Electricity and Process Heat Generation from Rice Husk Utilizing Technology of Separate Reactors for Pyrolysis and Gasification Focused on a Rice Mill

Master's Thesis

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Abstract

Agricultural biomass to energy holds promise for the sustainability of energy production and positive reduction of CO_2 emission. This thesis explores the potential of rice husk as a sustainable energy source for electricity and process heat generation focusing on a rice mill in Sri Lanka. It utilizes advanced thermochemical conversion technologies specifically separate reactors for pyrolysis and gasification to optimize the conversion of rice husk biomass into Bio-char and syngas. The research involves field studies, process modelling with Aspen Plus software, and analysis of the biochemical properties of rice husk. Findings reveal that biomass is a viable and significant energy source by evaluating operational parameters and technological efficiencies. The use of rice husk-derived syngas in a gas turbine cycle and the subsequent utilization of waste heat for process heating are highlighted, underscoring the potential to enhance energy security and the efficient use of agricultural waste. In conclusion, the study suggests that such technologies could substantially achieve the energy needs of local rice mills and strengthen the national grid, supporting a transition toward renewable energy sources in Sri Lanka.

Keywords: Rice husk, Thermochemical Conversion, Pyrolysis, Gasification, Sustainable Energy, Syngas, Biochar

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Nomenclature

TIT	Turbine Inlet Temperature
TOT	Turbine Outlet Temperature
CFD	Computational Fluid Dynamics
MW	Megawatt
kW	Kilowatt
MT	Metric Ton
GWh	Gigawatt hour
MWh	Megawatt hour
VM	Volatile Matter
FC	Fixed Carbon
M	Moisture
RRDI	Rice Research Development Institute
CCP	Changed Couple Device
GDP	Gross Domestic Production
TPH	Tons per hour
DCS	Department of Census and Statistics
LHV	Lower Heating Value
EUBIA	European Biomass Industry Association
USD	United States Dollar

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1 Introduction

In the context of global sustainability of energy, the switching to transition to renewable energy sources is growing rapidly worldwide. As a developing island nation county, it is a challenge for Sri Lanka to improve energy security and reduce the negative impact on the environment since the country currently heavily relies on fossil fuels with the growth of energy demand. In the early-stage country, electricity generation is mostly dependent on hydropower. However, Sri Lanka is showing significant progress in integrating wind and solar power into the national grid. However, the utilization of biomass for electricity generation which is one of the most promising sources of electricity generation globally is still in its early stages even though the country has the potential for agricultural residues.

Among all these agricultural sectors, the rice milling industry plays a key role in the country's economy since rice is the staple crop. However, the rice milling process generates a significant amount of rice husks as by product. These husks, if left without utilization or used in inefficient ways represent a lost opportunity for effective energy generation. Considering this, converting rice husks into a useful energy source presents a sustainable solution that could substantially offset the energy needs of rice mills while contributing to waste reduction and strengthening the national power grid. This study explores the potential of generating electricity using syngas and the production of Bio-char derived from rice husk feedstock. It utilizes cutting-edge of technologies, including separate reactors for pyrolysis and gasification tailored to optimize the conversion process. The focus is on one of the large rice mills in Sri Lanka, examining the applicability and efficiency of these technologies in a practical setup.

Pyrolysis and gasification are thermochemical processes that decompose organic material at high temperatures in the absence or presence of a controlled amount of oxygen, respectively. These technologies are not widely used in Sri Lanka and their implementation could represent a significant advancement in the way of biomass waste to energy production efficiently. Electricity generation from rice husk using gasification is now widely seen in neighbouring countries such as India, Thailand and China. By converting rice husks into syngas, which can be used to generate electricity and other product like Bio-char, which can be effectively used as soil amendment. These processes offer the dual benefit of enhancing the sustainability of rice mills and contributing to the effective use of rice residues.

Given the critical need for sustainable energy solutions in Sri Lanka for the future energy demand, this research holds significant potential. It aims to provide a viable model that can be replicated across other rice mills in the country, thereby fostering a sustainable approach to agricultural waste management and helping to achieve energy independence in the rural sector. This thesis not only addresses a gap in the current use of biomass in Sri Lanka but also contributes to the global discourse on renewable energy, offering insights into the scalability and adaptability of biomass conversion technologies of pyrolysis and gasification separately in similar agricultural settings worldwide.

1.1 Research Problem.

i. Can a rice mill generate its energy demand from its waste?
ii. How to optimize Rice husk to power generation process?

1.2 Purposes of Study

- Obtain knowledge of conceptual process design
- Acknowledge the gap between theory and practical application
- Conduct a feasibility study to convert rice husk to power with different technologies for the energy demand of the rice milling industry
- Apply and improve the knowledge obtained from Biomass conversion (MVKP 36) and Energy engineering (MVKP 10) courses.
- Improve the comprehension of rice husk thermochemical conversion.

1.3 Limitations

- The data for physical and chemical properties of rice husk are extracted from literature and not actual laboratory experimental data of rice husk in Sri Lanka.
- The study only focuses on rice husk feedstock and no other paddy residue like straw is considered due to the complexity of chemical kinetics.
- Only Aspen plus V14 Software is used for process modelling & simulations.
- This research focuses only on the primary equipment within the rice husk-based thermochemical conversion system and power plants, with no detailed examination of the complete range of equipment in the systems.
- Isentropic and mechanical efficiencies for compressors and turbines are assumed to be constant.
- Calculations and comparisons relevant to economic aspects are not made in this report
- The detailed gas cleaning system is not introduced to modelling and simulation and only components for separators are used and considered 100% impurities removed.

1.4 Structure of the report.

This thesis consists of six chapters; chapter 1 provides brief information about the study, research questions, purposes of the study and limitations. Chapter 2 describes the background of rice production, the characteristics of rice husk, the rice milling industry and details about focused rice mills. Chapter 3 mainly covers the thermochemical conversion process and product analysis after the conversion of biomass. Chapter 4 describes the methodology of the study including modelling using Aspen Plus software and presents the result with a discussion. Chapters 5 and 6 cover the conclusion and future recommendations.

2 Background

This section provides an overview and general information about the Sri Lankan paddy production industry, rice husk energy potential and rice husk energy conversion to electricity generation focusing on the rice milling industry.

2.1 Geographical, Socioeconomic, and Climate Overview of Sri Lanka

Sri Lanka is an island nation country which is strategically located in the Indian Ocean at the southern tip of India. The country covers a total land area of approximately 65,525 square kilometres. Geographically, Sri Lanka is distinguished by its teardrop shape and diverse topography geography, which can be divided into three main zones based on altitude the central highlands, plains and the coastal belts (John Pike, 2000). The Sri Lankan population is over 22 million, consisting of various cultures and ethnicities. The Sinhalese constitute the largest portion of the population, followed by significant communities of Sri Lankan Tamils. This demographic diversity plays a main role in the cultural richness of the nation.

Historically, Sri Lanka's economy was mostly based on agriculture, with trade and exchange heavily dependent on agricultural products. However, over the years, there has been a significant shift towards a more diversified economy. Today, significant contributions to the economy come from tourism, tea exports, textiles and the labour force working abroad. Despite these changes, the agricultural sector is accountable for 10% of the national gross domestic production (GDP) with rice production alone contributing 20.5% to the agricultural sector (BRS equity research, 2022).

Sri Lanka experiences four distinct climatic seasons and those are first inter-monsoon, southwest monsoon, second inter-monsoon, and northeast monsoon. The southwest monsoon (May to September) affects the southwest, while the northeast monsoon (December to February) impacts the northeast and east of the country (The World Bank Group, 2021).

2.2 Rice Production

Rice is the primary staple food in Sri Lanka accounting for over 45% of the daily caloric intake for its population (Senanayake and Premaratne, 2016). Historically, Sri Lanka has been self-sufficient in rice production. However, in recent years, the country has occasionally had to import rice from neighbouring countries such as India, China and Thailand to meet domestic demand during periods of drought and low rainfall reported years. Most rice produced domestically is consumed within the country. The Sri Lankan government has implemented a range of policies aimed at increasing and stabilizing rice production. These policies are supported by technological advancements, increased use of fertilizers and land expansion efforts (Wang *et al.*, 2012). As a result, rice production has seen a consistent upward trend. In 2023, Sri Lanka reported a rice production surplus with a production of 2.7 million MT against a demand of 2.57 million MT (Economynext, 2023).

Rice cultivation occurs on 560,000 hectares across the island, representing 34% of the total cultivated area. The sector supports approximately 1.8 million farming families, highlighting its significance as a livelihood for many in the country (RRDI - Bathalegoda, 2024). The agricultural cycle in Sri Lanka spins around two main growing seasons Maha and Yala. The Maha season spanning from September to February is the primary rice-producing period, accounting for about two-thirds of the annual production. This season benefits from the inter-monsoon and northwest monsoon rains ensuring well-distributed rainfall across the island. In contrast, the Yala season from April to September, relies on rains primarily in the southwest of the country and generally sees less area cultivated compared to the Maha season (Weerakoon *et al.*, 2011).

Sri Lanka's diverse agroecological zones are divided into Wet, Dry, and Intermediate zones, each has unique rainfall patterns. The main region for rice farming is the dry zone, where efficient water management is essential for paddy cultivation. Major districts such as Anuradhapura, Ampara, Polonnaruwa, Kurunegala, and Hambantota are crucial to the national paddy production as in Figure 1, highlighting the importance of rice as a major crop in these regions (Saddhananda, 2022).

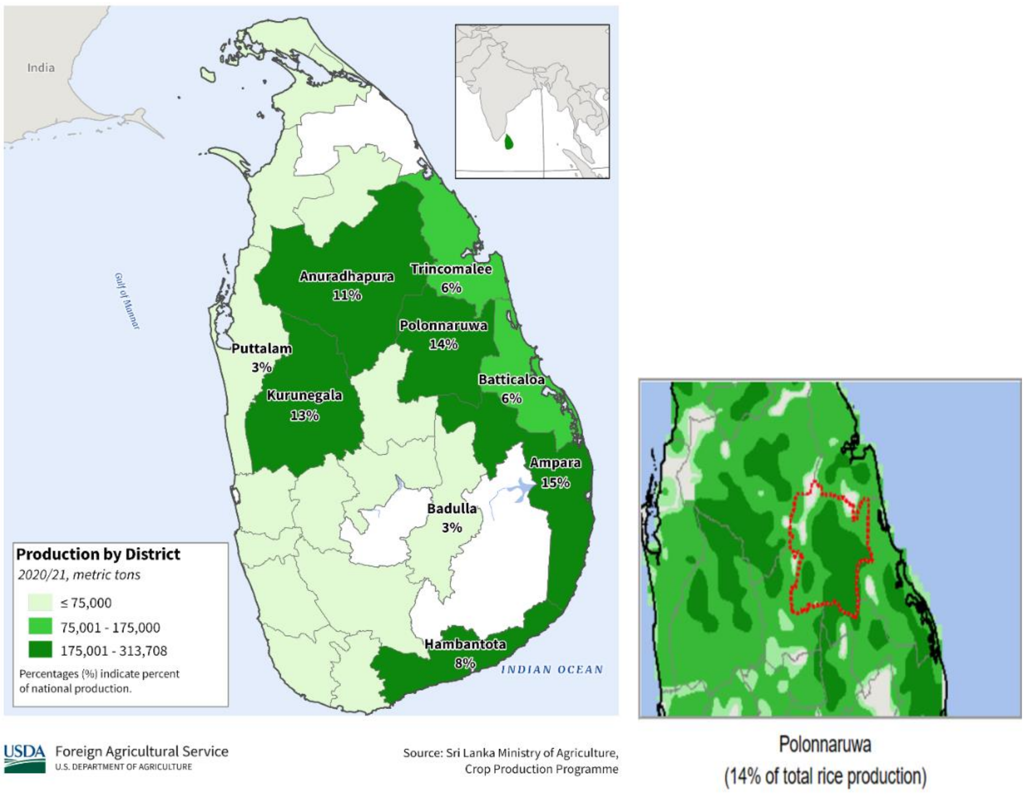

Figure 1. Districts rice production in Sri Lanka - 2020/2021 (ipad, 2021)

2.2.1 Paddy Grain

Paddy grain is composed of two major physical components, brown rice and husk with a bran layer in between the two. The husk is largely fibrous and inedible. It serves as a protective cover for endosperm. Beneath it lies the bran layer which is rich in nutrients including dietary fibre, essential fatty acids, different vitamins and minerals. The core of the rice grain is the endosperm which comprises mainly starch (Rathna Priya *et al.*, 2019). This composition varies among different rice varieties. Figure 2 illustrates the composition of the paddy. A comprehensive understanding of these chemical and physical properties is essential for optimizing rice processing techniques in milling, which removes the husk and bran, making the grain edible (Nguyen, 2014).

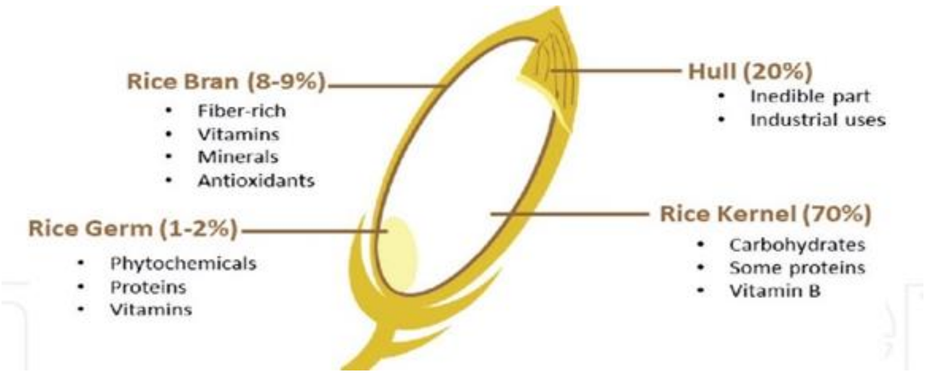

Figure 2. Rice paddy composition (Limtrakul (Dejkriengkraikul) *et al.*, 2019)

2.2.2 Paddy to Rice Processing and Value Addition with Parboiling

Value addition in paddy processing is important for enhancing the economic value and marketability of rice. The transformation of raw paddy into refined rice products involves several stages designed to improve the quality, nutritional value and consumer demand for the final product. Parboiling is a key method in the value-addition process which significantly enhances the attributes of rice. Figure 3 illustrates the entire modern paddy-to-rice process in the mill including the parboiling stage.

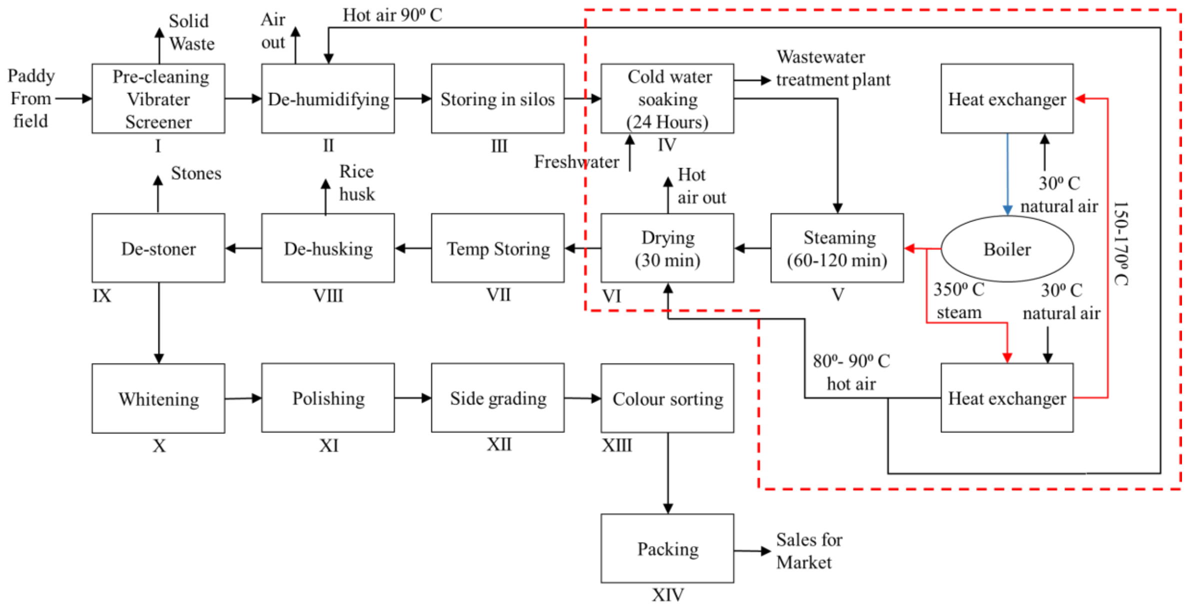

Figure 3. The flowchart of the paddy-rice milling process in the focused rice mill

As per the interview with the chief engineer, the following process of value addition of the rice milling process can be explained.

i. Pre-Cleaning: Raw paddy harvested from the fields is first subjected to a thorough cleaning process to remove impurities such as straw, soil particles and weed seeds. This is typically done using mechanical sieves and shakers that separate these unwanted materials from the grains.

ii. De-humidifying: Following the cleaning, this process involves regulating the moisture content of the paddy by circulating hot air through it with a blower. The hot air is generated by passing it through a heat exchanger. The primary aim of this process is to prevent the growth of fungi and mycotoxins that can occur during storage which are harmful to human consumption. This ensures the paddy remains dry and safe for long-term storage.

iii. Storing in Silos: The purpose of storing paddy in silos is to create a protective environment that shields the grains from excessive humidity, pests, and insects, which could lead to the degradation of paddy quality. Inside the silos, both temperature and humidity are controlled.

iv. Soaking: Soaking is part of the parboiling process and it can be conducted using either hot water or cold water (natural water -temperature 25 °C). In this selected rice mill, the cold-water soaking method is utilized for the parboiling process. During this phase, paddy grains undergo preparation for the gelatinization of starch by the next steaming phase, which involves increasing the moisture content within the grains. This preparatory step is essential for enhancing the yield of rice by ensuring a more uniform gelatinization process, which subsequently improves the milling quality and nutritional value of the final product.

v. Steaming: This is the main process of making parboiled rice and 350-300 °C steam is injected from different positions in the chamber to ensure a uniform temperature inside the chamber while wet paddy is moving from top to bottom. The temperature of the steam depends on the technology which is applied. The steaming process takes place in 60 to 120 minutes. This process enhances the gelatinization of starch within the grain and improves the quality of rice and its nutritional value.

vi. Drying: The final step of the parboiling process involves a three-stage drying system, consisting of two continuous tempering beds and three dryers. After steaming, the wet paddy is moved to the drying chamber from the top using an elevator, where hot air generated by a heat exchanger is blown through to dry the grains. The paddy is circulated in the drying chamber until its moisture content is reduced to 36%, after which it is transferred to the tempering beds. Before being moved to temporary storage silos, the moisture level is further reduced to 16% over a process lasting four hours during the three stages of the drying process.

vii. Temporary storing: Temporary storage of parboiled rice before starting the milling process.

viii. De-husking: In this process, a double rubber roller shelling machine is used to remove the husk and separate the rice.

ix. De-Stoner: This is the process of removing sand and stones from the rice after de-husking.

x. Whitening: This is the process of removing the bran layer from the rice kernel by minimizing the damage to the grain. Here abrasive whitening process is applied since it reduces the breakage of rice.

xi. Polishing: The surface of whitened rice is still rough and is smoothened by a humidified rice polisher. The process involves rubbing of rice surface against another rice surface with mystified air acting as lubricant between the two surfaces.

xii. Size grading: The process of separating broken rice by running it through a cylinder-shaped screen with holes that spin at a certain speed. Adjusting the rotational speed and angle of the trough can vary the average length of grains.

xiii. Colour sorting: Discoloured rice grains are removed from the white rice by rice colour sorting machines. Photo sensors/CCD (Charged Coupled Device) sensors generate a voltage signal when they detect discoloured grains and impurities, which are then removed by air jets produced through solenoid valves.

xiv. Packing: After completing all milling processes and value addition, packing is carried out by different weights according to market demand.

2.3 Rice Milling Industry in Sri Lanka

Rice serves as the main food for half of the global population and Sri Lanka requires approximately 2.9 million MT annually to meet domestic consumption needs (RRDI - Bathalegoda, 2024). This makes the rice processing industry the largest agricultural sector in the country, as per the (Wijesooriya and Priyadarshana, 2013) report, as of 2002, there were over 7,000 rice mills, most using semi-modern technology. The Polonnaruwa district is a key rice-producing region, hosting many large-scale mills. The industry is primarily focused on the local market with minimal exports. The supply chain involves farmers, collectors, and millers, but farmers face challenges such as high production costs, reduced government subsidies, and various agricultural issues like pest infestations and irrigation water shortages. Socio-economic factors such as credit availability and access to technology also impact on industry. Most small to medium-sized mills use conventional methods, resulting in lower production and quality. Except for one mega mill in Polonnaruwa, all mills rely on the national grid for electricity, making them vulnerable to power outages and tariff fluctuations. Additionally, the economic downturn impacts smaller mills due to decreased purchasing power, increased commercial bank interest rates, and limited financial capacity (Wijesooriya, Kuruppu and Priyadarshana, 2021). Table 1 shows the available rice mills in the Polonnaruwa district in the year 2019.

Table 1. Capacity with rice mills in Polonnaruwa (Wijesooriya and Kuruppu, 2022)

Mill Category	No. of mills	Per Day (MT)
Largest group 1	3	400
Largest group 2	3	150
Largest group 3	4	75
Medium	9	40
Small	86	10
Total	105	

2.4 Rice Husk

2.4.1 Physical and Chemical Properties of Rice Husk

Rice husk is a protective cover of the rice grain, and is a readily available lignocellulosic material with significant potential as an energy source in agricultural residues. A comprehensive understanding of the inherent characteristics of rice husk is essential for the effective design and operation of thermochemical conversion systems. It can be transformed into various applications through diverse thermochemical processes.

Physically, the average dimensions of rice husks range in width from 1 to 4 mm and can reach lengths up to 10 mm (Chabannes *et al.*, 2014). The bulk density of rice husk is relatively low, varying from 86 to 114 kg/m^3, which necessitates compaction into pellets or briquettes to optimize storage and transportation, this makes its use more economically viable. The lower heating values of rice husk are substantial, ranging from 13.24 to 16.20 MJ/kg on a dry weight basis (Mansary and Ghaly, 1997), highlighting its suitability as a biofuel.

From a chemical perspective, the analysis of rice husk can be categorized into ultimate, proximate, and biochemical composition analyses. The ultimate analysis determines the basic elemental composition, including carbon (C), hydrogen (H), oxygen (O), nitrogen (N), sulfur (S), and chlorine (Cl) content in the biomass. Proximate analysis focuses on the levels of fixed carbon (FC), volatile matter (VM), moisture, and ash content, which are critical metrics that directly influence the performance and efficiency of conversion processes. The biochemical composition analysis provides a detailed breakdown of the organic and inorganic components of the rice husk. Significantly, rice husk is composed of 75-90% organic matter such as cellulose and lignin, along with a significant amount of mineral components including silica, alkalis, and trace elements (Kumar *et al.*, 2012). Table 2 shows different methods of rice husk property and composition analysis. The substantial organic content highlights the energy capacity of rice husk, making it an ideal choice for biofuel production. In the rice milling industry, this biofuel is extensively utilized to power boilers, generating the steam necessary for drying and parboiling processes.

Table 2. Different methods of rice husk property analysis (Adeniyi, Ighalo and Aderibigbe, 2019)

Ultimate analysis (wt% moisture free)		Proximate analysis (wt% wet basis)		Chemical analysis (wt%)	
Characteristics	Value %	Characteristics	Value %	Characteristics	Value %
C	34.90	Moisture content(M)	8.59	Cellulose	37.34
H	5.15	Fixed carbon (FC)	8.48	Hemicelluloses	10.04
O	59.00	Volatile matter (VM)	58.22	Lignin	41.08
N	0.31	Ash (ASH)	24.71	Extractives	11.51
S	0.64	-	-	-	-
Cl	< 0.01	-	-	-	-

2.4.2 Potential of rice husk for energy generation

In general, there is a significant potential for rice husk in both energy and non-energy applications. Figure 4 illustrates these application details.

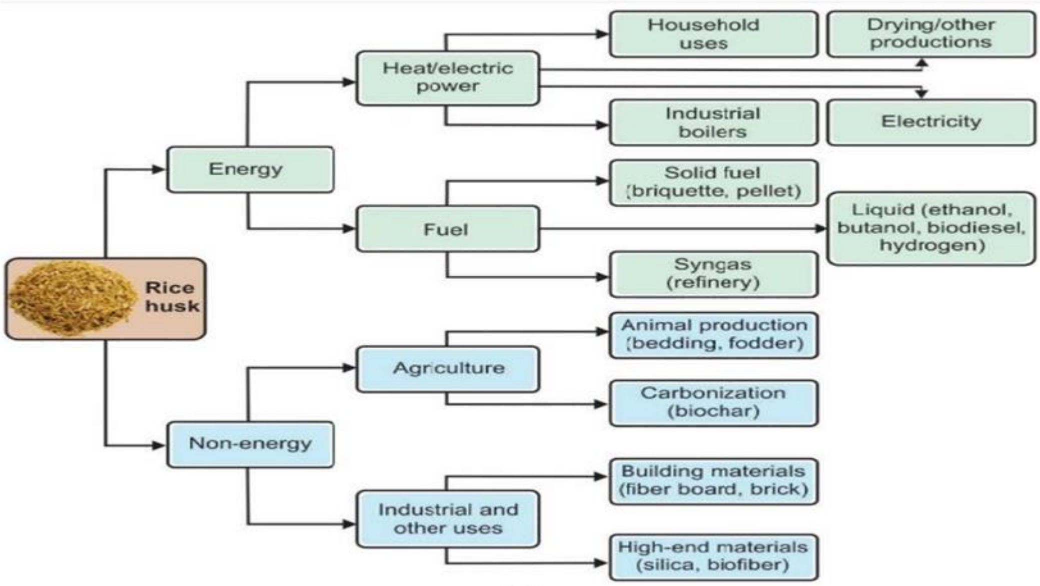

Figure 4. Applications of rice husk (Rice Knowledge Bank, 2024)

This Study focuses primarily on its role in energy generation. Rice husk is rich in organic carbon, containing approximately 30-50% by weight, and possesses a high calorific value. These properties make it an excellent resource for producing fuel, heat and electricity. The various methods for converting rice husk into energy using thermal, chemical, and biological processes are depicted in Figure 5.

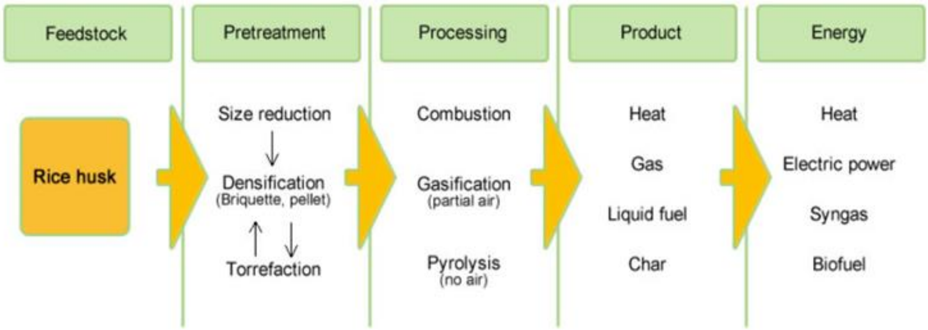

Figure 5. Conversion method of rice husk to energy (Rice Knowledge Bank, 2024)

Upon collection after rice milling, rice husk typically has a moisture content of about 14-15%, making it suitable for immediate use in energy conversion processes without extensive pretreatment. The primary thermal processes utilized are combustion, Pyrolysis, and gasification. These methods transform rice husk into usable energy forms such as heat, electricity, and biofuels (both solid and liquid). The heat generated from these processes can be used for residential heating and cooking, powering industrial boilers, drying processes, and generating electricity. This versatility highlights the importance of rice husk as a sustainable energy resource (Rice Knowledge Bank, 2024).

2.5 Application Status of Rice Husk for Electricity Generation in Polonnaruwa

Polonnaruwa is the major district for rice production in Sri Lanka, hosting several large-scale rice mills. Due to its significant rice production, there is a substantial accumulation of rice husk in the area, presenting a notable potential for energy generation. Despite this potential, most rice mills in the district, except Nipuna Rice Mill, primarily rely on electricity supplied from the national grid. Based on the paddy harvested in the district during the year 2022 and as per the study survey, Polonnaruwa has the potential to produce approximately 56 GWh of electricity annually using rice husk. This underutilized resource represents a considerable opportunity to enhance the energy self-sufficiency of the local rice milling industry and contribute to sustainable energy solutions in the region (as per author survey).

2.5.1 Focus Rice Mill.

Our study focuses on the New Rathna rice mill, one of the largest rice mills in Sri Lanka, selected from among three mega rice mills. It is situated in Welikanda, Polonnaruwa as shown in Figure 6. The rice mill was established in 1981 as a small operation utilizing conventional milling techniques. Over time, the mill has developed into one of the leading rice mills in Sri Lanka. Currently, the mill can process paddy reaching 400 metric tons per day. Additionally, it has a large storage capacity, with the possibility to accommodate up to 42,000 metric tons of paddy in its silo system. The factory spans a total land area of 200 acres, whereas the mill is situated on a 10-acre area. The rice mill currently serves an extensive variety of consumer demands while maintaining the highest levels of quality, cleanliness and environmental sustainability. A rice mill that specializes in processing and milling rice. Since the rice mill is located within the Polonnaruwa district's rich agricultural landscape and well-established irrigation systems, the mill strategically utilizes its location to ensure the efficient transportation and distribution of its products throughout Sri Lanka. This rice mill is the first in Sri Lanka to implement the latest "BUHLER" technology for parboiling rice production. The mill has a broad network for collecting paddy from the Polonnaruwa district and other neighbouring districts in Sri Lanka. Its activity is not confined to paddy milling but also includes paddy collection and rice distribution to shops around the country. This company produces a diverse range of rice products to meet the needs of consumers in the country. The current management team of this rice mill is focused on implementing sustainable practices in the sector. They have recently implemented a wastewater treatment facility to manage contaminated water produced.

During the rice production process, it complies with the environmental standards set by the country. However, the mill is actively exploring sustainable solutions for its primary byproduct, rice husk, by seeking efficient and cost-effective methods for its utilization within mill operations (as per interviews and surveys); (*New Rathna Rice Mill*, 2016).

Figure 6. Site image of the focused rice mill.

2.5.2 Rice Processing at the Mill

The selected rice mill operates with a significant daily production capacity of 400 metric tons (MT). The operational hours are extended to 20 hours each day for 25 days every month, ensuring consistent production throughout the year. The rice processing at the mill is mainly focused on parboiling, which accounts for 80% of the total production. The remaining 20% of the rice is processed without undergoing parboiling as raw rice. Figure 7 shows the rice value addition process inside the mill.

The mill is equipped with multiple production lines that are specifically designed to manage various rice types to meet changing market demands. The varieties consist of Keeri Rice, Nadu Rice, Samba, White Kekulu, and Broken Rice. The production lines are continually adjusted by market demands, guaranteeing maximum efficiency and product availability.


Figure 7. Image of the milling process in the mill.

2.5.3 Rice Husk Utilization

Our focused rice mill produces a substantial quantity of rice husk, approximately 80-90 MT per day as a by-product of the rice milling process. Rice husk is primarily generated during the de-husking phase, where the outer husk is removed from the grain. Additionally, during the polishing process, the grain is further refined to separate the bran layer, yielding byproducts such as broken grain particles and residual bran. Approximately half of the rice husk produced is utilized within the mill itself, serving as a fuel source for the boilers. The mill has six boilers, each with a capacity of 6 tons per hour (TPH) are employed to generate process heat essential for the parboiling and drying of paddy. This method of using rice husk for energy generation within the mill is not highly efficient considering the energy potential of the rice husk and there is still some portion of energy wastage.

However, the utilization of rice husk extends beyond internal consumption. The remaining 50% is commercially distributed to various external industries, where it finds applications as a raw material in cement production, brick manufacturing, and the poultry industry. It is also used as an organic fertilizer in agriculture. Despite these uses, a significant portion of the rice husk remains unutilized, leading to its disposal through landfilling and in some instances, open burning in fields. This practice highlights a gap in the efficient use of rice husk, as significant amounts of potential resources are still released into the environment, posing environmental concerns (from the interview).

2.5.4 Electricity Consumption of Rice Mill.

Almost all rice mills except one in Sri Lanka fulfil their operational and service-related electricity demands by accessing energy from the national grid. Typically, rice production processes in these mills consume both thermal and electrical energy and thermal energy is constituting a larger share of the total energy consumption (Roomi, Namal and Jayasinghe, 2007). However, electricity still plays a crucial role in various stages of the rice milling process in modern mills. The electricity is primarily used to power various essential machinery and processes throughout the rice milling operations. These include conveyor belts used for transferring paddy and rice within the mill, paddy cleaners, designers, rubber roll shellers, huskers, paddy separators, polishers, aspirators, graders, and elevators (Goyal and Chandra, 2010). Furthermore, electricity is integral to sorting and packing operations, which are vital for the final preparation of rice for the market.

According to a survey on energy consumption conducted at a selected rice mill, it requires 1.8 MW of power for full-load operations. Under normal conditions, the average electricity requirement is approximately 900 kW. Detailed data on electricity consumption for the year 2023 is provided in the referenced Table 3 highlighting the monthly energy usage across various operations within the mill and the corresponding electricity bill in USD.

Table 3. Monthly cost of electricity in 2023 (Author Survey 2023/2024)

Month	Energy consumption (MWh)	Electricity cost (USD)
Jan	602.58	54,563.96
Feb	798.52	99,053.21
Mar	925.85	114,043.91
Apr	514.60	66,747.20
May	765.62	95,564.52
Jun	605.58	77,005.57
July	808.48	89,787.10
Aug	772.06	85,861.63
Sep	767.32	85,664.90
Oct	751.03	93,524.14
Nov	847.59	104,687.80
Dec	903.59	111,245.31

2.5.5 Electricity Generation Potential through Excess Rice Husk of the Mill

According to the Department of Census and Statistics Sri Lanka, in the Polonnaruwa district, the paddy production during the Yala season of 2022 was reported at 222,414 MT and 271,313 MT for the Maha season of 2022/2023 (DCS, Sri Lanka, 2002). This substantial output highlights the significant potential for rice husk generation, as rice husk typically accounts for 18% to 23% of the weight of the paddy, varying with different paddy varieties in Sri Lanka. For our analysis, we have taken the husk-to-paddy ratio as 20% and the lower heating value (LHV) of rice husk as 13.6 MJ/kg, and a conversion efficiency of 15 (Rodrigo and Perera, 2013). With these parameters, the annual electrical generation potential from the rice husk produced by the Polonnaruwa district's paddy harvest in the year 2022 can be calculated to be approximately 55.95 GWh.

According to the daily rice husk production of the mill, it can generate approximately 45.33 MWh of electricity daily from its rice husk by-product. This energy potential underscores the vital role rice husk can play in contributing to sustainable energy solutions, not only to meet the electricity demands of the selected rice mill but also as a sustainable energy solution for the entire Polonnaruwa district.

2.5.6 Possibility of Rice Husk Collection from Area on Demand

Polonnaruwa district accounts for 14% of Sri Lanka's paddy cultivation, but it contributes nearly 50% of the total rice production in the country in the conversion of paddy to rice as most of the rice mills located in this district (Wijesooriya, Kuruppu and Priyadarshana, 2021). As a result, approximately half of the rice husk generated from the total paddy processed in Sri Lanka is available within the Polonnaruwa. The proximity of other major rice-producing districts such as Anuradhapura, Kurunegala, and Trincomalee further enhances the potential for rice husk collection, making the transportation and handling of additional rice husk economically viable.

Rice husk produced by small and medium-scale mills in these regions is already utilized in various applications, including brick production, agriculture (as a fertilizer), poultry farming, and as a raw material in cement production. It is noteworthy that these sub-industries are not exclusively dependent on rice husk for their operations, as they have access to multiple alternative raw materials. The considerable amount of rice husk generated by medium and small-scale mills in Polonnaruwa and coupled with the strategic geographic location of the district neighbouring other major rice-producing areas. This makes huge potential to increase energy generation from rice husk in the milling industry in Polonnaruwa (as per author survey). The utilization of these rice husk as an energy resource aligns with the goals of sustainable development by providing a renewable energy source that can meet the increasing energy demands while minimizing environmental impact.

3 Thermochemical Conversion and Product Treatment Process of Rice Husk

Thermochemical conversion processes, including direct combustion, pyrolysis, and gasification, are methods used to convert biomass into energy or value-added products.

3.1 Direct Combustion

Direct combustion is a thermochemical process that converts biomass like rice husk and rice straw into heat energy, suitable for decentralized energy production in rural areas (Quispe, Navia and Kahhat, 2017). However, it has limited efficiency and can emit pollutants like particulate matter, nitrogen oxides, and sulfur dioxide. Research and development efforts aim to improve combustion technologies and emission control measures to enhance the environmental performance of biomass-based energy production.

3.2 Pyrolysis

Pyrolysis is a thermochemical process that converts biomass into solid char, liquid Bio-oil, and producer gases. It occurs in controlled environments at temperatures between 300 °C and 650 °C, producing valuable products like Bio-char, Bio-oil, and syngas (Athira, Bahurudeen and Appari, 2019). However, it faces challenges like optimizing operating conditions and energy input, and scaling up from laboratory to commercial production presents technical and economic challenges. Despite these, pyrolysis offers a promising approach for converting biomass into valuable products.

This has been a non-commercially proven technology. Thermal degradation of organic materials can take place through the use of an indirect external source of heat to maintain the temperature between 300 °C to 650 °C for several seconds in the absence of oxygen. Products are char, oil and syngas composed primarily of O_2, CO, CO_2, CH_4 and complex hydrocarbons. Syngas can be utilized for energy generation (Basu, 2013). Figure 8 illustrates the Pyrolysis process in a biomass particle.

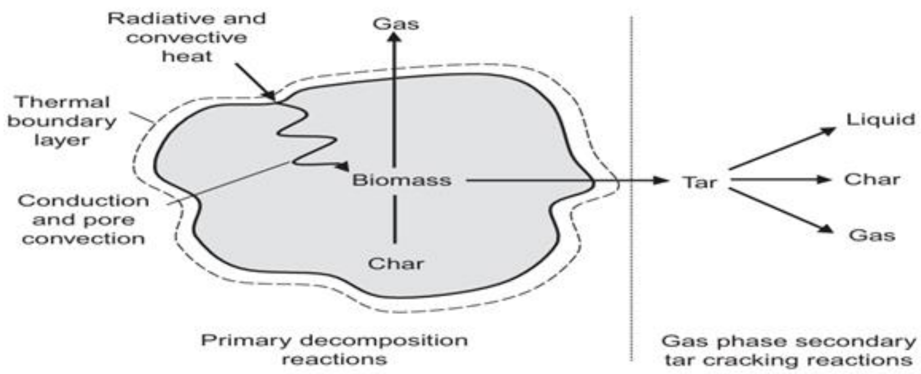

Figure 8. Pyrolysis process in a biomass particle.

The generic reaction of Pyrolysis is as follows.

$$C_nH_mO_p + \text{heat} \rightarrow \sum_{\text{Liquid}} C_aH_bO_c + \sum_{\text{Gas}} C_xH_yO_z + \sum_{\text{Solid}} C \quad (1)$$

3.3 Gasification

Gasification is a thermochemical process that converts biomass into synthesis gas, primarily hydrogen, carbon monoxide, and methane (Balat *et al.*, 2009). It offers benefits like feedstock flexibility and energy efficiency. Challenges include complex engineering, tar formation, and high initial investment. Despite these, gasification holds significant potential for energy and chemical applications. Research focuses on improving processes, reducing costs, and enhancing efficiency. Figure 9 shows the ternary diagram of the Biomass gasification process.

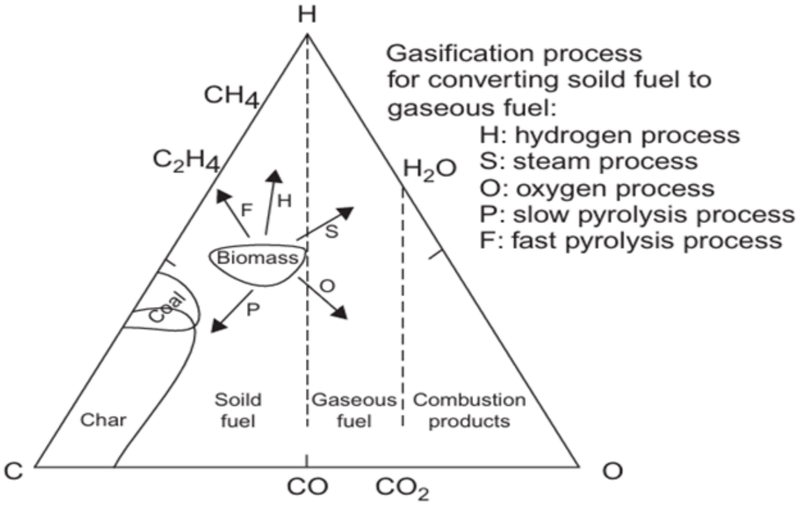

Figure 9. Ternary diagram of Biomass showing in gasification process (Basu, 2013)

3.4 Product Analysis

During the thermochemical conversion of biomass with both processes of pyrolysis and gasification, the primary products differ based on the process conditions of heating rate, residence time and maximum reaction temperature. Pyrolysis typically yields producer gas, tar (Bio-oil) and Bio-char. In contrast, gasification mainly produces syngas and Bio-char, with a small fraction of ash also present in the products. The yield of Biochar can be increased through slow pyrolysis, which involves longer reaction times at lower temperatures to enhance the carbonization of the biomass. Conversely, the production of gaseous products is increased with fast pyrolysis which uses higher temperatures and rapid heating rates to break down the biomass more quickly, maximizing gas and tar outputs while reducing the char yield. Bio-oil yield can be improved with flash pyrolysis with moderate temperature with fast resident time (Mofijur *et al.*, 2019) (EUBIA, 2024).

3.4.1 Syngas

Syngas is primarily composed of hydrogen (H_2) and carbon monoxide (CO) and is the crucial feedstock for the chemical and energy sectors. It can be produced from a variety of hydrocarbons, including natural gas, coal, petroleum coke, and biomass. When derived from biomass, it is referred to as bio-syngas. The production of biomass-based syngas involves the thermochemical conversion of solid biomass into a gaseous mixture at high temperatures. This process not only yields hydrogen and carbon monoxide but also produces carbon dioxide, methane, and smaller quantities of other gases, resulting in a versatile and adaptable gas mixture. This mixture is ideal for generating electricity, heat and biofuels. A critical aspect of this process is managing the ratio of hydrogen to carbon monoxide, which significantly influences the synthesis of desired products. To optimize the hydrogen content in syngas, a shift reaction is introduced. This reaction is usually conducted in a separate reactor as the conditions within the main gasifier such as temperature may not be favourable for this reaction. This adjustment enhances the efficiency and adaptability of syngas for various applications (Basu, 2013).

3.4.2 Biochar

Biochar is a carbon-rich residue derived from the pyrolysis of biomass, such as rice husks, under controlled, low-oxygen conditions. Containing at least 50% carbon by weight, with 75% being fixed carbon (Maguyon-Detras *et al.*, 2020), Biochar is highly effective for applications that demand high heating value with minimal emissions of sulfur and nitrogen oxides. Furthermore, the porous nature of Bio-char not only improves soil structure, fertility, and water retention but also decreases soil acidity and enhances nutrient availability. This contributes significantly to increasing the resilience of plants and improving soil health by increasing beneficial microbial activity. By converting agricultural waste like rice husks into Bio-char, this process not only addresses waste management challenges but also aids in carbon sequestration. Also, Biochar is popular in water purification products (Ebe and Ano, 2020).

3.4.3 Bio-oil

Bio-oil is also known as pyrolysis oil which is a liquid by-product created by rapidly heating organic material, such as biomass in a low-oxygen environment followed by quick cooling. This process transforms biomass into a liquefied form that is easier to pump, store, and chemically modify or process. Bio-oil primarily consists of an emulsion of oxygenated organic compounds, polymers, and water. It contains up to 40% oxygen by weight, making it significantly different from petroleum oil. Specially, it is not mixable with petroleum oils and typically contains 20-30% water. Additionally, Bio-oil has a lower heating value than petroleum oil, is acidic, and becomes unstable, especially when heated. It also has a higher density than water and frequently includes solid inorganics and carbon char, further distinguishing it from traditional petroleum products (van de Beld *et al.*, 2023).

4 Methodology

4.1 Field Study

The field study was covered based on the rice cultivation and production in Polonnaruwa district to understand rice husk potential and date required for process design for electricity generation for own demand of focused rice mill. Methods of gathering data consisted of interviews with the Subject Matter Officer (paddy) in the Agriculture Department in Polonnaruwa district for information on paddy production and rice husk potential from the area and the Chief Engineer of the mill for collecting technical data on the rice milling process and its energy requirement. Further, we referred government statistics report for validation of data. All interviews were conducted over the phone and answers to the questionnaire were taken in written documents. Some sensitive information relevant to the selected rice mill could not be taken due to company policy and the entire study was able to manage with available data. Data collected from an oral and written questionnaire of responsible personnel and statistics report of the government of Sri Lanka and other available literature were used for calculation of rice husk production, electricity demand for full load operation and average electricity demand, and steam requirement for mill operation.

4.2 Working Principle of Rice Husk Biomass Combustion

Unlike other biomass sources, rice husk has a smaller size, requiring more feedstock to produce the designated power. This thesis explores a technology that uses separate reactors for pyrolysis, gasification, and combustion. Dried biomass feedstock is fed into the pyrolysis reactor to produce pyrolyzed gas, char, and Bio-oil.

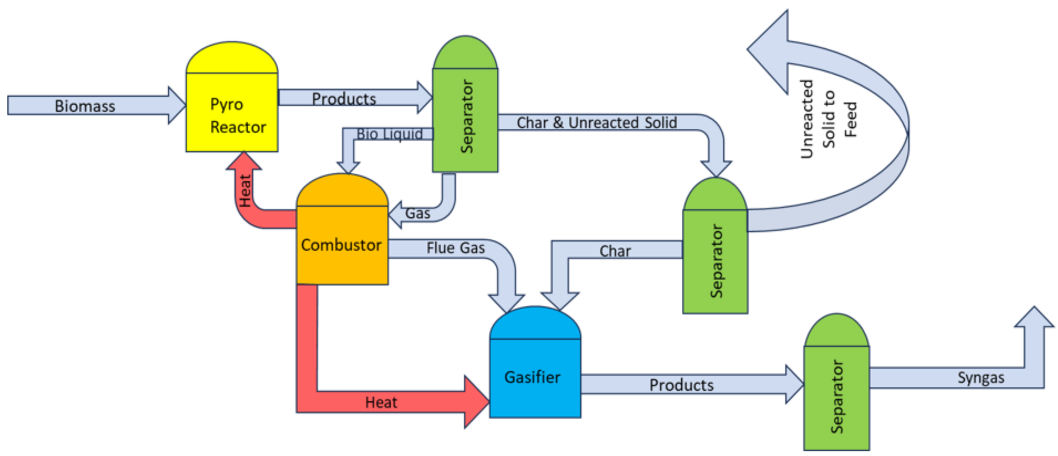

Figure 10. Process flow of biomass conversion

4.3 Pyrolysis

4.3.1 Pyrolyzed Gas

After the separation process, the gas is fed to the combustor for combustion. The combustion of the pyrolyzed gas generates the necessary heat for both the pyrolysis and gasification processes. Following combustion, the high-temperature flue gas is cooled down by an air-cooled heat exchanger to reach the required temperature for further processing. The flue gas, containing H_2O and CO_2, is then directly used for the steam gasification process. Figure 11 shows the Pyrolysis process.

Table 4. Mass balance of Pyrolysis

	Temperature (°C)	Flow Rate (kg/hr)
Pyrolysis Reactor	550	5,000
Pyrolyzed Gas	550	647
Bio Oil	550	2,585
Bio Char	550	1,408
Unreacted Solid	550	360

4.3.2 Bio-Oil and Flue Gas

The pyrolysis system also produces Bio-oil. While Bio-oil can be sold to other industries based on demand, its processing is beyond the scope of this thesis. Therefore, all Bio-oil is fed into the combustor to achieve high efficiency. The relationship between the plant's power output and Bio-oil will be discussed in the following chapter.

The flue gas is utilized for steam gasification and provides the necessary heat for the gasifier. The high-temperature flue gas from the combustor is further cooled by an air-cooled heat exchanger to meet the gasifier's required temperature. In theory, the Separator block in Aspen Plus can isolate only H_2O and CO_2 for steam gasification.

4.3.3 Bio Char

Biochar is another product of pyrolysis and can be sold to other facilities. In practical applications, Biochar cannot be easily separated from unreacted solids. However, in Aspen Plus, this separation can be achieved using a separator block. In this simulation, the process approach aims for maximum operational efficiency. Therefore, all Biochar is fed into the gasifier to produce the maximum amount of syngas. Unreacted solids tend to diminish as the temperature of the pyrolysis reactor increases. A key point to note is that the reactor's heat duty increases with the rising temperature of pyrolysis. A small amount of unreacted solids can be recirculated into the biomass feeding system.

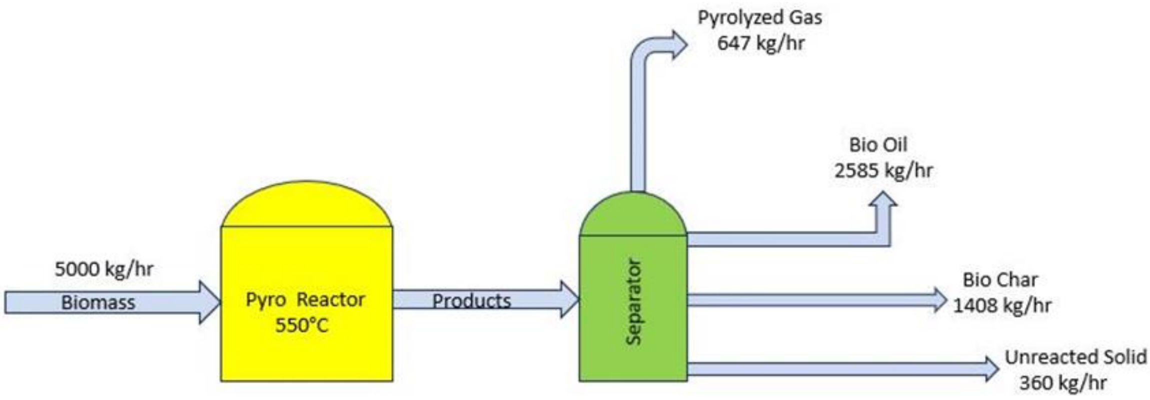

Figure 11. Pyrolysis process.

4.4 Gasification

In this configuration, a dedicated gasifier is employed for the synthesis of syngas, the primary output of the system. Given the centrality of syngas production, the gasifier operates at elevated temperatures. Biochar generated from the preceding pyrolysis reactor undergoes steam gasification with the flue gas from the combustor, which contains water vapour and carbon dioxide. Following separation, both syngas and surplus steam are yielded as products of the gasification process. Figure 12 shows the gasification process.

Table 5. Mass balance of the gasification process

	Temperature (°C)	Flow Rate (kg/hr)
Bio Char Inlet	550	1,408
CO_2 Inlet	800	3,886
H_2O Inlet	800	2,476
Syngas	800	7,016
Excessive H_2O	800	754

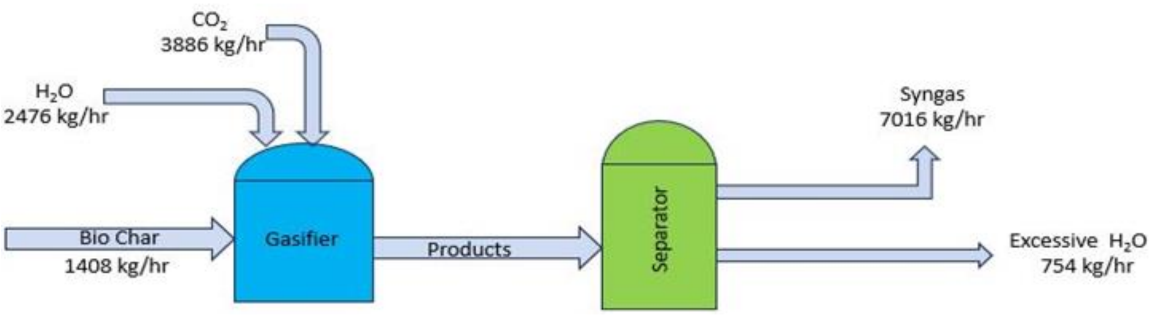

Figure 12. Gasification process

4.5 Model Set Up by Aspen Plus

Aspen Plus is a theoretical and powerful simulation environment widely used in the process industry. In this simulation, rice husk is utilized as the biomass, and the approach is based on the chemical composition of the organic compounds found in rice husk. Typically, biomass is composed of cellulose, hemicellulose, and lignin, along with moisture, ash, and other extractives. To simplify the process, this simulation focuses solely on the compositions of cellulose, hemicellulose, and lignin. The dried rice husk, having been brought to an evaporated temperature, is introduced into the pyrolysis reactor to initiate the process.

In Aspen Plus, all chemical compounds involved in the simulation are identified before the simulation step. The accompanying Table 9 details the chemical compounds used in this Aspen Plus environment. According to the literature, the selection of reactors depends on the simulation requirements. The process simulation emulates the actual decomposition of organic compounds, with yield products varying across temperature ranges. Consequently, RCSTR, RStoic, and RGibbs reactors are utilized for the pyrolysis, combustor, and gasifier processes, respectively. Table 6 provides detailed descriptions of these reactors.

Table 6. Expression of reactors

Reactor	Expression
RCSTR (Pyrolysis)	Calculate the products of the pyrolysis process by the rate-controlled reactions based on known kinetics
RStoic (Combustor)	It is a stoichiometric reactor based on known fractional conversion or extent of reaction
RGibbs (Gasifier)	It can calculate the products based on the Gibbs Free Energy minimization

4.6 Model Set-Up for Pyrolysis

Rice husk, composed of cellulose, hemicellulose, and lignin, is fed into the RCSTR (Pyrolysis) reactor at a flow rate of 5,000 kg/s and a temperature of 100 °C. Within the RCSTR, the organic compounds in the rice husk decompose in response to the operational temperature. To ensure accurate simulation, the precise stoichiometric reactions and chemical kinetics must be defined for the RCSTR. Consequently, the decomposition reactions of the rice husk are modelled by 17 chemical equations, as detailed in Table 9. Table 7 illustrates the chemical composition of the rice husk.

Table 7. Chemical composition of rice husk (Adeniyi, Ighalo and Aderibigbe, 2019)

Compound	Percentage (%)
Cellulose	41.34
Hemicellulose	13.58
Lignin	45.08

Table 8. Process variables of RCSTR

Variables	Value
RCSTR Temperature	550 °C
RCSTR Pressure	1 bar
RCSTR Flow Rate	5000 kg/hr

Table 9. Properties setup (Gorensek, Shukre and Chen, 2019)

	Component ID	Type	Component name	Alias
1	BIOMA-01	Solid	BIOMASS-CELLULOSE	$C_6H_{10}O_5$-B1
2	ACTIV-01	Solid	ACTIVATED-CELLULOSE	$C_6H_{10}O_5$-B5
3	ACTIV-02	Solid	ACTIVATED-HEMICELLULOSE-1	$C_5H_8O_4$-B4
4	ACTIV-03	Solid	ACTIVATED-HEMICELLULOSE-2	$C_5H_8O_4$-B5
5	C-RIC-01	Solid	C-RICH-LIGNIN	$C_{15}H_{14}O_4$-B1
6	O-RIC-01	Solid	O-RICH-LIGNIN	$C_{20}H_{22}O_{10}$-B1
7	H-RIC-01	Solid	H-RICH-LIGNIN	$C_{22}H_{28}O_9$-B1
8	C-RIC-02	Solid	C-RICH-LIGNIN-INTERMEDIATE	$C_{15}H_{14}O_4$-B2
9	HO-RI-01	Solid	HO-RICH-LIGNIN-INTERMEDIATE	$C_{19}H_{22}O_8$-B1
10	H_2O	Conventional	WATER	H_2O
12	ACETY-01	Solid	ACETYLATED-XYLAN	$C_7H_{11}O_5$-B1
13	GLYCO-01	Conventional	GLYCOL-ALDEHYDE	$C_2H_4O_2$-D1
14	GLYOX-01	Conventional	GLYOXAL	$C_2H_2O_2$
15	CH_3CHO	Conventional	ACETALDEHYDE	C_2H_4O-1
16	5-HYD-01	Conventional	5-HYDROXYMETHYLFURFURAL	$C_6H_6O_3$-N5
17	N-PRO-01	Conventional	N-PROPIONALDEHYDE	C_3H_6O-3
18	CO_2	Conventional	CARBON-DIOXIDE	CO_2
19	CO	Conventional	CARBON-MONOXIDE	CO
20	CH_4	Conventional	METHANE	CH_4
21	C_3H_6O	Conventional	ACETONE	C_3H_6O-1
23	NITROGEN	Conventional	NITROGEN	N_2
24	LVG	Conventional	LEVOGLUCOSAN	$C_6H_{10}O_5$-N1
25	CHAR-01	Solid	CHAR(CARBON)	C-B1
26	METHA-01	Conventional	METHANOL	CH_4O
27	FORMA-01	Conventional	FORMALDEHYDE	CH_2O
28	ETHAN-01	Conventional	ETHANOL	C_2H_6O-2
29	BIOMA-02	Solid	BIOMASS-GLUCOMANNAN	$C_5H_8O_4$-B1
30	BIOMA-03	Solid	BIOMASS-XYLAN	$C_5H_8O_4$-B2
31	FURFU-01	Conventional	FURFURAL	$C_5H_4O_2$
32	XYLOS-01	Conventional	XYLOSAN	$C_5H_8O_4$-B6
33	3-HYD-01	Conventional	3-HYDROXYPROPANAL	$C_3H_6O_2$-B1
34	H_2	Conventional	HYDROGEN	H_2
35	FORMI-01	Conventional	FORMIC-ACID	CH_2O_2
36	ETHYL-01	Conventional	ETHYLENE	C_2H_4

37	ACETI-01	Conventional	ACETIC-ACID	$C_2H_4O_2$-1
38	P-COU-01	Conventional	P-COUMARYL-ALCOHOL	$C_9H_{10}O_2$-B1
39	PHENO-01	Conventional	PHENOL	C_6H_6O
40	SECON-01	Solid	SECONDARY-LIGNIN-INTERMEDIATE	$C_{11}H_{12}O_4$-B1
41	HIGH-01	Solid	HIGH-MW-LIGNIN	$C_{24}H_{28}O_4$-B1
42	ACROL-01	Conventional	ACROLEIN	C_3H_4O
43	SINAP-01	Conventional	SINAPYL-ALDEHYDE	$C_{11}H_{12}O_4$-B2
44	METHY-01	Conventional	METHYL-PHENYL-ETHER	C_7H_8O-1
46	NITRI-01	Conventional	NITRIC-OXIDE	NO
47	NITRO-01	Conventional	NITROUS-OXIDE	N_2O
48	NITRO-02	Conventional	NITROUS-OXIDE	N_2O
49	O_2	Conventional	OXYGEN	O_2

Table 10. Chemical equation and kinetics setup (Humbird et al., 2017)

E_n (kcal/kmol)	A_n ($K^{-xn}s^{-1}$)	Stoichiometry		
47,000	1.5×10^{14}	BIOMA-01	→	ACTIV-01
19,100	2.5×10^{6}	BIOMA-01	→	5 H_2O + 6 CHAR(-01)
10,000	3.3	ACTIV-01	→	LVG
31,000	6×10^{7}	ACTIV-01	→	0.95 GLYCO-01 + 0.25 GLYOX-01 + 0.2 C_3H_6O + 0.25 5-HYD-01 + 0.2 CH_3CHO + 0.16 CO_2 + 0.23 CO + 0.9 H_2O + 0.1 CH_4 + 0.61 CHAR(-01)
31,000	1×10^{10}	BIOMA-02	→	0.7 ACTIV-02 + 0.3 ACTIV-03
28,500	1×10^{10}	BIOMA-03	→	0.35 ACTIV-02 + 0.65 ACTIV-03
11,000	3	ACTIV-02	→	0.6 XYLOS-01 + 0.2 3-HYD-01 + 0.12 GLYOX-01+ 0.2 FURFU-01 + 0.4 H_2O + 0.08 H_2 + 0.16 CO
3,000	1.8×10^{-3}	ACTIV-02	→	0.4 H_2O+ 0.8 CO_2 + 0.05 FORMI-01 + 1.6 CO + 1.25 H_2 + 0.3 FORMA-01 + 0.625 CH_4 + 0.375 ETHYL-01 + 0.875 CHAR(-01)
31,500	5×10^{9}	ACTIV-03	→	0.2 H_2O + CO + 0.575 CO_2 + 0.4 FORMA-01 + 0.1 ETHAN-01 + 0.05 GLYCO-01 + 0.35 ACETI-01 + 0.025 FORMI-01 + 0.25 CH_4 + 0.3 METHA-01 + 0.225 ETHYL-01 + 0.725 H_2 + CHAR(-01)
37,200	1×10^{11}	C-RIC-01	→	0.35 C-RIC-02 + 0.1 P-COU-01 + 0.08 PHENO-01 + 0.41 ETHYL-01 + H_2O + 0.3 FORMA-01 + 1.02 CO + 0.7 H_2 + 0.495 CH_4 + 5.735 CHAR(-01)
37,500	6.7×10^{12}	H-RIC-01	→	HO-RI-01+ 0.5 N-PRO-01 + 0.5 ETHYL-01 + 0.2 GLYCO-01 + 0.1 CO + 0.1 H_2
25,500	3.3×10^{8}	O-RIC-01	→	HO-RI-01 + CO_2

24,800	1×10^4	C-RIC-02 → 0.3 P-COU-01 + 0.2 PHENO-01 + 0.35 GLYCO-01 + 0.7 H_2O + 1.8 CO + 0.65 CH_4 + 0.6 ETHYL-01 + H_2 + 6.75 CHAR(-01)
30,000	1×10^8	HO-RI-01 → 0.9 SECON-01 + H_2O + 0.45 CH_4 + 0.9 METHA-01 + 0.9 H_2 + 0.05 CO_2 + 2.1 CO + 0.05 FORMI-01 + 0.2 ETHYL-01 + 0.025 HIGH--01 + 0.1 ACROL-01 + 4.25 CHAR(-01)
12,000	4	SECON-01 → 0.7 SINAP-01 + 0.3 METHY-01 + 0.6 CO + 0.3 CH_3CHO
8,000	8.3×10^{-2}	SECON-01 → 0.6 H_2O + 2.6 CO + 0.6 CH_4 + 0.4 FORMA-01 + 0.5 ETHYL-01 + 0.4 METHA-01 + 2 H2 + 6 CHAR-01
24,300	1×10^7	SECON-01 → 0.6 H_2O + 2.6 CO + 1.1 CH_4 + 0.4 FORMA-01 + ETHYL-01 + 0.4 METHA-01 + 4.5 CHAR-01

4.7 Result of Pyrolysis

The RCSTR (Pyrolysis) reactor produces three primary products: Bio-char, Bio-oil, and pyrolyzed gas. As previously mentioned, the process focuses on optimizing gas production to generate the necessary heat for both the pyrolysis and gasification stages. However, optimizing Bio-char production is also essential for steam gasification. Figure 13 and Figure 14 illustrates the production of Bio-char and gas in relation to the varying temperatures of the RCSTR (Pyrolysis) reactor.

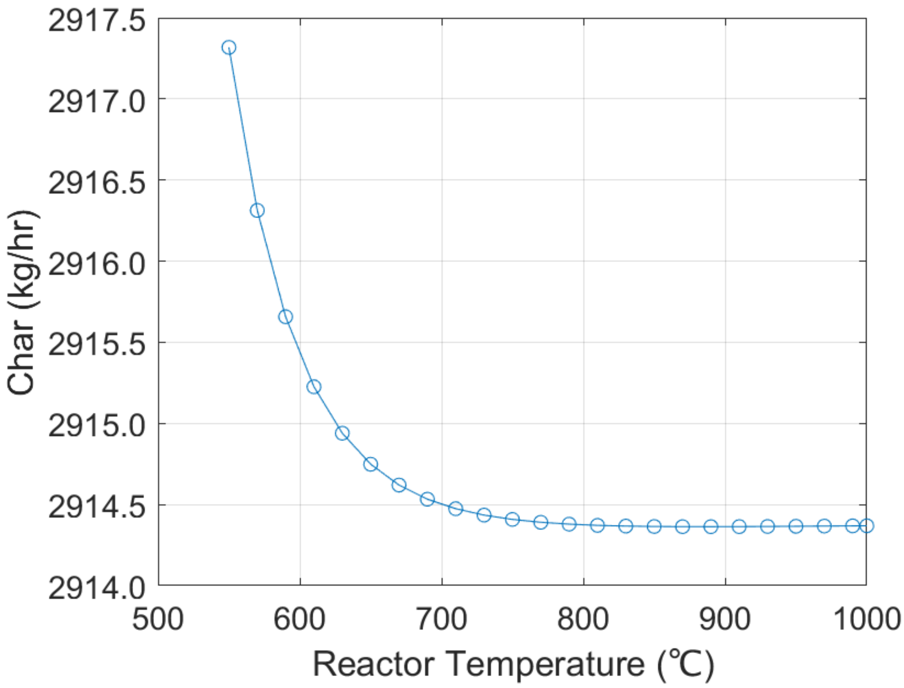

Figure 13. Char Production from Pyrolysis reactor (RCSTR)

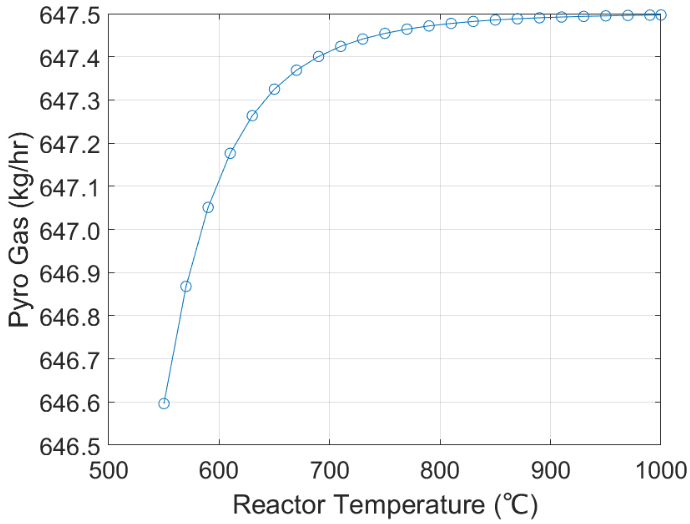

Figure 14. Gas Production from Pyrolysis reactor (RCSTR)

As shown in Table 12, char production decreases with increasing temperature. However, this trend represents the total value of char, including small amounts of biomass residues and other solids. The optimal operating temperature is determined based on the required pyrolyzed gas production to generate sufficient heat duty from the combustor.

At lower temperatures, more char is produced, providing more reactants for the gasifier to produce additional syngas. Conversely, less gas is produced at lower temperatures, leading to reduced fuel dosing into the combustor and resulting in a smaller amount of flue gas and heat duty. This insufficient heat supply from the combustor would affect both the pyrolysis and gasification processes.

To ensure adequate heat generation, the optimal operating temperature is set at 550 °C. The output products, expressed in mass flow rate, are depicted in Figure 11. The flow sheet of the Aspen Plus simulation for pyrolysis is presented in Figure 15.

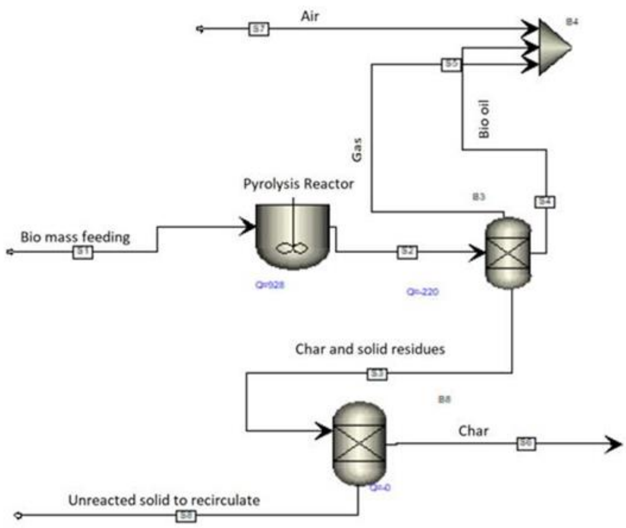

Figure 15. Model setup for Pyrolysis

4.8 Model Set Up for Combustor

The combustor provides the necessary heat for the entire system. Thus, the gas produced from pyrolysis must be sufficient to meet the required heat supply. The amounts of gas and char production are regulated by the pyrolysis operation temperature. Additionally, Bio-oil is produced as a byproduct of pyrolysis. In other processing plants, Bio-oil can be further refined for commercial purposes. However, for this simulation, syngas and char are the primary products. Consequently, the Bio-oil is fed into the combustor to enhance combustion efficiency and heat duty.

At the combustor's inlet, there are three streams: pyrolyzed gas, Bio-oil, and air. In the Aspen Plus environment, the RStoic reactor is suitable for use as the combustor because it has built-in chemical equations for combustion. A mixer block is also utilized to simplify the calculations within the reactor. The regulation of combustion temperature and pressure automatically calculates the heat duty generated from the combustion process. The optimal process parameters and mass flow of products are detailed in Table 11**.**

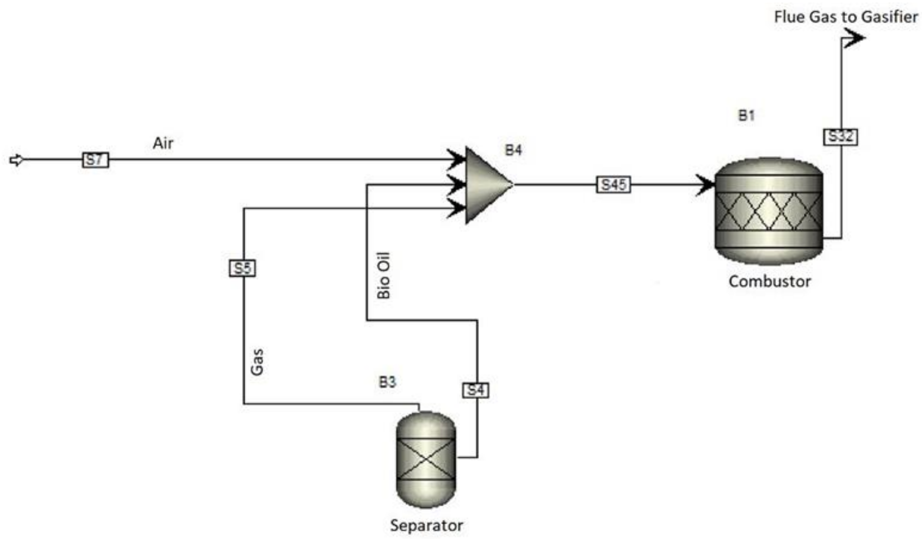

Figure 16. Aspen Plus flowsheet of combustor

4.9 Result of Combustor

The primary function of the combustor is to supply the required heat and maintain the necessary temperature for the entire process. Air, pyrolyzed gas, and Bio-oil are introduced into the combustion chamber as inlet streams. The flow of pyrolysis products, both gas and oil, has already been optimized within the pyrolysis system, ensuring these products remain at a constant optimal condition. Consequently, the amount of air fed into the combustor can be regulated to achieve the desired heat and temperature. Burning the air-fuel mixture as a lean mixture can increase the generated temperature. However, the operational temperature is fixed within the reactor setup, necessitating only the optimization of heat duty.

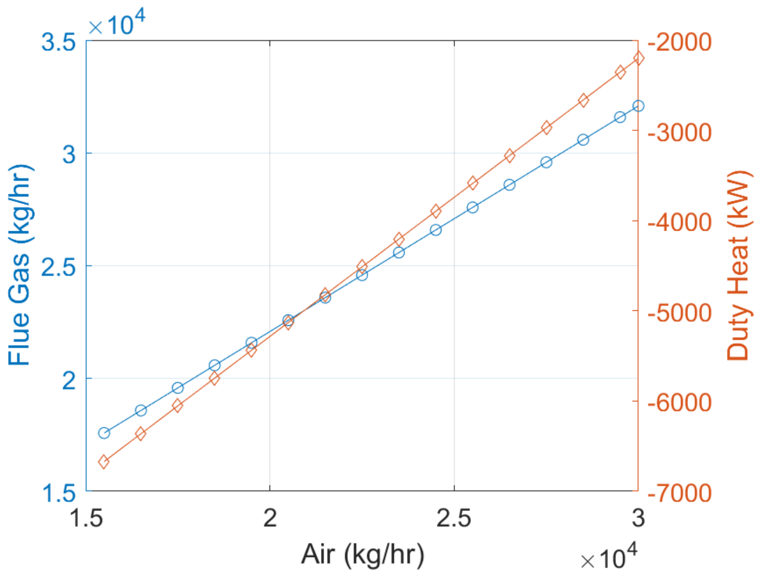

Figure 17. Analysis curve for the relation between air flow, heat duty and flue gas

Figure 17 demonstrates that the heat duty is inversely proportional to the air flow into the reactor. Conversely, the mass flow of flue gas is directly proportional to the air flow. Thus, an increase in air flow results in reduced heat duty, potentially leading to an insufficient heat supply for pyrolysis and gasification. Although minimizing the air flow can prevent an insufficient heat supply, it can also result in a rich mixture. Simulation analysis indicates that the optimal air flow rate is 15,500 kg/hr, as reducing the air flow below this value would cause an imbalance in oxygen molecules.

Table 11. Optimum parameter of combustion system

Combustor (1000 °C and 1 bar)	
Inlet Streams	**Outlet Streams**
Pyrolyzed gas (T = 550 °C, m = 647 kg/hr)	H_2O (T = 1,000 °C, m = 2,476 kg/hr)
Bio-oil (T = 550 °C, m = 2,586 kg/hr)	CO_2 (T = 1,000 °C, m = 3,886 kg/hr)
Air (T = 30 °C, m = 15,500 kg/hr)	Air (T = 1,000 °C, m = 1,2371 kg/hr)

4.10 Model Set-Up for Gasification

Gasification plays a crucial role in the simulation, as it is responsible for producing syngas for power generation. This simulation specifically considers steam gasification, leveraging the immediate availability of flue gas from the combustor, which contains H_2O and CO_2. The chemical reaction for gasification is as follows:

$$\text{Char} + H_2O \rightarrow CO + H_2 \tag{2}$$

$$CO + H_2O \rightarrow CO_2 + H_2 \tag{3}$$

$$\text{Char} + CO_2 \rightarrow 2CO \tag{4}$$

The RGibbs reactor in Aspen is well-suited as the gasification reactor. Specific input values for operating temperature and pressure must be provided.

Table 12. Input specification for RGibbs reactor (gasifier)

Variables	Value
RGibbs Temperature	800 °C
RGibbs Pressure	1 bar
RGibbs Flow Rate	7770 kg/hr

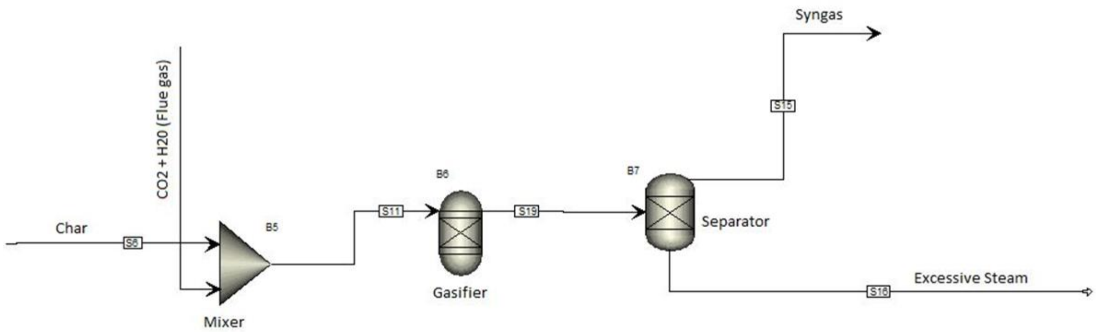

Figure 18. Model setup for gasification

4.11 Result of Gasification

Syngas production hinges primarily on the quantities of char, flue gas, and gasification temperature introduced into the gasifier. Consequently, optimizing these parameters individually is paramount. Within the gasification system, the focus shifts solely to optimizing syngas production within the constraints of minimal operating temperature and heat duty. Elevated operation entails greater heat duty demands, while lower temperatures risk diminishing syngas output.

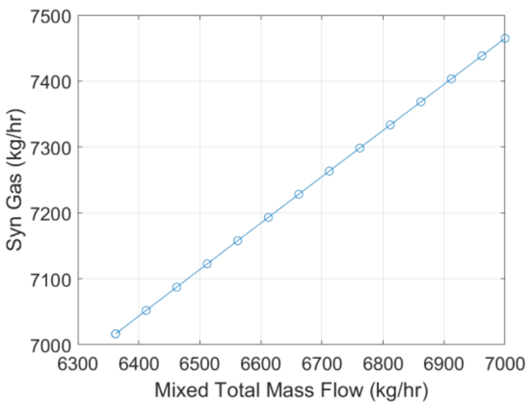

Figure 19. Trend for Syngas production based on flue gas

According to Figure 19, the flue gas must be sufficiently enough to react with the Bio-char inside reactor.

Table 13. Input and products of Gasifier

Gasifier (800°C and 1 bar)	
Inlet Streams	**Outlet Streams**
Biochar (T = 550 °C, m = 1,408 kg/hr)	Syngas (T = 800 °C, m = 7,016 kg/hr)
Flue gas, H_2O and CO_2 (T = 800 °C, m = 6,362 kg/hr)	Excessive H_2O (T = 800 °C, m = 754 kg/hr)

A minimal excess of water vapor emanates from the gasifier. Hence, it can be inferred that the char has undergone complete reaction with the flue gas, resulting in a negligible quantity of surplus flue gas.

4.12 Discussion for Biomass Conversion

In this simulation, pyrolysis, combustor and gasifier are formed as a equilateral triangle. Optimization of one unit is important for another.

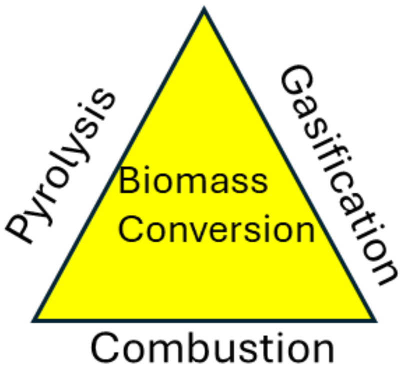

Figure 20. The triangle shape of the entire unit

Figure 20 illustrates the equilateral triangle configuration of the process. The optimal process parameters outlined in the preceding sections denote the peak operational load scenario. Depending on the power requisites, the conversion process can undergo dynamic fluctuations from one-time frame to another. Nonetheless, a triangular interconnection among pyrolysis, combustion, and gasification must be maintained under all operational conditions. Additionally, the feeding of rice husk can act as compensation when one unit operates under suboptimal conditions.

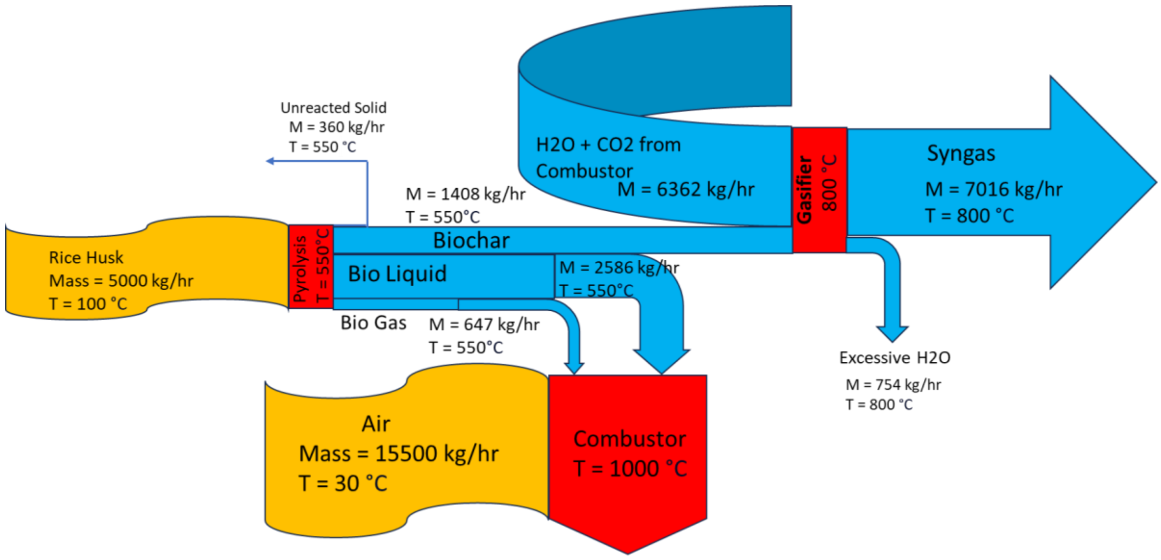

Figure 21. Sankey diagram of rice husk conversion process

The Sankey diagram illustrates the mass balance of the entire biomass conversion process. The incoming mass flow to the system, comprised of rice husk and air, totals 20,500 kg/hr. Ultimately, the production of syngas amounts to 7,016 kg/hr. Consequently, the efficiency of converting rice husk into syngas at maximum operational capacity typically stands at 34%. Further discussion on energy conversion efficiency will follow in subsequent sections. Despite the relatively small quantity of unreacted solids generated during pyrolysis, these solids can be reintroduced into the feeding system for subsequent cycles.

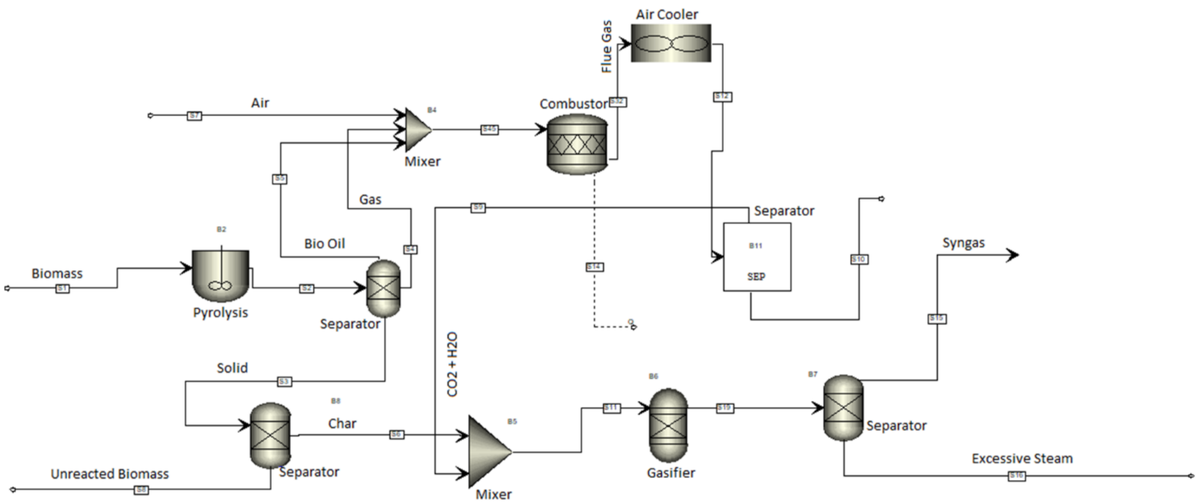

Figure 22. Aspen Plus configuration of overall biomass process

Within Aspen Plus, the separator and mixer block play pivotal roles in streamlining material separation processes. Additionally, an air cooler is strategically positioned downstream of the combustor to adjust the temperature of the flue gas, ensuring it aligns with the gasifier's operational specifications.

4.13 Heat Optimization

As previously discussed, the combustor serves as the primary source of heat for the entire system. Thus, ensuring adequate heat generation from the combustor is crucial for optimal system performance. The Table 14 outlines the optimal heat generation from the combustor and the heat requirements for the remaining two units.

Table 14. Heat and temperature for overall process

	Q (kW)	Temp (°C)
Heat Generated from Combustor	6,169	1,000
Heat Required by Pyrolysis	928	550
Heat Required by Gasification	4,765	800

The values in the table are intended for the full load operation of biomass power plant. From Aspen Plus simulation, it is acknowledged that combustor can supply the heat for the entire process.

4.14 Working Principal for Power Generation from Syngas Via Gas Turbine

The gas mixture derived from the gasification process is directed to a separator to produce clean syngas.This gas treatment process can be carried out using several technologies commonly used in the industry. The syngas cleaning process is one of the most significant and critical steps in the power generation process, as a lower impurity level in the syngas composition is essential to meet the operational requirements defined by the gas turbine manufacturer. This ensures the longevity of the turbine components. The final gas composition of syngas derived from the rice husk conversion process is presented in Table 15.

Table 15. Composition of derived syngas from rice husk

Type of gas	Molar fraction
CO	0.460923
CO_2	0.221883
H_2	0.316718
CH_4	0.000477

Since thesis focuses on electricity generation using gas turbines, the next step involves cooling the syngas and increasing its pressure before admission to the gas turbine. During the compression process, the syngas temperature increases rapidly and needs to be reduced. This temperature reduction is achieved through intermediate cooling processes. The pressure increase of the syngas is accomplished in three stages with intermediate cooling to manage the temperature rise and ensure efficient compression. For this purpose, three compressors and three air cooled heat exchangers are utilized after down stream of separator.Following Table 16 is presented fuction and propeties of the components.

Table 16. Parameter setup of the Syngas cooling and pressurization

component	Function	Propeties of outlet stream	
		Temperature (°C)	Pressure-bar
Air Cooler - 1	reduce temperature from 800 °C to 30 °C	30.00	1.0
Compressure - 1	Increase the pressure from 1 to 3 bar	149.70	3.0
Air Cooler - 2	Reduce the temperature to 30°C	30.00	3.0
Compressure - 2	Increase presure from 3 to 10 bar	163.06	10.0
Air Cooler - 3	reduce temperature to 30 °C	30.00	10.0
Compressure - 3	Increase the pressure from 10 to 17.5 bar	87.61	17.5

4.15 Gas Turbine

In a gas turbine, atmospheric air is admitted into the turbine compressor and then this air is compressed to a high pressure and high temperature.The modern compressors achieve compression ratios typically ranging from 10:1 to 30:1 and it depends on manufracture design. Increasing the air temperature is significant as it is compressed.

This compressed air is then directed into the combustion chamber. Inside the combustion chamber, treated syngas is injected and mixed with the compressed air. The syngas is supplied at a precisely controlled pressure to ensure optimal mixing and combustion. Igniters fixed in the combustion chamber initiate the combustion process making the fuel-air mixture to burn rapidly and completely. This combustion process generates high temperature with high-pressure exhaust gases. These high-energy exhaust gases are then directed through the turbine section. As the hot gases expand through the turbine blades, they impart kinetic energy to the blades, causing them to rotate. The turbine is connected to a shaft that drives the generator. The mechanical energy from the rotating turbine shaft is converted into electrical energy by the generator. The exhaust gases, after passing through the turbine, still possess a significant amount of thermal energy. These hot exhaust gases are then directed to a heat recovery steam boiler in a downstream of cycle. The general process flow is illustrated in the Figure 23, showing the integration of the gas turbine with a syngas fuel supply, combustion chamber, turbine section with electrical generator.

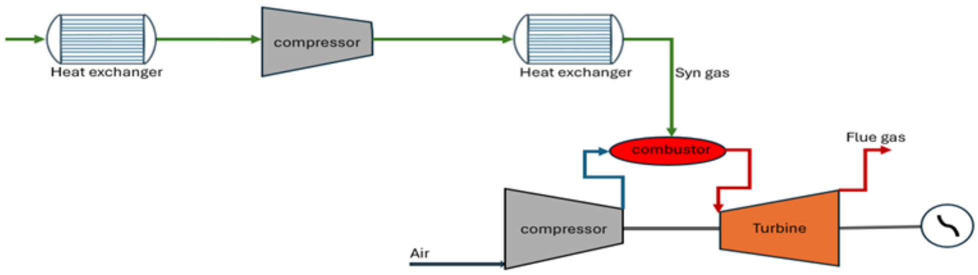

Figure 23.Electricity generation of gas turbine cycle

4.16 Heat Reocery Steam and Hot Air Generation.

The exhaust flue gas from the gas turbine which is still at a high temperature is directed to a fire tube boiler to generate the steam required for the paddy parboiling process.The boiler operates by directing the hot exhaust gases through a series of fire tubes submerged in water contained within the boiler shell.Flue gases transfer their heat to the water in the boiler and water convert into steam. This steam is then used in the paddy parboiling process.

The water fed into the boiler comes from a water storage tank. This tank is primarily filled with recycled water from various processes within the rice mill.Additionally, a fresh water supply line is connected to the storage tank to ensure to maintain water flow rate, especially when the demand for steam increases.To further optimize, the use of waste heat recovery system is integrated to generate hot air alongside steam production. After passing through the fire tube boiler, hot flue gases are directed to an air preheater. In the air preheater, the flue gases transfer their remaining heat to incoming air, which is then used for drying processes wet paddy and drying of rice husk feed stock before pyrolysis.Below Figure 24 illustrates the steam and hot air production process.

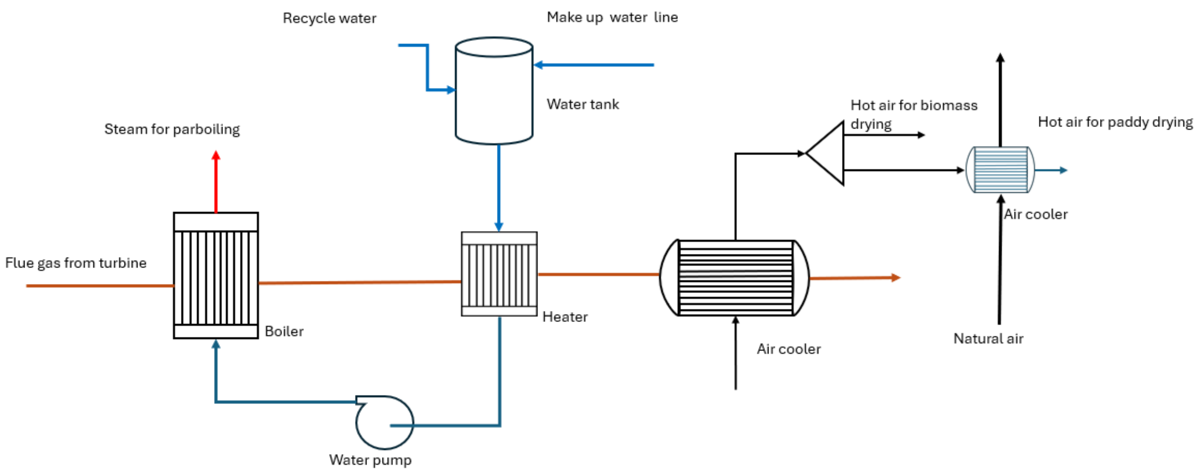

Figure 24. Heat recovery steam production cycle

4.17 Aspen Plus Model for Electrcity Generation

Preparation of syngas for gas turbine admission: In the Aspen Plus, 03 compressor(B 14,B 16,B 17) and 03 air coolers (B 9,B 10,B 12) are connected in series to pressurize and cool them before admit to combuster. The compressor block is labeled COMPR and the air cooler block is labeled AIRCOOLER in Aspen Plus. The parameters for all these components are set as shown in Table 17 and Table 18. The mass flow rate of the syngas into combustor is 7,016 kg/hr.

Compressor,combustor and Turbine: The temperature and pressure of the inlet air are specified in the stream settings. The pressure ratio of the compressors and their parameters are set according to Table 18. Both the isentropic and mechanical efficiencies of the compressors and turbines are considered to be 0.85 and 0.90 respectively.Since compressor exit pressure of air is at 14 bar,to proper mixing syngas with air in combuster,syn gas presure is set to 17.5 bar as per equation This setup ensures that the syngas is properly conditioned for efficient combustion and power generation in the gas turbine system.Flow sheet of aspen plus simuation circuit is presented in Figure 25.

$$P_{Syngas} = 1.25 \times P_{Exit\ compressor} \text{ (Bjäreborn and Åkerman, 2010)} \quad (5)$$

Table 17. Model setup of cooler block

Compenent name	Block ID	Set value for temperture (°C)	Valid phase
Air cooler	B 9	30	Vapor only
	B 10	30	
	B 12	30	

Table 18. Model setup of compressor and turbine

Component name	Block ID	Type	Discharge pressure(bar)
Compressure	B 14	Isentropic	3
	B 16		8
	B 17		17.5
	B 19		14
Turbine	B 22		1

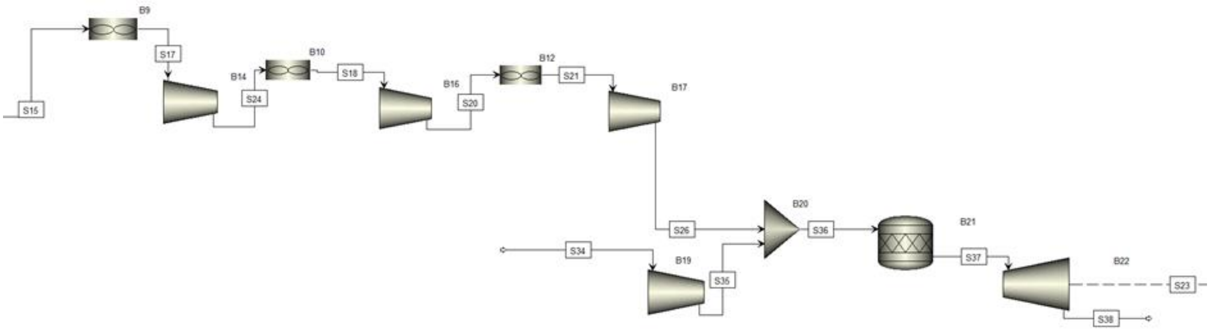

Figure 25. Model circuit of gas turbine cycle

Before admission to the combustor, the pressurized syngas and air are mixed using a mixer (B 20) in Aspen plua. This fuel-air mixture is then sent to the combustor (B 21). In Aspen Plus, the combustor is modeled as a reactor.In this moder,here it has used RStoic reactor block for combuster.specifically using the RStoic reactor block since the chemical reactions occurring in the reactor are known and detailed kinetics are not required. The setup parameters for the mixer and combustor are illustrated in Figure 26.

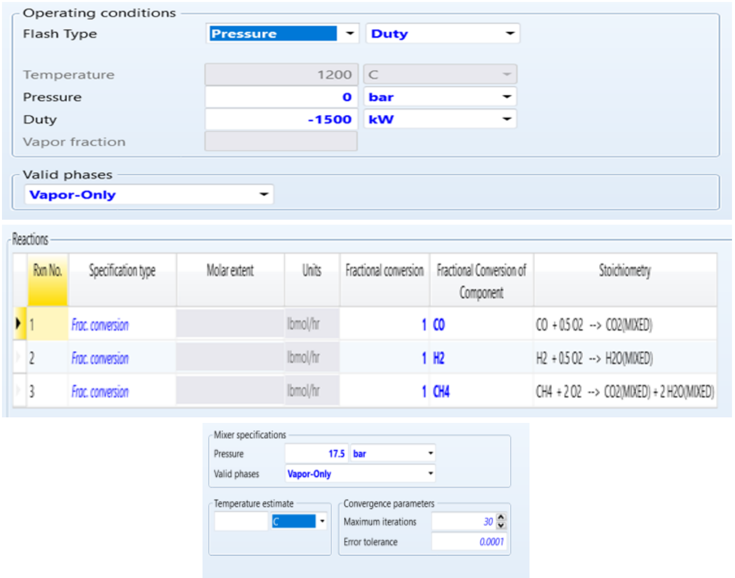

Figure 26. Input set up RStoic reactor,

To validate the gas turbine model, data referenced from the journal paper by (Niu *et al.*, 2021) and (Ong'iro *et al.*, 1995) were used for modeling and simulation. The relevant data are provided in Table 19.

Table 19. Gas turbine cycle validation data

Parameters	Value for model of syngas
Gas turbine inlet temperature (°C)	1,260
Gas turbine outlet temperature (°C)	578
Exhaust gas flow(kg/s)	60.5
Compressor pressure ratio	14:1

4.18 Aspen Modeling for Heat Recovery Steam and Hot Air Generation

To set up the model for a heat recovery steam generation circuit for the parboiling process in Aspen Plus, started by connecting the flue gas stream from a gas turbine to a HeatX block, which is configured as a fire tube industrial boiler. Intially it is defined the input stream with a temperature of 643°C and a mass flow rate of 52,016 kg/hr. Within the HeatX block, specifed the cold stream outlet temperature as 350°C and configured the block to generate steam with flow rate of 3,500 kg/hr. Block is modeled using the shortcut method and set the flow direction to counter-current for efficient heat transfer. Once the flue gas exits the HeatX block, connected it to a pre-heater to increase the temperature of water supplied from a reservoir tank up to 80°C. This involves defining a pre-heater block downstream of the HeatX, where the residual heat from the flue gas is used to pre-heat the incoming water. After the pre-heating step,utilized the pump block from the Pressure Changer group in Aspen plus to pump the pre-heated water at 80°C to the boiler at a pressure of 7 bar. This pump block should be configured to handle the specified conditions to ensure seamless integration into the system. By following these steps, the heat recovery steam generation circuit is effectively modeled in Aspen Plus achieving efficient energy utilization for the parboiling process. Figure 27 illustrates entire model circuit of steam production.

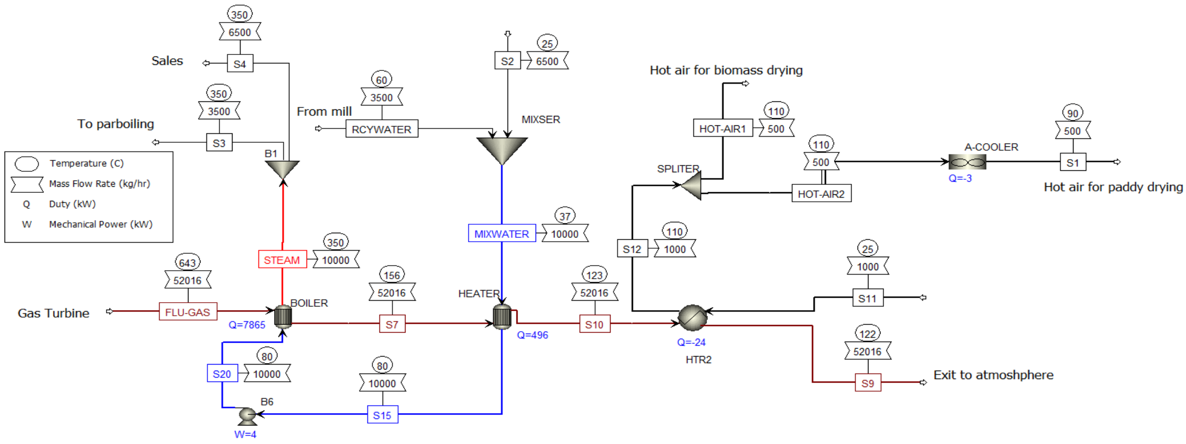

Figure 27. Model circuit of steam production

To set up the model for hot air generation for rice husk drying and paddy drying after the parboiling process in Aspen Plus, directed the flue gas stream arriving from the preheater another heater (HTR 2) selelcted from heat block in Aspen Plus and configured it with the input value for the cold side temperature set at 110°C and ensured the valid phase was set to vapor phase. Natural air at 25°C was introduced as stream S11 on the cold side, with the outlet stream set as S12. This outlet stream S12 was then connected to a splitter to divide the hot air stream into two lines. One of these streams was needed to control the temperature at 90°C for drying the paddy after parboiling. Figure 28 illustrates entire model circuit of hot air production.To achieve this, we connected an air cooler to this line to reduce the temperature. We ensured that all connections between blocks, such as heaters, pumps, air coolers, and the splitter, were accurately configured. Additionally, we set the appropriate thermodynamic models and properties for the flue gas, water, and air streams to ensure accurate simulation results.

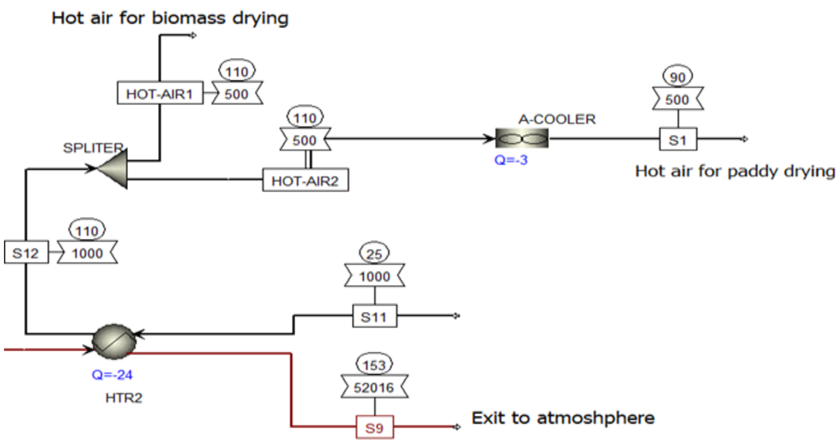

Figure 28. Model circuit of hot air production

4.19 Result and Discussion for Electricity Generation.

The study is aimed to target the power output of 5 MW. To achieve this, the power output was optimized using an Aspen Plus model simulation. Key parameters like turbine inlet temperature (TIT) is maintained within a range of 1200-1400°C, the mass flow rate of syngas is fixed to 7016Kg/hr and the air compressor inlet and outlet pressures are set at 1 and 14 bar respectively.

Figure 29 and Table 20 present the final optimized results of the gas turbine electricity generation cycle after simulation

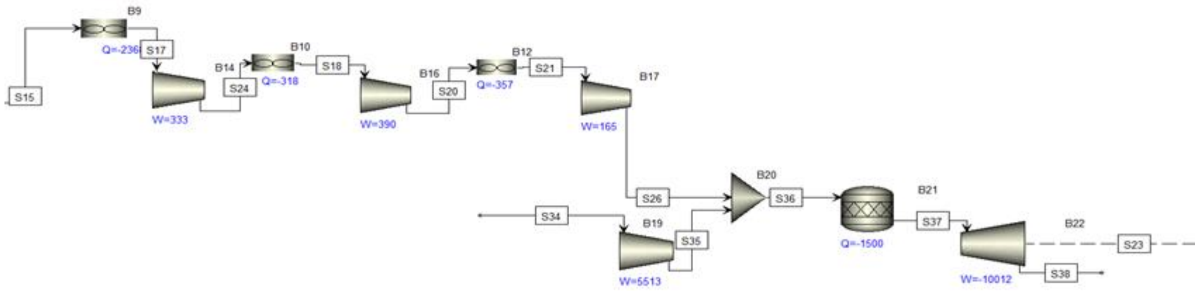

Figure 29. Model of the power generation with gas turbine

Table 20. Property setup of the power generation cycle

Description	**Value**
Turbine inlet temperature	1259 °C
Turbine outlet temperature	643 °C
Syn gas mass flow	7016 kg/hr
Syn Temp	87.61 °C
Syn gas pressure	17.5 bar
Air mass flow	45000 kg/hr
Air inlet temp	25 °C
Compressor outlet pressure	14 bar
Compressor outlet temperature	407 °C
Net power of Turbine	4499 kW

The investigation into optimizing the net power output of the gas turbine has focused on the effects of air inlet temperature. It has been observed that reducing the inlet air temperature results in a significant improvement in turbine power output. This enhancement is primarily attributed to the increased air density at lower temperatures, which, in turn, raises the mass flow rate of air through the turbine. This finding highlights an inverse relationship between ambient temperature and power output as illustrated in the Figure 30.

However, it's crucial to note that while lowering the inlet temperature boosts turbine power, the methods used to achieve this cooling such as installing chillers and other cooling accessories consume additional energy and it also leads increment in the work done by the compressor. Therefore, although there is an overall increase in turbine power output, the energy costs associated with these modifications must also be considered to accurately assess the net efficiency gain.

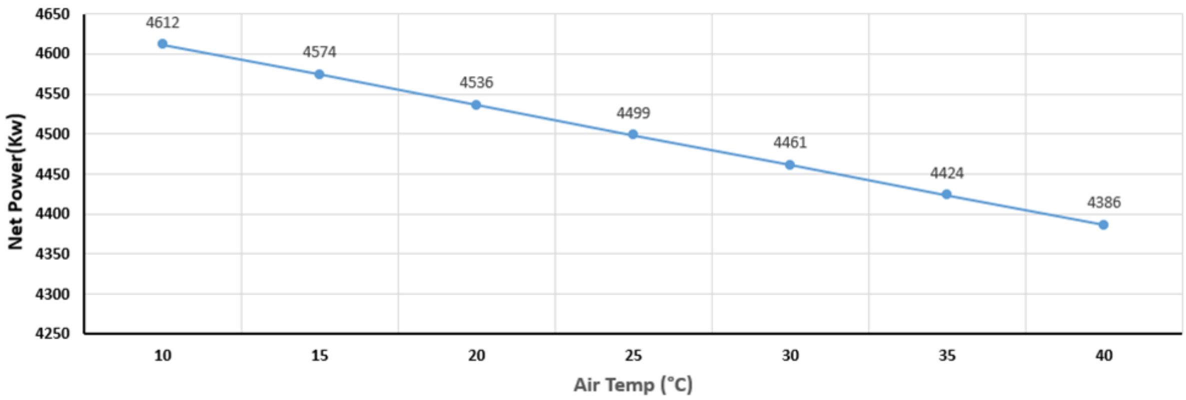

Figure 30. Turbine net power vs ambient air temperature

Furthermore, a simulated model was employed to conduct a detailed analysis of how variations in compressor airflow rates affect the inlet and outlet temperatures of the turbine, as well as the net power output. These changes were systematically examined to assess their impact on the turbine's thermal and mechanical performance.

Temperature variation: The simulation significantly shows that both the inlet and outlet temperatures of the turbine decrease as the airflow rate increases. This trend indicates an enhanced cooling effect due to the increased volume of air flowing through the turbine, which effectively dissipates heat.

Net Power Output: The turbine's net power output decreases with higher airflow rates. This reduction is directly linked to the lower temperatures at the turbine's inlet and outlet, which suggest a reduce the capacity for thermal energy conversion into mechanical power.

Figure 31 visually illustrates these relationships, clearly showing how both temperatures and net power output decreases as the airflow through the compressor increases.

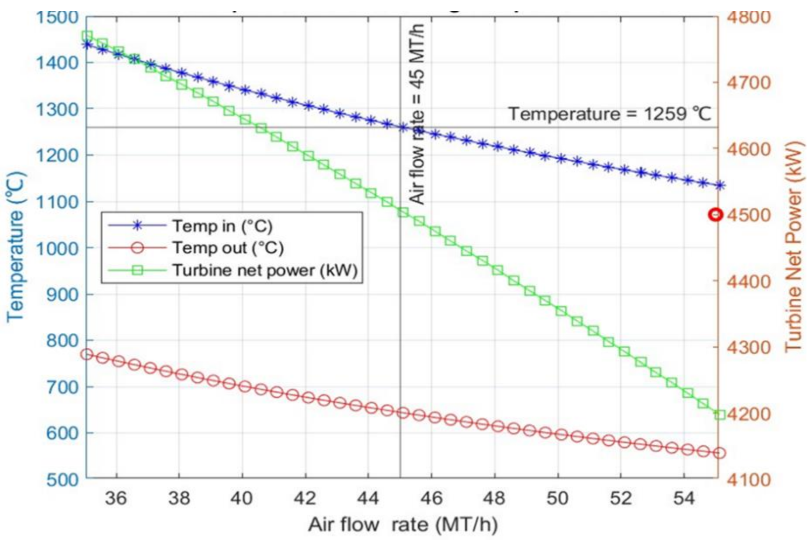

Figure 31. TIT, TOT and net power vs air flow rate

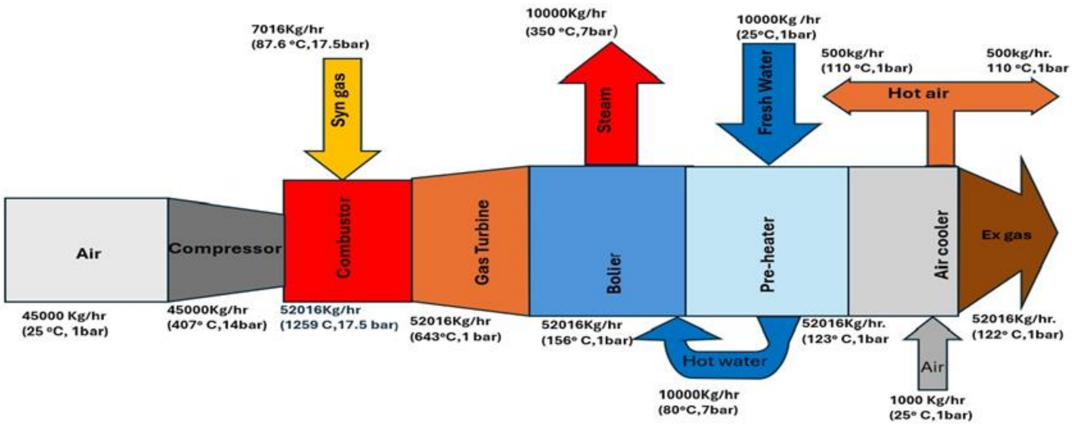

Figure 32. Sankey diagram of mass balance for gas turbine cycle.

Figure 32,Sankey diagram illustrates the mass balance of the gas turbine cycle. It visualizes the incoming mass flow of syngas and the optimized air intake values for the compressor as the initial input values at the beginning. Additionally, the diagram incorporates other crucial inputs, such as the mass of feed water and air, integrated at middle of the process of the cycle. This diagram clearly shows how mass flows are distributed and used within the system.

Table 21. Summary of overall result of electricity generation

Description	Value
Feed stock mass flow	5000 kg/hr
LHV of rice husk	13.6 MJ/kg (Rodrigo and Perera, 2014)
Equivalent value of 1 kW	3.6 MJ
Total energy mass flow	5000 × 13.6/3.6 kW
Compressor work done	5513 kW (as per simulation)
Gross power of turbine	10012 kW (as per simulation)
Net power of Turbine	**4499 kW** (as per simulation)
Mill demand at full load	1800 kW (from survey)
Possible supply for grid	**2474 kW**
Generator efficiency	95% (Assumed)
Electrical power out put	4274 kW
Conversion efficiency - Rice husk to electricity	**22.63 %**
Syngas LHV	7.74 MJ/kg (Michela Costa *et al.*, 2014)
Syngas flow rate	7016 kg/hr
Total energy in syngas	7016 × 7.74/3.6 kW
Combustion efficiency - syngas to electricity	**28.33 %**

The overall results indicate an efficient conversion of rice husk to electricity, with a conversion efficiency of 22.63%. The net power output of the turbine is 4,499 kW, while the mill's full load demand is 1,800 kW, allowing for a potential surplus of 2,474 kW to be supplied to the grid. The electricity output, considering a generator efficiency of 95%, amounts to 4,274 kW. Additionally, the syngas produces a total energy output that translates to a combustion efficiency of 28.33% when converting syngas to electricity. This showcases a robust system capable of converting biomass efficiently into electrical power.

4.20 Result and Discussion Heat Recovery Steam and Hot Air Generation

The simulation results show that using the high temperatures in turbine exhaust gases can efficiently produce the steam needed for mill operations. Further simulations were conducted to determine the maximum achievable steam output with increasing the feed water input which was identified to be 10,000 kg/hr. That means an excess of 6,500 Kg/hr steam can be produced from the cycle which can be sold out to other industries in the area. Figure 33 illustrates this analysis. This level of production does not adversely affect the generation of hot air downstream, indicating an optimal balance in the system's operations. This optimal steam generation is achieved through precise management of the feed water flow rate. Additionally, the results indicate that the production of hot air can be further increased since the availability of sufficient exhaust gas mass flows in the system and maintaining a certain temperature upstream of the air cooler.

These findings highlight the considerable potential to fine-tune heat recovery processes, enabling the maximization of both steam and hot air production simultaneously. This optimization contributes to significant improvements in the overall energy efficiency of the system, underlining the value of integrated heat recovery solutions in industrial settings.

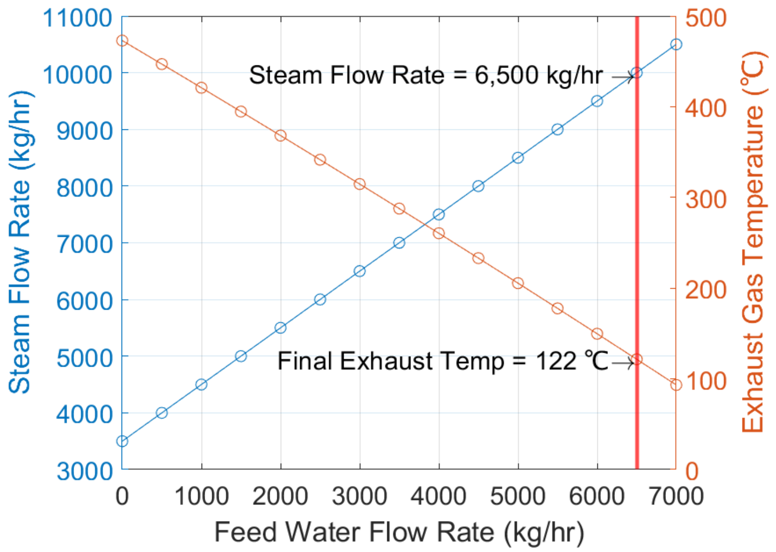

Figure 33. Steam production with feed water input.

5 Conclusion

The RCSTR (Pyrolysis) reactor's production of Bio-char, Bio-oil, and pyrolyzed gas is vital for biomass conversion. Optimizing gas production ensures sufficient heat for pyrolysis and gasification, while Bio-char supports steam gasification. Lower temperatures yield more Bio-char but less gas, affecting heat supply.

An optimal temperature of 550 °C balances gas and Bio-char production, ensuring adequate heat generation. A correct air-fuel mixture, with an optimal air flow rate of 15,500 kg/hr, is crucial for efficient combustion. The integrated operation of pyrolysis, combustion, and gasification units forms an equilateral triangle, dynamically adjusting to power requirements. The system achieves a 34% conversion rate of rice husk to syngas at full capacity.

Syngas cleaning, essential for power generation, ensures low impurity levels and prolongs turbine life. The cleaned syngas is cooled and compressed in three stages before entering the gas turbine, where it is mixed with compressed air and combusted to generate electricity. Hot exhaust gases from the turbine produce steam for the paddy parboiling process, optimizing thermal energy use.

The system's efficiency, demonstrated by Aspen Plus, ensures reliable power generation and process heat supply. The turbine's net power output is 4499 kW, with a surplus of 2474 kW for the grid. The conversion efficiency of rice husk to electricity is 22.63%, with a combustion efficiency of 28.33%. This system effectively converts biomass into electrical power and process heat, contributing to sustainable energy generation.

To optimize rice husk power generation using pyrolysis and gasification, maintain an optimal reactor temperature of 550°C to balance Bio-char, Bio-oil, and pyrolyzed gas production. Precisely regulate the air-fuel mixture in the combustor, with an optimal air flow rate of 15,500 kg/hr, for efficient combustion. Integrate pyrolysis, combustion, and gasification units efficiently to ensure system stability and optimization. Use Aspen Plus simulations to fine-tune parameters, ensuring the combustor meets heat demands and reprocess minor unreacted solids. Ensure syngas pressurization and cooling through three stages of compressors and air coolers for efficient combustion in the turbine, maximizing power generation. However, to sustain power plant operations for 20 hours, an additional 20 MT/day of rice husk must be sourced from other mills, supplementing the 80 MT/day produced in-house. This ensures a consistent supply of biomass, maintaining efficient power generation and meeting the energy demands of the rice mill.

6 Future Recommendations

The simulation process primarily relies on theoretical models. Consequently, this conceptual process design can evolve into an applied process system for future studies. The research will proceed as outlined below:

- Essential investigation into practical heat transfer mechanisms or process designs is crucial to supply heat effectively from the combustor throughout the entire system.

- Advanced analysis using Computational Fluid Dynamics (CFD) will further study the heat control system to ensure the requisite amount of heat is supplied for both pyrolysis and gasification.

- Detailed process designs for phase separation units and the syngas treatment system are also imperative aspects of the research agenda.

Apart from the biomass conversion, investigating whether rice husk can serve as a pivotal resource for alleviating energy poverty in developing countries necessitates comprehensive evaluation. This study will explore the viability of utilizing rice husk as a sustainable energy source, considering its abundance and potential for conversion into useful energy products. By assessing technological feasibility, economic viability, and environmental impact, this research aims to determine the role rice husk can play in empowering communities and facilitating energy independence in resource-constrained regions.

7 Reference

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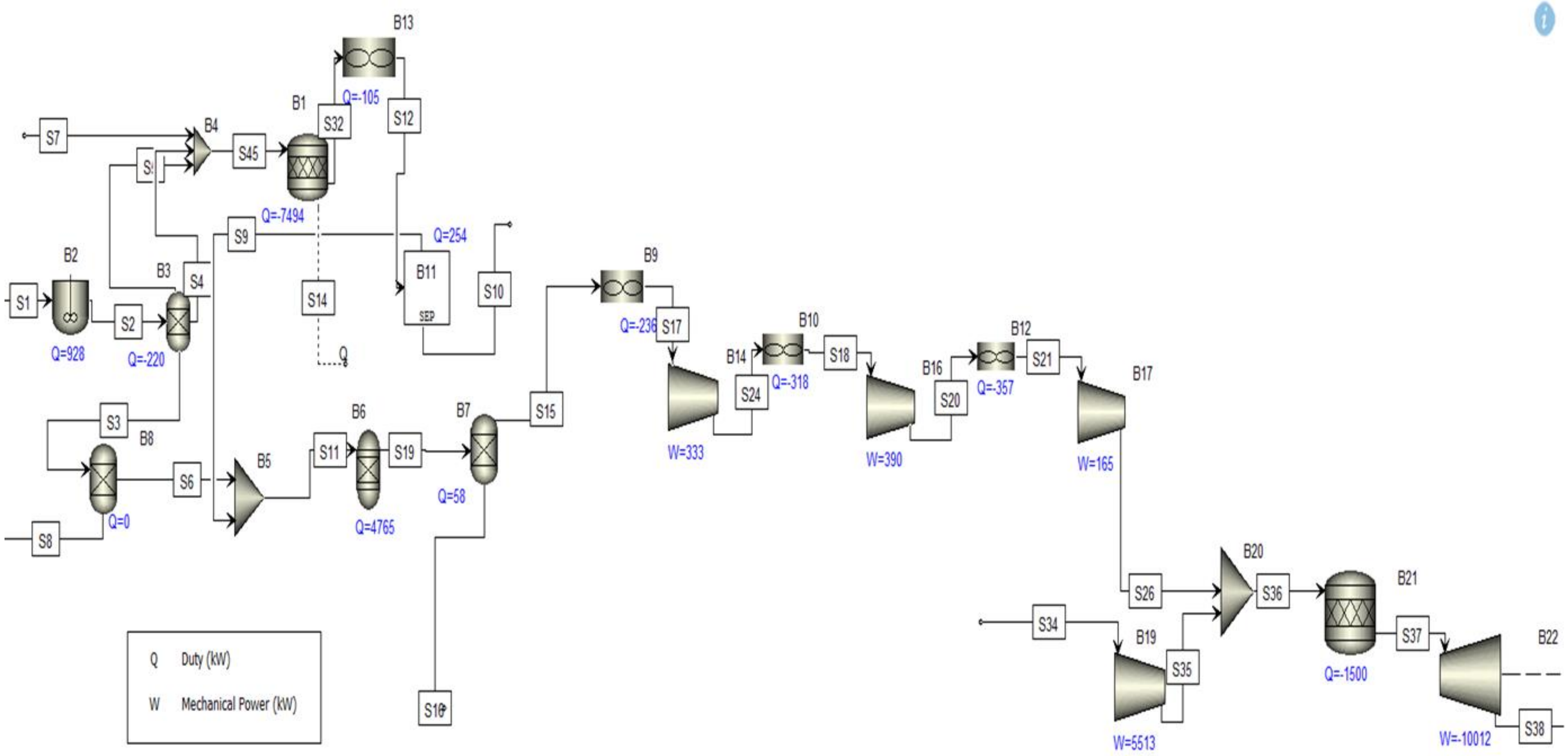
8 Appendices

8.1 Appendix A: Aspen Plus Model Circuit for Rice Husk Conversion and Electricity Generation



8.2 Appendix B:

8.2.1 Monthly Electricity consumption with energy Cost of the Mill in 2023

Table 22. Electricity cost of New Rathna Mill in year 2023 – industrial rate 3 category

Months	kVA charges			kWh (D)			kWh (O)			kWh (P)			Total energy (MWh)	Total (Rs)	Total (USD)
	Max Apparent Power	Rate (Rs)	Total (Rs)	Units (kWh)	Rate (Rs)	Total (Rs)	Units (kWh)	Rate (Rs)	Total (Rs)	Units	Rate (Rs)	Total (Rs)			
Jan	1,872	1,400	2,620,800	325,344	28	9,109,632	192,984	14	2,701,776	84,252	34	2,864,568	602.58	17,296,776	54,563.96
Feb	1,776	1,500	2,664,000	423,540	36.5	15,459,210	255,816	33.5	8,569,836	119,160	39.5	4,706,820	798.52	31,399,866	99,053.21
Mar	1,848	1,500	2,772,000	472,740	36.5	17,255,010	295,476	33.5	9,898,446	157,632	39.5	6,226,464	925.85	36,151,920	114,043.91
Apr	1,704	1,500	2,556,000	266,280	36.5	9,719,220	154,140	33.5	5,163,690	94,176	39.5	3,719,952	514.60	21,158,862	66,747.20
May	1,776	1,500	2,664,000	394,332	36.5	14,393,118	238,200	33.5	7,979,700	133,092	39.5	5,257,134	765.62	30,293,952	95,564.52
Jun	1,689	1,500	2,533,500	335,448	36.5	12,243,852	172,800	33.5	5,788,800	97,332	39.5	3,844,614	605.58	24,410,766	77,005.57
July	1,752	1,500	2,628,000	410,304	33	13,540,032	254,964	28	7,138,992	143,208	36	5,155,488	808.48	28,462,512	89,787.10
Aug	1,680	1,500	2,520,000	405,048	33	13,366,584	235,092	28	6,582,576	131,916	36	4,748,976	772.06	27,218,136	85,861.63
Sep	1,764	1,500	2,646,000	381,516	33	12,590,028	246,132	28	6,891,696	139,668	36	5,028,048	767.32	27,155,772	85,664.90
Oct	1,716	1,680	2,882,880	369,600	37	13,675,200	240,912	31	7,468,272	140,520	40	5,620,800	751.03	29,647,152	93,524.14
Nov	1,824	1,680	3,064,320	410,326	37	15,182,062	283,452	31	8,787,012	153,816	40	6,152,640	847.59	33,186,034	104,687.80
Dec	1,836	1,680	3,084,480	460,994	37	17,056,778	286,704	31	8,887,824	155,892	40	6,235,680	903.59	35,264,762	111,245.31

8.3 Appendix C:

8.3.1 Initial Plant Size Calculations

Paddy processing capacity in full load operation: 400MT

Husk to paddy ration: 20%(Rodrigo and Perera, 2014)

Rice husk to electricity conversion ratio : 15% (Rodrigo and Perera, 2014)

Lower heating value of the rice husk: 13600MJ/MT

Operating hour of the plant: 20 hrs per day

Energy potential of rice husk: 400 × 0.20 × 13600 MJ= 1088000MJ

Conver to kWh: 1088000 MJ / 3.6 (3.6 MJ= 1 kW)

Initial estimated plant capacity:(302222.22 kWh x 0.15)/20h =2266.67 kW electricity

Focusing to **3MW** Capacity

8.3.2 Rice Husk Electricity Potential in Polonnaruwa area

Total paddy production in year 2022: 222,414(Yala) and 271,33 (Maha)-493,727 MT

Expected rice husk qty: 98,745.4 MT

Energy Potential of rice husk: 98,727 MT × 13600 MJ/MT-1,342,937.440 MJ

Convert to kW: 1,342,937,440 MJ ÷ 3.6 -373,038,177.8 kW

Expected electricity yield: 373,038,177.8 × 0.15 **-55.95 GWh**

8.3.3 Rice Husk Electricity Potential in the Mill(New Rathna Rice Mill)

Mill rice husk production daily: 80MT

Energy Potential of rice husk: 80 MT × 13600 MJ/MT -1088000 MJ

Convert to kW: 1,088,000 MJ ÷ 3.6 – 302,222.22 kW

Expected electricity yield: 302,222.22 × 0.15 **-45.33 MWh per day**

8.3.4 Calculating Steam Requirement for Parboiling Process of Mill

Steam requirement for 1000 kg paddy: 190 kg (As per the survey)

Ration of production parboiling rice: 80%

Total steam requirement: 190 × 400 × 0.80 = 60,800 kg

Steam mass flow rate: (60,800 kg/hr) / 20 hr = 3,040 kg/hr

Consider requirement as **3,500 kg/hr**

8.3.5 Rice Husk to Electricity Conversion Efficiency

Optimized input of Rice Husk: 5,000 kg/hr

Energy yield of Rice Husk: 5,000 × 13,600 MJ/kg

Convert to kW: (5,000× 13,600) ÷ 3.6 = 18,888,888.89 kW

Generator efficiency: 95 %

Electricity Output: 4,499 ×0.95 = 4,274 kW

Conversion efficiency: **22.63%**

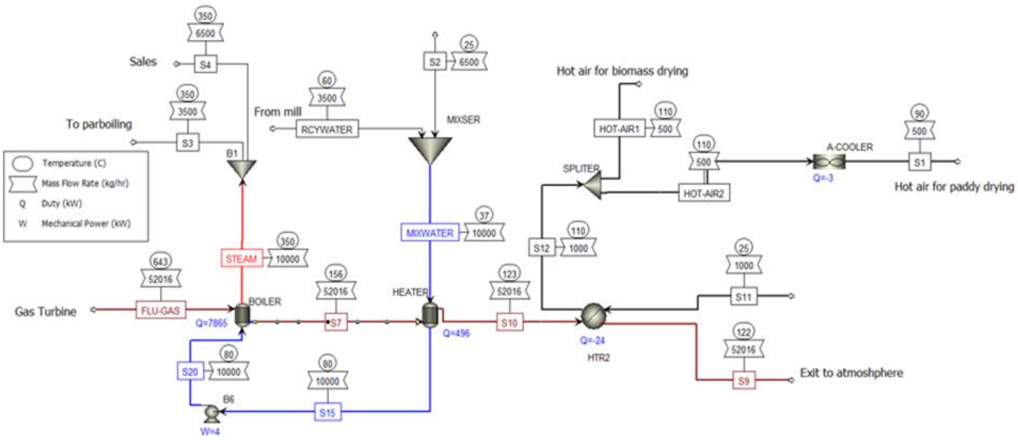
8.3.6 Combustion Efficiency - Syngas to Electricity

Syngas flow rate: 7,016 kg/hr

LHV of Syngas: 7.74 MJ/kg

Combustion efficiency: 4,274 ÷ (7,016 × 7.74 ÷ 3.6) = **28.33%**

8.3.7 Heat Recovery Steam and Hot Air Generation Aspen Plus Circuit



8.3.8 Questioner of Chief Engineer -New Rathna Rice Mill

<u>Questioner form for survey-New Rathna Rice Mill ,Sri Lanka</u>

Master Thesis Project- Sustainable Energy Engineering Course 2022-2024,
Lund University, Sweden.

Title: Electricity and process heat generation from rice husk derived Syngas and biochar utilizing pyrolysis and gasification technologies in a Sri Lankan rice mill

Date: **24th February 2024**

Interviewer:

1. Name: **KADBP Nanayakkara**
2. Designation: **Chief Engineer**
3. Telephone :**+94779675124**
4. Email Id:**bernardpna@gmail.com**

General details

1. Total Capacity of paddy processed in the mill (ton/day): **400MT**
2. Number of operating days per year (days): **30 X 12**
3. Working hours per day: **20 hrs**
4. How many quantity of rice husk produced per day if mill operate full capacity **(Approx):80-90MT**
5. What are main methods of rice production in your mill(parboil/ raw rice): **parboiling 80% and raw 20%**
6. How much of electricity power required for full load mill operation: **2 MW.**
7. Paddy storing capacity: **42000MT**
8. How many no's of silos available in the mill: **9 silos**
9. Possibility of buying rice husk from outside: **yes it can be purchased from outside within close proximity in the area and having big potential availability**

Details for existing steam generation for mill

1. For which processes steam and hot water required in the mill: **By using boilers, directly get the steam and and steam mix with water in the tank and get hot water.after normal water soaking and hot water soaking is done and then steaming the paddy**
2. Which technologies do you use for existing boilers in the mill: **Fire tube**
3. How many boilers your mill have: **6 no's of 6TPH , 7-8 bar, temperature 350°C**
4. What is combustion method of fuel: **direct combustion of rice husk**

5. How many quantity of rice husk daily used for boiler: **approximately 30-35 MT**
6. Approx steam weight/ volume required for 1 MT of paddy : **3.42 kg/m^3 (190Kg for 1000 kg paddy)**
7. Source of feed water supply and disposal method:
   i. Quantity required for daily fresh water : **400 m^3**
   ii. Any treatment of water: **yes aerobic and anaerobic waste water treatment**

8. Rice husk production monthly basis quantity for one year.(Jan- dec 2023).

Jan: 2170MT	Feb: 1080MT	Mar:1630 MT	Apr:1630MT
May: 1080MT	June: 1080MT	July: 1080 MT	Aug:1080MT
Sep: 1080MT	Oct: 1080MT	Nov:1630MT	Dec: 2170 MT

9. Can you explain the parboiling method used in your rice mill in few words:

   First fresh water soaking 24hrs and paddy transfer to hot ater tank for 1-2 hrs hot water soaking and then steaming with 1-2 hrs and drying paddy with hot air.

   Soaking: **normal water 25°C, 24hrs duration,80 °C hot water 1hrs duration.**

   Steaming: **160° C steam,6 bar pressure,1-2hrs duration**

10 Current drying method used for paddy: hot air blower system, temperature **70-90 C and 1-2 hrs. duration.**

Date:24th Feb 2024

Signature:

8.3.9 Questioner of Subject Matter Officer -Agriculture Department of Sri Lanka

Questioner form for survey of Rice production in Polonnaruwa District in Sri Lanka

Master Thesis Project- Sustainable Energy Engineering Course 2022-2024,
Lund University, Sweden.

Title: Electricity and process heat generation from rice husk derived Syngas and biochar utilizing pyrolysis and gasification technologies in a Sri Lankan rice mill

Date:

Interviewer:

1. Name: KAK Premarathne
2. Designation: Subject matter Officer (Paddy) ,Department of Agriculture Department, North central Province
3. Telephone :+94718319227
4. Email Id:kakpremarathne@gmail.com

General details

1. How many metric tons of paddy production in Polonnaruwa District in year 2022/2023?

   Yala 2022- 222414 MT and Maha 2022/2023-271313 MT as per department of census Sri Lanka
2. How many hectares of land are used in paddy cultivation in Polonnaruwa district in year 2023? Approximately 71000 hectares
3. How many rice mills are available in Polonnaruwa district approximately?

   As per Harti survey in year 2019, there are 03 rice mill in 400MT capacity,03 rice mills in 150MT,04 rice mill in 75MT capacity,05 medium rice mill in 40MT capacity and 86 rice mill in 10MT capacity in Polonnaruwa. Approximately total 105 rice mills are available in the area.
4. What are the main usages of rice husk produced from Mills in area?

   Big rice mills mainly use rice husks as fuel for their boilers. They sell other extra husks to a cement factory in Trincomalee, brick makers, poultry feed producers and farmers who use them as fertilizer. Small mill owners often burn the remaining husks in open fields.
5. How much rice production contribute from Polonnaruwa area to Sri Lanka?

   50% rice production in Sri Lanka is taken placed in mills in Polonnaruwa and mega rice mill purchase paddy from adjacent district farmers and supplier, and they are keeping big share in rice market.
6. Is it rice husk abundant in this district for collection?

   Yes, special we can collect rice husk from medium and small rice mill easily, but 50% rice husk produced from big rice mill, they use for their boilers.
7. How many rice mills produce electricity from their waste rice husk in Polonnaruwa?

   Only Nipuna rice mill has a steam power generation plant and other rice mills depend on national grid.