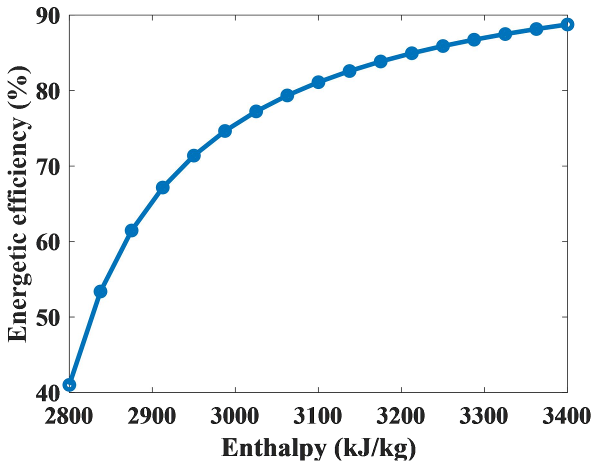

Figure 2. Impact of enthalpy at the turbine inlet on the energy efficiency of the machine.

Figure 3 illustrates the impact of isentropic enthalpy on the energy yield of the biomass power plant. As isentropic enthalpy increases from 1000 to 2500 kJ/kg, the exergy efficiency of the biomass plant shows a gradual rise from 27% to 53%, followed by a more substantial jump to approximately 73%. This trend suggests that optimizing heat flow management is key to enhancing efficiency. The initial slow growth in exergy efficiency indicates that the plant may have been operating below its optimal conditions at lower enthalpy levels. As the enthalpy increases, it likely allows for better thermal utilization, consequently improving the conversion of biomass into energy. The significant rise in efficiency at higher enthalpy levels points to the effectiveness of advanced technologies and methodologies implemented in the biomass-to-energy conversion process. This may involve enhanced heat exchangers, improved combustion techniques, or better steam management. Such advancements not only optimize the energy output but also minimize waste, reinforcing the sustainability of biomass as a renewable energy source. Overall, these findings highlight the importance of enthalpy in optimizing biomass energy systems and suggest that further research and development in this area could lead to even greater efficiency gains in the future.

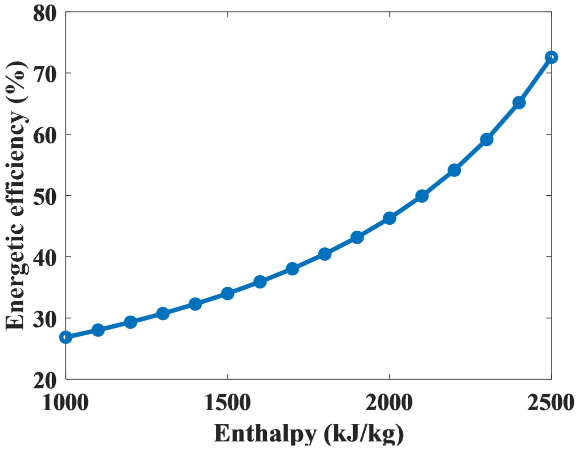

Figure 3. Impact of isentropic enthalpy hs1 on energy efficiency.

Figure 4 reveals that the increase in enthalpy at the turbine outlet from 2700 to 2900 kJ/kg has a detrimental effect on the energy efficiency of the biomass power plant, causing a significant drop from 94.7% to approximately 68%. This decline suggests that a considerable amount of energy that could otherwise be converted into useful work is being lost, which severely impacts the overall efficiency of the plant. Such a sharp decrease in efficiency could indicate underlying issues with the turbine's design or its operating conditions. For instance, if the turbine is not properly designed to handle the higher enthalpy levels, it may struggle to convert thermal energy into mechanical energy effectively. This could be due to factors such as inadequate blade design, which fails to optimize the energy transfer process, or possibly excessive wear and tear that diminishes performance. Additionally, operational parameters like fluid flow and pressure must be meticulously managed. Poorly adjusted fluid flow rates may lead to turbulence and inefficiencies in energy conversion, while sub-optimal pressure conditions can hinder the turbine's ability to extract energy from the steam efficiently. The significant loss of energy efficiency at higher enthalpy levels highlights the need for a comprehensive evaluation of the turbine's performance and operational settings. Addressing these issues through redesign or optimization could enhance the plant's energy conversion efficiency, resulting in more effective utilization of biomass resources and improved overall plant performance. Hai et al. [31] did not use dried banana peels, and its work presents an energy efficiency of 35.54% using coal as fuel.

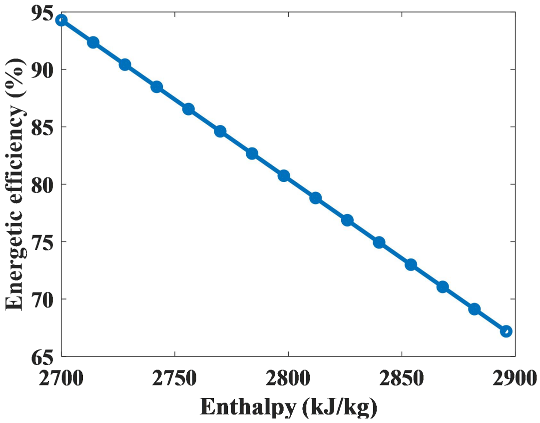

Figure 4. Impact of enthalpy at the turbine outlet on the power plant's energy efficiency.

Figure 5 illustrates the effect of the pump's output enthalpy on the exergy efficiency of the biomass power plant. Notably, as the output enthalpy from the biomass plant pump increases from 450 to 500 kJ/kg, there is a sharp decline in exergy efficiency, dropping from 41% to 18%. Following this rapid decrease, the efficiency continues to decline at a much slower rate, stabilizing around 8%. This significant reduction in efficiency can largely be attributed to several factors. First, friction losses within the pump become more pronounced at higher enthalpy levels, which can impede the energy transfer process. As the pump works harder to move the fluid, increased friction can lead to wasted energy, ultimately lowering the overall efficiency. Additionally, inefficiencies in energy transfer may stem from the pump's design or operational parameters. If the pump is not optimally calibrated for the specific conditions of the biomass system, it may fail to operate at peak performance, resulting in energy losses during the transfer process. Furthermore, non-optimal operation of the pump, possibly due to variations in fluid properties or flow rates, can exacerbate these issues. For instance, if the fluid viscosity changes with temperature, the pump's performance may be further compromised, leading to additional inefficiencies. Overall, these findings underscore the critical importance of optimizing pump design and operation in biomass power plants. Addressing these inefficiencies through better engineering practices or advanced control strategies could significantly enhance the exergy efficiency of the system, leading to improved performance and better utilization of biomass resources.

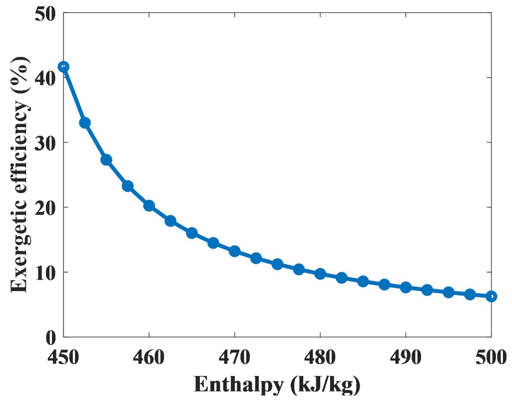

Figure 5. Impact of the pump h_3 output enthalpy on exergetic efficiency.

Figure 6 illustrates the relationship between biomass mass and CO_2 emissions, demonstrating that increasing the mass of biomass from 50 to 2000 kg results in a significant rise in CO_2 emissions, from 2 kg to 38 kg. This trend highlights a crucial aspect of biomass energy production: while biomass is often considered a renewable energy source, its combustion does produce CO_2, which can impact overall greenhouse gas emissions. The observed increase in emissions is directly linked to the combustion process itself. As more biomass is burned, more carbon is released into the atmosphere in the form of CO_2. This relationship underscores the importance of considering the entire lifecycle of biomass energy, from cultivation to combustion, when evaluating its environmental impact. Moreover, while biomass is often touted as a carbon-neutral energy source, it is essential to recognize that the carbon dioxide released during combustion can outweigh the benefits if not managed properly. For instance, if the biomass is sourced from unsustainable practices or if the regrowth of biomass does not occur at a pace sufficient to sequester the emitted CO_2, the environmental benefits may be diminished. Additionally, this data prompts a closer examination of alternative biomass management strategies. Implementing practices such as carbon capture and storage (CCS) or optimizing combustion technologies could mitigate the emissions associated with biomass combustion. In summary, while biomass presents a renewable option for energy production, the increase in CO_2 emissions with greater biomass use highlights the need for careful management and innovative strategies to minimize its environmental footprint. This understanding can guide future policies and practices aimed at balancing energy production with sustainability.

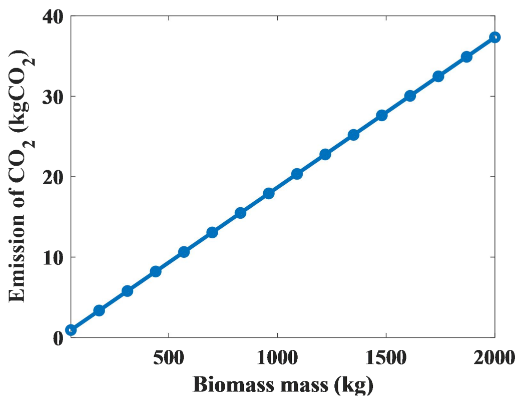

Figure 6. Impact of biomass mass on CO_2 emissions.

Figure 7 highlights the substantial influence of enthalpy at the turbine inlet on the electrical output of the biomass power plant. As the enthalpy increases from 2800 kJ/kg to 3400 kJ/kg, the electrical output escalates dramatically from 3 MW to 27 MW, representing an impressive 88% increase. This significant rise in output can be attributed to several factors related to the optimization of the combustion and energy conversion processes. Higher enthalpy levels imply that the steam entering the turbine carries more thermal energy, which can be converted more efficiently into mechanical energy. This enhanced energy conversion is likely due to improved thermal conditions that allow for better expansion and utilization of steam within the turbine. Furthermore, the ability to operate under more favorable conditions suggests advancements in turbine design and technology. Modern turbines may incorporate features that enhance their efficiency at higher enthalpy levels, such as improved blade geometry and materials that withstand higher temperatures and pressures. These innovations enable turbines to extract more energy from the steam, thereby increasing the overall electrical output. Additionally, this correlation between enthalpy and electrical output underscores the importance of maintaining optimal operational parameters within the plant. Proper management of combustion processes, including fuel quality and combustion temperature, can further enhance enthalpy levels and, consequently, energy production. In conclusion, the findings from Figure 7 indicate that optimizing enthalpy at the turbine inlet can lead to significant improvements in electrical output for biomass power plants. This reinforces the need for ongoing research and development in turbine technology and operational practices to maximize energy efficiency and output in biomass energy systems. These results are slightly higher than that of Lehneis et al. which had an electricity production of 2.2 × 107 W in 2025 over a time varying from 0 to 360 days during its work on the landscape of bioenergy electricity production in Germany [32].

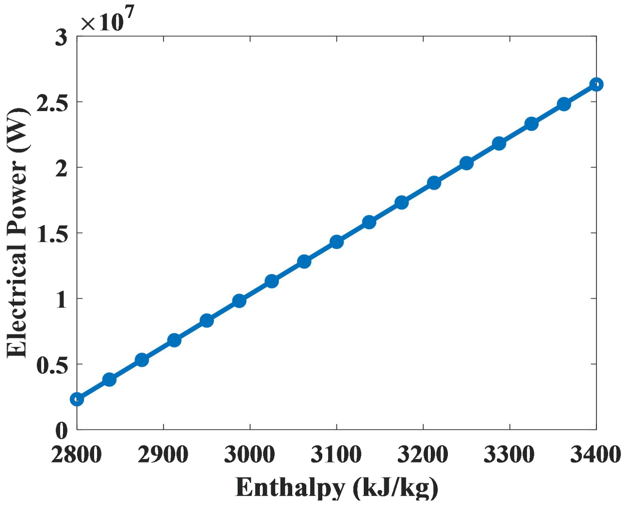

Figure 7. Impact of enthalpy at the turbine inlet on the electrical power produced.

The trade-offs between CO_2 emissions and energy efficiency in a biomass power plant comes down to analyzing the tensions between environmental and technical performance: biomass power plants offer a renewable alternative, but their high energy efficiency can increase CO_2 emissions if combustion is poorly controlled. Optimizing efficiency while limiting emissions requires advanced technologies and sustainable management, illustrating the trade-off between technical performance and environmental impact.

5. Conclusion

In the present study, a material, energy and exergo-environmental balance model taking into account the effects of enthalpies was developed to study the performance of a biomass power plant. The biomass power plant uses dried banana peels as fuel. The main optimal parameters of the biomass power plant to achieve higher energy efficiency, power output and energy yield were determined. The main results are presented below:

(1) The increase in enthalpy at the pump outlet reduces the exergy efficiency of the machine.

(2) The increase in the mass of dry banana peelings increases the amount of CO_2 emissions released by the biomass power plant.

(3) The increase in enthalpy at the turbine inlet increases the machine's electrical power.

(4) Increasing the enthalpy at the turbine inlet increases the energy efficiency of the biomass power plant to its maximum value of 88% for an optimum enthalpy value of 3400 $kJ.kg^{-1}$

Symbols

η_{tg}	overall isentropic efficiency of the turbine-generator set, %
h	enthalpy, $kJ.kg^{-1}$
$\dot{m}$	steam mass flow rate to the turbine,
$\%C$	carbon content of biomass
F	CO_2 emission factor per tonne of carbon burned, t CO_2/t C
m	mass of biomass burnt per year, $t.year^{-1}$
P_{elec}	electrical power produced by the steam turbine-generator unit, W
s	entropy, $J.K^{-1}$
η_{ex}	exergetic efficiency, %

Conflict of Interest

All authors declare that they have no conflicts of interest.

Generative AI Statement

The authors declare that no Gen AI was used in the creation of this manuscript.

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