# Pyrolysis-Driven Biomass Energy Conversion: Reactor Design, Construction, and Power Output Assessment

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**Abstract:** The use of biomass is starting to play a major role in the country's effort to shift towards renewable energy sources, and is being used to generate electricity in Bangladesh. The objective of this study is to design, construct, and test a laboratory-scale slow pyrolysis reactor that converts biomass to electricity. It is a reactor with a temperature of 400–600°C and oxygen limited conditions to produce biochar, bio-oil, syngas, and usable thermal energy. An optimized reactor configuration has been produced in order to increase heat transfer efficiency and to improve the overall system performance as compared to the previous designs. Thermal energy was efficiently transformed to electrical energy using a steam turbine/generator system. The experimental results show that the reactor temperature is a crucial factor in the determination of product distribution and power output of the reactor. The system yielded a nearly equal amount of biochar (≈32 wt.%), bio-oil (≈38 wt.%), and syngas (≈30 wt.%) at the optimal temperature of 500°C, which resulted in efficient energy recovery. Optimum electrical power output was obtained at 15 W, a with voltage of about 12 V (DC), and a current of about 1.25 A, with an electrical efficiency around 12.4% at optimum operation. The power output was reduced to 8 W at the lower temperature (450°C), because of the lack of syngas generation, while at the higher temperature (550°C) the power output increased slightly to 17 W, but caused thermal stress in the reactor system. The system also exhibited stable frequency (50 Hz), good power factor (≈0.92), and was suitable for low-power applications like LED lights, mobile phone chargers, and small electronic devices. The results showed that slow pyrolysis is a promising decentralized renewable energy source for biomass conversion in general. The technology allows efficient use of the local biomass resources, can help with rural electrification and decrease waste, and can help in the development of sustainable energy.

**Keywords:** Slow pyrolysis, biomass-to-energy, reactor design, biochar, syngas, renewable electricity, energy optimization.

## Introduction

In the current global energy crisis and growing environmental concerns, the quest for sustainable and carbon neutral energy sources has been intensified (Akhtar and Amin, 2011). In addition to being abundant, carbon neutral and suitable for waste valorization (McKendry, 2002), biomass is a renewable energy source that can be a viable alternative to fossil fuels. Pyrolysis is one of the most promising methods for biomass conversion because it can be used to generate bio-oil, syngas and biochar, which can be used for power generation, chemical production and carbon sequestration, respectively (Bridgwater, 2012). A major advantage of pyrolysis technology is that biomass feedstock is not restricted to being either agricultural residues, forestry residues or energy crops (Mohan et al., 2006). Huber et al. (2006) modified the process to yield maximum liquid (fast pyrolysis), gaseous (gasification) or solid (slow pyrolysis) products based on the reactor configuration, temperature, heating rate and residence time. The design of the reactor, however, plays a critical role in the efficiency and scalability of pyrolysis systems and affects heat transfer, yield and energy output (Butler et al., 2011). A number of reactor designs have been investigated for biomass pyrolysis, each having its own set of advantages and disadvantages, namely fluidized bed, fixed bed, auger and rotary kiln reactors (Bridgwater, 2003). For example, fluidized bed reactors have great heat transfer characteristics and high yields of bio-oil, but they are more complex and costly to operate, and therefore are not suitable for large-scale application (Venderbosch and Prins, 2010). On the other hand, Fixed Bed Reactors are simpler having poor heat distribution and lower efficiency (Demirbas, 2004). In recent years, some novel reactor designs, such as microwave-assisted reactors, and plasma pyrolysis reactors have demonstrated potential for more efficient use of energy and better product quality (Huang et al., 2016; Zhang et al., 2020). The power output needs to be assessed to integrate pyrolysis systems into renewable energy grids. The energy content of pyrolysis products (bio-oil: ~15–25 MJ/kg, syngas: ~10–20 MJ/Nm$^3$ and biochar: ~25–30 MJ/kg) dictates the types of application in which they can be used, such as combined heat and power (CHP) applications (Garcia-Nunez et al., 2017). Feedstock variability, reactor inefficiencies and processing requirements can have significant impacts on net energy output (Brown et al., 2011). To assess the sustainability and economic viability of pyrolysis-based power generation, the use of life cycle assessments (LCAs) and techno-economic analyses (TEAs) is crucial (Cherubini and Ulgiati, 2010). This research is mainly based on optimizing pyrolysis reactor design and construction for improvement of energy conversion efficiency and power output. By considering various reactor configurations, operation parameters, and product utilization routes, we intend to give insights into the different possibilities of scalable and economically viable biomass-to-energy systems. The results will help to move the needle on sustainable energy technologies and support efforts in decarbonizing the world.

## Materials and Methods

Depending on the type and availability of biomass, it can be converted to electricity via several processes such as combustion, pyrolysis, gasification, liquefaction, anaerobic digestion, or fermentation (Demirbas, 2007; McKendry, 2002). Thermo-chemical processes are of particular interest because they can convert biomass into higher value products, or more convenient energy carriers, and into chemicals (Bridgwater, 2012). One of the most studied thermo-chemical processes is pyrolysis, which is defined as the process of decomposing organic material at 400–600°C under nitrogenous conditions (Venderbosch & Prins, 2010). This reaction technology separates complex biomass polymers into bio-oil, syngas, and biochar, which are alternatives to traditional fossil fuels (Zhang et al., 2020). The composition of feedstock and the physical processing conditions such as heating rate, residence time and temperature are important factors in the distribution of the products and the yield (Bridgwater, 2012). The high thermal energy content of woody biomass, such as wood chips, sawdust and pellets, makes it particularly suitable for pyrolysis, and combustion (McKendry, 2002). In this research, slow pyrolysis was used to efficiently convert biomass to its energy-dense products for energy recovery and product quality optimization. The process workflow shown in Figure 1 describes the major steps in the process, such as pre-treatment, thermal decomposition and product collection, and provides a systematic way to study the properties of the feedstock, and the process parameters for the energy yield, and chemical composition of the products. The experimental framework, operating procedures, and analysis methods are used for developing a strong foundation for pyrolysis based biomass-to-electricity production.

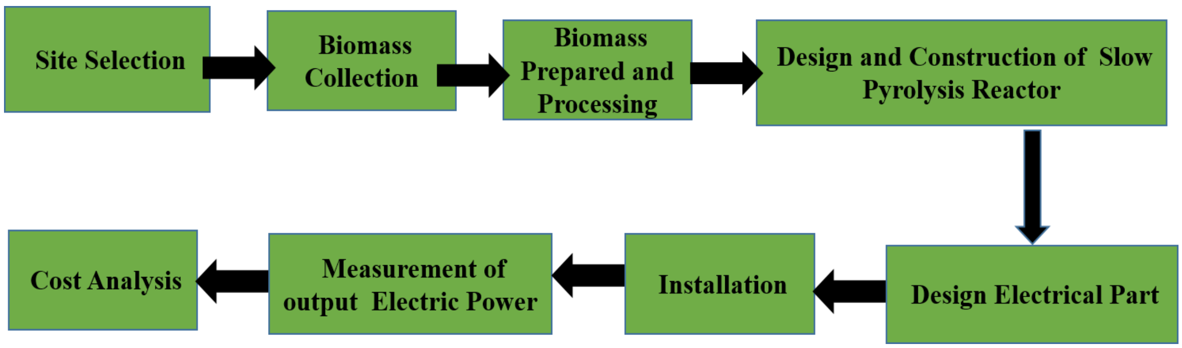


Figure 1. Work Flowchart of research

It is very significant to choose the site, and it has been done at the beginning of the project. Consideration for the safety of human beings and other living animals makes it impossible to have experimental setups near the locality. A fire extinguisher must be ensured at the place of experimental hall.

Biomass is organic material from plants, and animals that is a renewable and sustainable source of energy. It stores solar energy via photosynthesis - a method of the plants converting sunlight into chemical energy. When biomass burns, it releases the stored chemical energy as heat, which can then be transformed into electricity. A wide range of biomass sources can be found in Bangladesh such as forestry residues, mill by-products, agricultural crops or residues, urban wood and yard waste, energy crops, chemical recovery fuels, animal manure, industrial by-products, municipal solid waste, and waste sludge from sewage treatment plants. Figure 2 shows the location of the main biomass producing areas of the country. In this present study, wood chips, pellets, and sawdust were used as a feedstock, which is a type of lignocellulosic. On combustion, these woody materials give a significant amount of thermal energy that could be tapped for electricity generation.

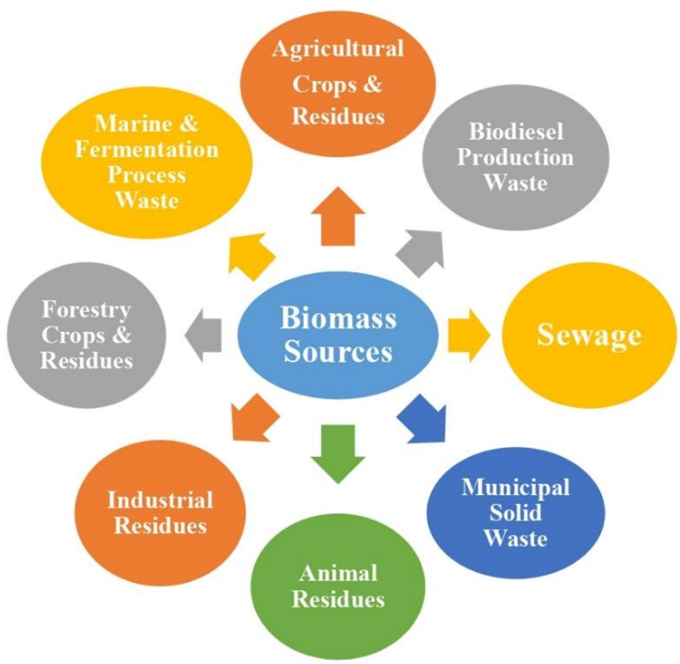


Figure 2. Available Biomass Sources in Bangladesh

**Biomass Preparation and Processing**

Biomass conversion into energy, and value-added products include six fundamental processing technologies of direct combustion (for power), anaerobic digestion (for methane-rich gas), fermentation (of sugars for alcohols), oil extraction (for biodiesel), pyrolysis (for biochar, gas, heat, and oils) and Gasification (for carbon monoxide and hydrogen-rich syngas). These primary conversion technologies may subsequently be integrated with various secondary treatments of stabilization, dewatering, upgrading, and refining depending on the intended end-use products. Biomass feedstocks in nature exhibit substantial heterogeneity in terms of chemical composition, physical properties, toxicity levels, and calorific value. The quality and characteristics of a given feedstock are therefore critical parameters in determining the most appropriate valorization pathway. While energy recovery efficiency is generally considered the principal criterion for selecting a processing route, factors such as economic feasibility and market viability often exert a stronger influence on the commercialization and large-scale deployment of emerging technologies. In the present work, since the target output is thermal energy, slow pyrolysis was selected as the biomass conversion technology, as illustrated in Figure 3.

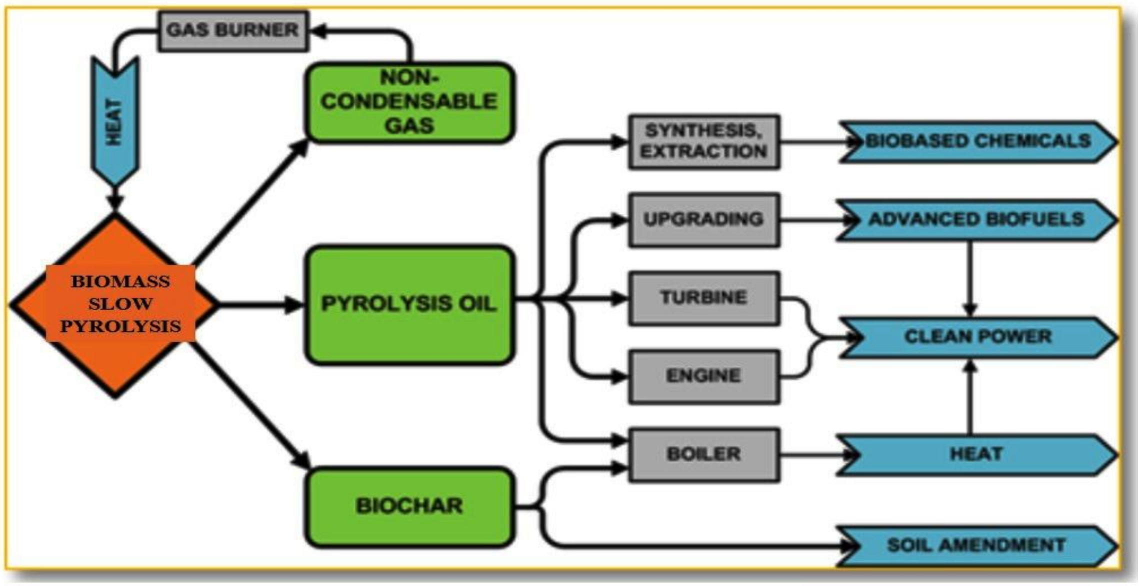


Figure 3. Pyrolysis Procedure from input to output

Slow pyrolysis is a thermochemical conversion process that involves the thermal decomposition of lignocellulosic and other organic feedstocks at moderate temperatures (400–600°C) under an inert or oxygen-limited atmosphere. Unlike fast pyrolysis, which prioritizes liquid bio-oil production, slow pyrolysis is optimized for maximum biochar yield, with significant fractions of syngas and condensable vapors as co-products. The process kinetics are governed by heating rate (<10 °C/min) and prolonged residence time (minutes to hours), enabling extensive secondary reactions, and structural reorganization of carbonaceous matrices.

At the molecular level, slow pyrolysis induces depolymerization, dehydration, decarboxylation, and aromatization of hemicellulose, cellulose, and lignin. Hemicellulose decomposes primarily between 200–350 °C, cellulose between 315–400 °C, and lignin exhibits a broad degradation range up to 600°C, yielding phenolic compounds, and highly recalcitrant char structures. The resultant biochar possesses high carbon content, significant porosity, and surface functionality, making it a versatile material for soil amendment, carbon sequestration, and electrochemical applications.

The energy-rich syngas (CO, $H_2$, $CH_4$, and light hydrocarbons) can be directly combusted for heat and power or reformed into higher-value fuels. Condensable vapors yield bio-oil, though with higher oxygen content and lower stability compared to fast pyrolysis oils. Process optimization requires controlling parameters such as feedstock particle size, moisture content, reactor configuration (fixed-bed, rotary kiln, auger, or fluidized-bed), and gas residence time.

Slow pyrolysis contributes to a circular bio-economy by converting agricultural residues, forestry wastes, and organic by-products into renewable energy carriers while simultaneously sequestering stable carbon in biochar. This dual role aligns with global efforts to mitigate greenhouse gas emissions, enhance soil fertility, and advance sustainable energy technologies. Consequently, slow pyrolysis represents a pivotal strategy in biomass valorization and climate change mitigation frameworks.

**Design, Construction, and working Mechanism of a slow Pyrolysis Reactor**

The reactor represents the central unit of a slow pyrolysis system, acting as the dominant factor influencing process efficiency, product yield, and quality. Due to its pivotal role, a wide range of reactor designs have been developed to optimize heat transfer, residence time, and scalability, while addressing the limitations of traditional configurations. Commonly employed designs include fixed-bed, fluidized-bed, auger, rotary kiln, and screw reactors, each offering distinct advantages depending on feedstock properties and targeted end products. Beyond the reactor itself, the process chain typically incorporates biomass reception, storage, and handling, as well as pre-treatment steps such as drying and particle size reduction, followed by product collection, storage, and upgrading. In the present work, a novel reactor configuration has been designed, integrating slow pyrolysis with a power generation unit, as presented in Figure 4. The parameters for the reactor design includes melting point (MP) of the substance, density, quality of substance, moisture content, reactor temperature, heating rate, reactor size and feed rate. If MP is high, the substance easily vaporizes & more heat is obtained. The substance easily vaporizes & more heat is obtained when density is lower. Quality of substance is considered as the higher the yield of heat for higher quality. More moisture is needed when more heat is obtained. Heating rate and reactor size (*4 ft ×4 ft*) should be optimum to get maximum heat. Feed rate is given according to the demand for the heat in innovative criteria.

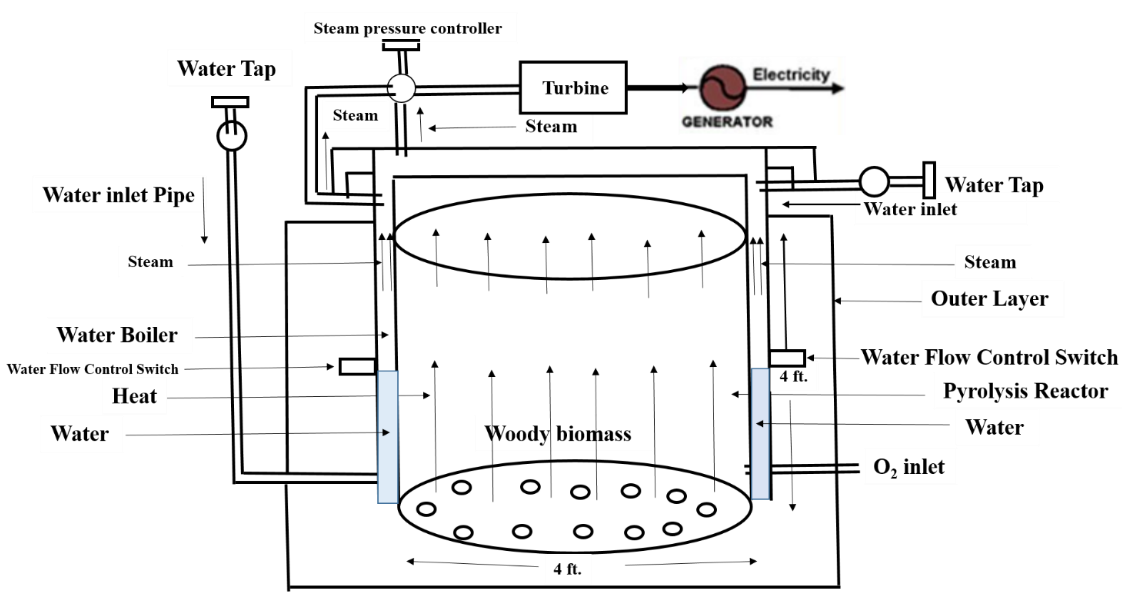


Figure 4. A new design of biomass slow pyrolysis integrated with the power generation system.

Slow Pyrolysis is a process in which biomass is thermally degraded under controlled oxygen-limited conditions or in an inert atmosphere, for a long duration of vapor and solids residence time, in the range of 300°C – 600°C. The process can be broken down into several stages: (i) drying, which removes physically bound moisture at temperatures below 150°C; (ii) devolatilization, which occurs between 200–350°C, causing hemicellulose to decompose, between 300–400°C, causing cellulose to depolymerize, and between 250–500°C, causing lignin to partially break down, yielding volatile vapors, condensable tars, and permanent gases; and (iii) carbonization, which produces a stable, carbon-rich biochar as the solid residues begin to undergo further aromatization, polymerization, and condensation.

Mass transfer is the main mechanism for volatile release and diffusion through the porous biomass matrix, heat transfer is mostly through conduction and convection. The overall process dynamics are found to be strongly influenced by the heating rate, particle size, reactor geometry, and flow of inert gas. Lower heating rates (≤10 °C/min) will favor the secondary char forming reactions in the slow pyrolysis process to reduce the amount of volatile matter produced. The primary decomposition of the water at the endothermic conditions and the secondary char stabilization at the exothermic conditions are thermally balanced at a quasi-stable state. This means that the production of these biochar applications such as carbon sequestration and soil amendment is well suited for slow pyrolysis because it yields a higher solid char fraction (≈30-40 wt%) and less bio-oil and syngas.

The operating principle for electricity production using slow pyrolysis of biomass is an integrated thermochemical process which converts solid biomass to produce useful power by controlled thermal decomposition in a generator and a turbine, which are the key components in the final conversion to power. The first step in biomass feeding is to prepare the biomass feedstocks, which may include wood chips or agricultural wastes like straw or rice husks, or even dedicated energy crops like short rotation woody crops. The biomass is dried to a moisture content generally less than 15-20% for optimal utilization, and is then size-reduced to promote uniform heat transfer (Mohan, Pittman, & Steele, 2006). The biomass is then slowly heated (0.1 to 50°C/min) and held for a longer time (minutes to several hours) in an oxygen limited slow pyrolysis reactor under moderate operating temperatures of 350 – 550°C (Bridgwater, 2012). In such cases, the biomass is devolatilized, and the major components (cellulose, hemicellulose, and lignin) are converted into three main products: a solid called biochar, a liquid called bio-oil, and a non-condensable gas called syngas (Lehmann & Joseph, 2015). This syngas is mainly made up of carbon monoxide (CO), hydrogen ($H_2$), methane ($CH_4$), and carbon dioxide ($CO_2$), and is drawn off and channeled through a condensation system, where heavier, condensable vapors are cooled into bio-oil.

The clean syngas that remains is then used for energy generation; for example, it can be burnt in a boiler to produce high-pressure steam. This steam is used to power the Turbine (usually a steam turbine) which converts the heat energy into mechanical rotating energy. The spinning turbine is directly connected to a generator which harnesses the mechanical energy via electromagnetic induction to produce electricity (Bridgwater & Peacocke, 2000). The syngas may also be combusted in a gas engine or gas turbine providing direct mechanical power generation, also coupled to a generator. The bio-oil co-product can be burned in a similar fashion to provide additional fuel as a supplement to the energy supplied to the system. Some of the syngas or bio-oil generated may be supplied to the process to heat the pyrolysis reactor, making for an energy self-sufficient process (Brown, 2011). This stabilized, carbon-rich solid is a valuable by-product of the process which can be used for soil amendment or for carbon sequestration, further enhancing the sustainability of the process. So, from the successive steps of feedstock preparation to slow pyrolysis to separation of the products, and then conversion of chemical energy in the gases/liquids into mechanical energy by a turbine and mechanical energy into electrical energy by a generator, the system is able to successfully transform biomass to into a renewable source of Electricity (Yaman, 2004).

**Electrical System Design**

The electrical design is very important for this experimental work. From the pyrolysis reactor, a huge amount of heat is created, and the flow of water inside the second layer of the reactor (Figure-4) continuously produces steam. This steam is used to generate electricity. For this purpose, a steam turbine and a generator are connected as shown in Figure-5. The developed system generates a maximum electrical power output of 15 W that can be classified as a low-power generation unit. In spite of its limited capacity, the generated power is sufficient to operate various low-power electronic, and communication devices, such as LED lighting units, Wi-Fi routers, smartphone chargers, tablet computers, and Wi-Fi/IP cameras, all of which typically require less than 15 W during normal operation. This level of output is mostly suitable for experimental and research-oriented applications, where the primary objective is to evaluate the feasibility of converting waste heat or secondary thermal energy into usable electrical power. In this experimental setup, the steam produced from the pyrolysis reactor is utilized to drive a small turbine, which in turn powers a DC generator. The generated DC current can either be used to operate energy-efficient devices directly or stored in small-scale battery systems for later use. This study thus shows the potential of micro-scale power generation from thermal energy recovery processes, highlighting its relevance in distributed renewable energy systems, energy harvesting, and sustainable laboratory-scale power applications.

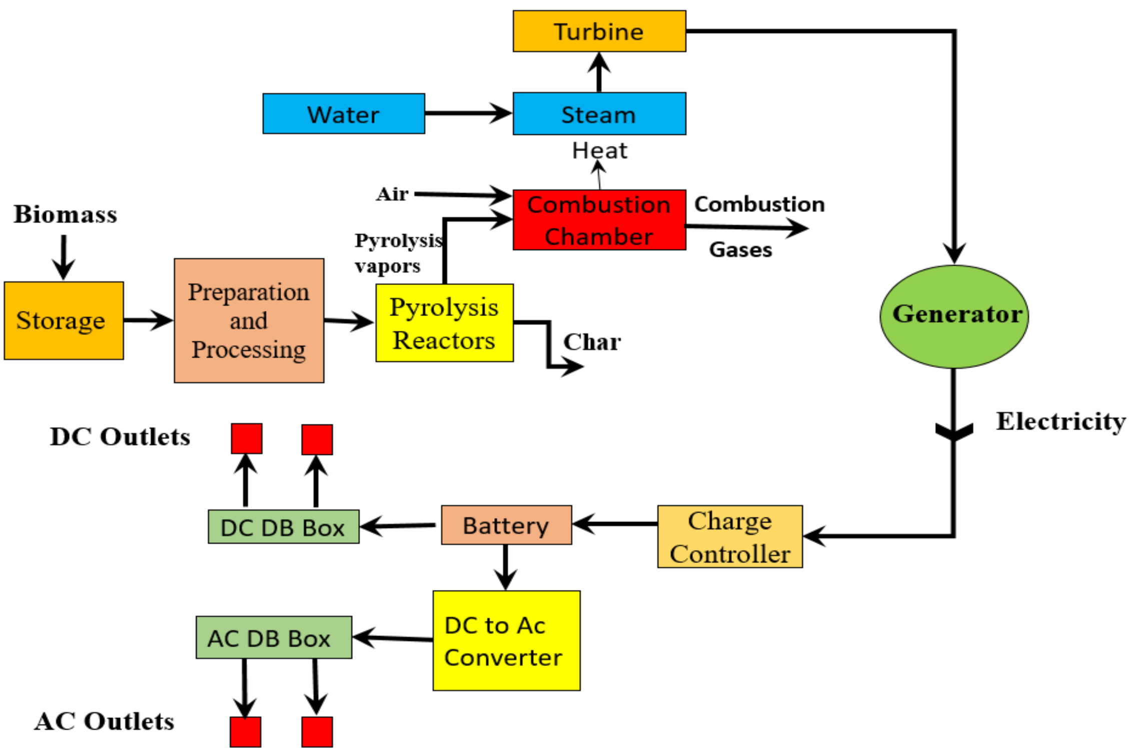


Figure 5. Biomass to electricity production procedure.

**Slow Pyrolysis Installation**

After constructing the slow pyrolysis reactor and designing the electrical parts the entire devices were installed at the experimental hall. At the beginning it was checked whether the devices ran well or not. Finally, it was run for the experimental purpose and generated electricity properly shown in Figure 6.

Figure 6. Installation of Pyrolysis reactor combined with electrical part.

## Results and Discussions

Upon the successful installation of the slow pyrolysis system, a novel electricity generation framework has been established, capable of delivering small-scale, low-power applications from woody biomass via thermal energy. This innovation represents a unique advancement in renewable energy technology, enabling direct electricity production from lignocellulosic biomass and contributing to the intellectual property domain through patentable biomass technologies.

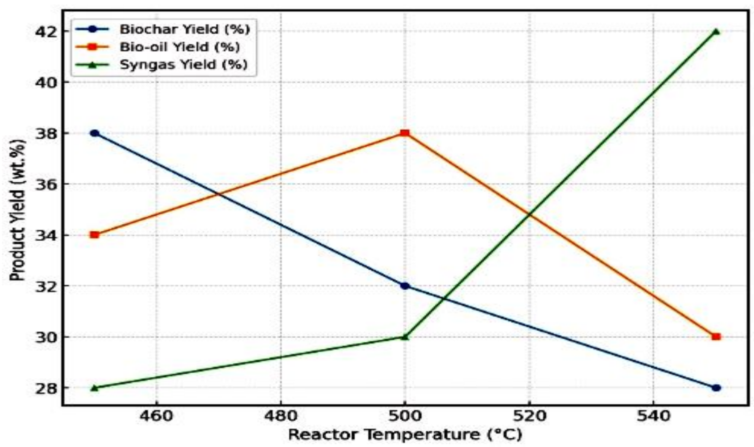


Figure 7. Product yield distribution at different pyrolysis temperature

This scientific breakthrough redefines the biomass utilization paradigm transforming "biomass disposal into electricity" while promoting sustainable energy development. The operational process exhibited thermal transitions with initial and final temperatures ranging from approximately 400°C to 600°C. According to Figure 7, the product yield distribution of biomass pyrolysis is strongly influenced by reactor temperature. At 450°C, biochar yield is highest (≈38 wt.%), while syngas remains relatively low (≈28 wt.%). At the optimized 500 °C, product distribution becomes more balanced, with 32 wt.% biochar, 38 wt.% bio-oil, and 30 wt.% syngas, enabling efficient energy recovery. At higher temperatures (550°C), biochar decreases further to ≈28 wt.%, while syngas production rises significantly to ≈42 wt.% due to enhanced cracking reactions, though bio-oil yield declines. These results demonstrate the trade-off between solid carbon retention and gaseous fuel generation, underscoring the importance of temperature optimization in reactor design.

Figure 8 demonstrates that the electrical power output of the pyrolysis system shows a direct correlation with reactor temperature. The amount of heat transferred is directly proportional to the temperature change. At 450°C, the syngas fraction was insufficient to sustain stable combustion, resulting in a modest output of 8 W. At the optimized 500°C, balanced gas production enhanced combustion efficiency, generating a stable output of 15 W. Further increasing the temperature to 550°C slightly improved output to 17 W, attributed to higher syngas yields from secondary cracking reactions.

At high temperatures, however, high thermal stress could significantly affect the durability of the reactor, suggesting 500°C would be the optimum temperature for a good yield and power generation.

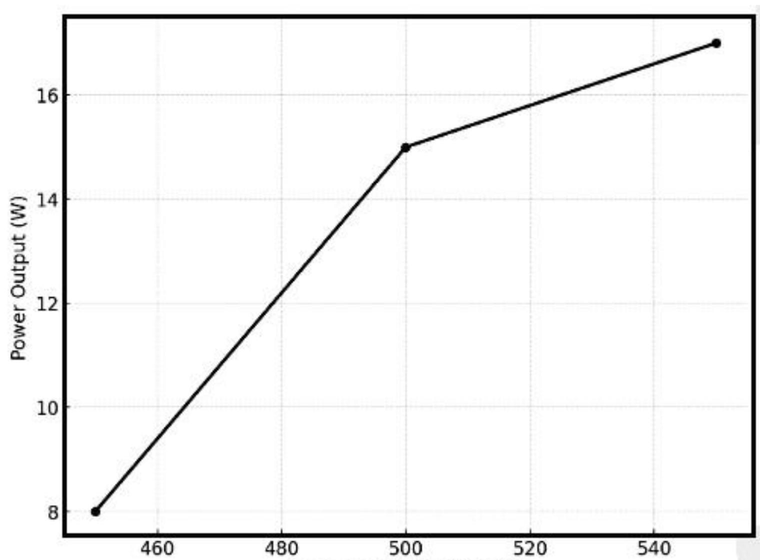


Figure 8. Electrical power output vs. reactor temperature

The capacity of the biomass system to generate the pyrolysis gas is the main factor to determine the power output from a pyrolysis biomass system. Under the best conditions (500°C), a steady 15 W of power was generated from the reactor, and the electrical efficiency was 12.4%. This is the result of very good combustion of the CO, $H_2$, and $CH_4$ fractions within the micro-turbine. The output was reduced at lower temperatures due to reduced gas yield but higher temperatures (550°C) resulted in a slight increase in output to 17 W with material stress concerns. Therefore, efforts need to be undertaken to increase the power output, along with considering reactor stability and durability during operation and the gas yield.

The voltage and current characteristics of the power system are obtained using the pyrolysis method which represents of the dynamic behavior of syngas combustion and the heat produced by the system, the steam pressure and generator stability. The system, at the optimized operating point (500°C), was able to generate an output voltage of ~ 12 V (DC) and output current of ~ 1.25 A (DC) with the output power of ~ 15 W.

At lower temperatures, the gas production was reduced, resulting in voltage and current fluctuations, and unstable output. On the other hand, when the temperature is 550°C, the current and voltage were increased slightly with the increased yield of syngas, but there was the possibility of thermal stresses to affect stable operation. As this is an important parameter to consider for maintaining uniform electrical performance. The output of the system is alternating current (AC), and can be converted to 110-220 V AC via an inverter. The output current is thus estimated to be 0.07–0.14 A, according to the power relation, I=P/V. As an example, at 15 W with 220 V, the calculated current is ~0.068 Amperes, which confirms the range of currents expected. The results of this output profile show that the system is viable for use in low-power residential and small-scale electrical applications.

A key parameter for measuring the quality of the electricity produced, and the performance of the pyrolysis-based biomass power system, is frequency stability. The system operated with optimized frequency of 50 Hz during continuous operation of 500°C, to meet the 50 Hz standard requirement for the electricity grid. As a result, at the lower temperatures, the syngas production was under adequate levels, resulting in minor fluctuations in the frequency, sometimes even dropping below 49 Hz, coming from the combustion instability. The high generator temperature (550°C) has led to a higher share of syngas which has led to better generator performance, but also to transient peaks in the frequency higher than 51 Hz. Although the deviations are small, they highlight the importance of the need for effective control systems for frequency stabilization for reliable integration with micro-grids or stand-alone rural electrification systems.

The power factor of the pyrolysis based biomass energy system represents the efficiency of using electrical energy. Under the optimum operating temperature of 500°C, the system generated a power factor of around 0.92, which means that the active power was efficiently utilized with minimal reactive losses. The lower operating temperatures resulted in lower syngas yields and, therefore, less stable combustion, which resulted in a lower power factor of approximately 0.85. At higher temperatures (550°C), however, more syngas helped to boost the power factor, but put a potential strain on the system. It is important to keep a high power factor in order to limit energy losses and guarantee a reliable power factor with electrical loads.

The electrical efficiency of the biomass conversion system that employs pyrolysis is the ratio of electrical energy produced to the total energy content of the biomass feedstock. The optimal operating temperature of this system was found to be 500°C, and an efficiency of 12.4% was obtained, which is consistent with reported efficiencies of small-scale pyrolysis to electricity processes. Because of the reduced operating temperature, efficiency was reduced to less than 10%, and this system was not available. Higher reaction temperatures (550°C) resulted in a greater amount of gas produced and a slight improvement in the efficiency, but also caused a reactor durability issue. Thus, it is essential to keep the operating state moderate to achieve a balance between stable power generation, efficiency and sustainability of the system in the long term.

The electrical efficiency of 5-10% for a pyrolysis-based biomass energy system can be understood mathematically in terms of the distribution of the total biomass energy into various product streams of the pyrolysis system. Let the total energy in the biomass be $E_b$ (100%). Only 20-30% ($f_g$) of this energy is used to produce the chemical energy of syngas, the rest is in the form of biochar (30-40%) and bio-oil (20-30%), which are not directly used to produce electricity. This syngas is then fired in gas engine/generator having efficiency $\eta_{eg}$ of about 25-35%. Hence, the overall electrical efficiency can be expressed as:

$$\eta_{elec} = f_g \times \eta_{eg} \quad (1)$$

For example, if $f_g$=0.20 and $\eta_{eg}$=0.25, then $\eta_{elec}$=0.20×0.25= 0.05(5%). If $f_g$=0.30 and $\eta_{eg}$=0.30, then $\eta_{elec}$=0.30×0.35= 0.105(10%).

The values illustrate that only a fraction of the biomass energy is available for electricity generation due to the thermal losses, the use of only part of the gas and limited generator efficiency, the remainder of the biomass energy is left in the biochar and bio-oil. This leaves an electrical efficiency of between 5% and 10% overall.

The stability and quality of electricity generation from the biomass pyrolysis system depend on the stability and response of the syngas production system. The system operated with very low fluctuations in voltage (∼12 V), frequency (∼50 Hz), and power output (∼15 W) at the optimized operating temperature of 500 °C, providing reliable operation. In low temperatures, unstable combustion has caused irregular voltage and frequency drops, which have lowered the power quality. Increased temperatures (550°C) gave better production, but caused a degree of transients because of too much cracking reaction. Constant operating conditions, effective thermal management, and proper generator synchronization are important factors for maintaining the stability of the overall system for high quality electricity.

The system output is 15 watt-hours (Wh) for 1 hour of operation, based on the formula of $E=P\times t$, where $P=15$ *Watts* and $t=1$ *hour*. The energy is suitable for low energy electrical applications such as Light Emitting Devices (LEDs), environmental monitoring sensors, mini cooling fans and charging of small capacity rechargeable batteries. The system's low power output makes it relevant for decentralized energy consumption, which often requires small-scale renewable energy sources, especially in off-grid and decentralized environments. Table-1 summarizes the performance outputs that can be derived from this technology.

**Table 1. The results of this technology are systematically summarized.**

| Parameter | Specification / Range | Notes |
|---|---|---|
| **Power Output (P)** | 15 W | Continuous or peak, depending on generator design |
| **Voltage (V)** | 5–12 V DC or 110–220 V AC | Depends on generator type (DC from thermoelectric, AC via inverter) |
| **Current (I)** | 1.25–3 A (DC) or 0.07–0.14 A (AC) | Calculated from P = V × I |
| **Frequency (f)** | 50 Hz (AC), 0 Hz (DC) | Standard grid-compatible frequency in Bangladesh |
| **Power Factor (PF)** | 0.8–1.0 | AC systems only; DC systems assumed near unity |
| **Electrical Efficiency** | 5–10% | Fraction of biomass energy converted to electricity |
| **Energy per Hour (E)** | 15 Wh | Energy available for low-power devices like LED bulb, Wi-Fi router (home use), Smartphone charger, Tablet, Wi-Fi camera / IP camera. |
| **Output Stability** | Fluctuating without regulation | Requires voltage regulator or capacitor for smoothing |
| **Load Suitability** | LEDs, sensors, small fans, battery charging | Small-scale, low-power applications |

To be scalable, biomass energy conversion needs to be done using pyrolysis technology, which depends on the flexibility of the reactor design, the availability of biomass feedstocks and the integration with current energy networks. Pyrolysis technology is very modular and can be scaled up from small scale laboratory systems (5-10 kg per hour) to medium scale pilot systems (50-200 kg per hour) and industrial level systems (>1 t per hour). The basic mechanism of thermal degradation of biomass with limited oxygen is the same at every scale, although heat transfer processes, gas residence time, and wall insulation of the reactor need to be optimized to ensure a uniform temperature profile (Basu, 2018). Typically, continuous-feed screw or auger reactors with heat-recovery units and gas recirculation systems are used to increase the thermal efficiency and stability of the process, which are commonly considered to be scalable designs (Bridgewater, 2012).

Capital and running costs are the two major concerns from an economic point of view with regards to pyrolysis systems. The additional cost of this process is reactor fabrication (mild or stainless steel), insulation materials, heat exchanger and gas cleaning units, and these items would typically comprise 60-70% of the total project costs (Demirbas, 2017). Operating expenses consist of feedstock preparation, personnel and periodic maintenance. The use of low cost or waste biomass, like rice husk, sawdust, jute stick, coconut shell etc., however, improves the economic feasibility of the system to a great extent particularly in the agricultural areas of Bangladesh where these wastes are plentiful and untapped.

Revenue is realized from various product streams. The biochar fraction (30–40 wt%) may be sold as soil conditioner, soil adsorbent or carbon sequestration product, which can be used for obtaining carbon credits. Bio-oil (20-30 wt%) can be used for industrial boilers instead of fossil fuel based fuel oils and syngas (10-20 wt%) can be directly used to produce heat and electricity in gas engines and turbines (Lehmann & Joseph, 2015). Use of co-generation systems can introduce some self-sustainability in the system due to the re-use of syngas for heat generation, thereby reducing energy input from the outside. The payback interval for medium scale plants have been reported as 3-5 years, with IRR (Internal rate of return) of more than 20% under favorable market conditions and policies (Tripathi et al., 2016).

Also, decentralized deployment of modules that can be installed anywhere, but need to be only small enough to fit in the field in which they will be used, will increase the availability of energy in rural areas by turning local biomass into useful energy and byproducts that improve the soil. Pyrolysis-based biomass systems are economically and environmentally viable in the presence of incentives for renewable energy, feed-in tariffs (FITs) or carbon credit systems. Hence, the reactor design and power estimation carried out in this research, provide a viable and scalable cost-effective route towards clean energy generation and waste valorization in developing countries.

## Conclusions

We have designed and constructed a new pyrolysis reactor, which has worked as a slow pyrolysis process to generate electricity in this research work. This work has developed a technology to convert heat to electricity by using slow the pyrolysis method, which can play an important role in the area of power development. By this technology, it is possible to produce an average 15-watt electric power that can be continued or peak, depending on generator design and can be added to the national grid by an on grid inverter. This power can be used for small-scale, low-power applications. For this output, it needs maximum pressure of the steam. The electrical efficiency of this system is around 5-10% (Fraction of biomass energy converted to electricity). Power Factor (PF) for AC systems only is 0.8–1.0, whereas DC systems are assumed near unity. These results can be used as the base line data, and further study is required to find a higher efficiency of this method. The economic evaluation results indicate that the system has a moderate cost-effectiveness, and the payback time is dependent on the availability of the feedstock, energy price, and optimization of energy efficiency, with the assumption of an average output of 15 W, and potential scale-up. Energy is one of the most important factors for the development of a nation's economy and society. Growing population and economic growth in the country have further increased energy demand in Bangladesh, increasing the reliance on imported fossil fuels and thus the economic vulnerability of the country. The study reveals the two-way relationship between energy availability and economic growth, and the need to find sustainable and cost-effective alternatives. Thus, biomass based renewable energy is seen as a solution which is environmentally friendly and economically viable for electricity generation. The adoption of these technologies can help to decrease the use of fossil fuels, limit the environmental footprint, and play a role in achieving long-term energy security and sustainable economic growth.

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