Retrofitting Coal Plants for Biomass Energy Technical and Economic Potential in Indonesia

MSc SET Thesis Project

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Retrofitting Coal Plants for Biomass Energy Technical and Economic Potential in Indonesia

Thesis report

by

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Preface

As I dive into this exciting research journey, I'm filled with enthusiasm and a clear purpose to explore biomass co-firing in Indonesia. The motivation behind this report is to bridge a crucial knowledge gap that's holding back progress in sustainable energy practices in the country. With a strong passion for sustainable energy, my aim is to assess the techno-economic potential of retrofitting existing coal-fired power plants (CFPPs) for biomass co-firing.

Throughout this thesis, my main goal is to find the most available biomass residues suitable for co-firing, evaluate the feasibility of retrofitting CFPPs through technical assessments, and explore the economic viability of these implementations. I strive to provide valuable insights and recommendations to the Indonesian Ministry of Energy and Mineral Resources, advocating for greener energy policies.

This report is the result of countless hours of meticulous research and thoughtful considerations. I want to express my heartfelt gratitude to Professor Kornelis Blok for his invaluable guidance during my thesis work. Special thanks to Professor Wiebren de Jong for the helpful feedback, Dr. Mar Perez for her continuous support and insights and Priscilla for helping me schedule all my meetings. I'm also grateful for the encouragement from my friends and family throughout this academic journey.

I'm excited to present the findings of this research, knowing that there may be challenges and limitations to address. Nonetheless, I'm committed to contributing to the advancement of biomass co-firing practices in Indonesia. With the urgency to combat climate change and embrace sustainable energy, I'm hopeful that this report will spark positive change and pave the way for a greener, more resilient future for Indonesia and beyond.

Yasmin Fauziah

Executive Summary

The energy sector contributes around 75% of global greenhouse gas emissions. Indonesia ranks twelfth in energy consumption and ninth in global carbon dioxide (CO_2) emissions from fuel combustion. Expected economic growth will drive a 3.5% annual rise in energy consumption. Coal represents 50% of Indonesia's electricity generation capacity, producing 31.5 EJ annually and emitting 3 kton CO_2/ kton coal. Despite being a major coal producer, Indonesia aims for net zero emissions by 2060, reducing carbon emissions by 29% by 2030.

Biomass energy in Indonesia, traditionally for cooking, has expanded in the New and Renewable Energy (NRE) sector with sustainable biofuel and biogas. Biomass potential is estimated at 32.6 GW, and co-firing offers a sustainable avenue for biomass residue utilization. Pilot projects by Perusahaan Listrik Negara (PLN) to retrofit coal plants for biomass co-firing have made limited progress, with co-firing percentages below 20%, and coal remaining dominant.

This report aims to bridge a significant knowledge gap that hinders the progress of biomass co-firing in Indonesia. Its primary objective is to assess the techno-economic potential of retrofitting existing CFPPs in Indonesia for biomass co-firing. The assessment will involve identifying the most abundant biomass residues suitable for co-firing, exploring various retrofit scenarios based on technical considerations, conducting an economic feasibility analysis of CFPP retrofitting, and proposing policy recommendations for Indonesia's Ministry of Energy and Mineral Resources.

The study found that agricultural by-products account for 70% of available biomass, followed by forestry residues (17%) and Municipal Solid Waste (MSW) (13%). Among agricultural residues, rice, and palm oil residues exhibit the highest potentials, with 0.49 EJ and 0.29 EJ respectively. In terms of forestry residues, solid and sawdust residues from pulpwood and sawn wood lead with potentials of 0.098 EJ and 0.078 EJ respectively.

The technical potential for co-firing was estimated at 450 TWh, which is equivalent to the estimated electricity demand in 2030. Practical implementation necessitates further exploration, with proposed CFPP retrofit scenarios based on co-firing percentages. These scenarios encompass pre-treating biomass through drying and pelletizing before combustion. For co-firing up to 10%, minimal modifications allow co-milling with coal and have minor effects on boiler efficiency. Co-firing between 20-50% demands separate biomass milling and storage due to potential equipment efficiency reduction. Co-firing at 50% or higher entails extra boiler modifications addressing heightened fouling and slagging risks due to biomass's higher inorganic content. These strategies are designed to optimize co-firing efficiency with varying biomass proportions.

Utilising the Levelised Cost of Electricity (LCOE) methodology, the assessment of economic potential yielded a range of outcomes spanning from 2.2 to 10 $c/kWh, based on two distinct case studies. In Case Study I, an investigation into the LCOE of a 200MW CFPP located in West Kalimantan, employing Palm Kernel Shells (PKS), was conducted. In Case Study II, a 600MW CFPP utilizing rice husks in West Java was investigated. Additionally, the LCOE results spanned a range due to two distinct scenarios—one accounting for the initial investment cost of the CFPP and the other excluding it. This broad range in LCOE is attributed to these variations and the fluctuation in low-end and high-end biomass feedstock prices. Among these fluctuations, the minimum LCOE was observed in Case Study I at the 10% co-firing level without factoring in the investment cost and considering the low-end PKS price. On the other hand, the maximum LCOE was recorded for the same case study at a 50% co-firing level, considering both the investment cost and high-end PKS price.

The LCOE range is comparable to the values of sub-critical/ultra sub-critical coal plants indicating the economic feasibility of co-firing in Indonesia. For plant sizes from 30 to 1000 MW, LCOE remained below the national Biaya Pokok Produksi (BPP) or cost of electricity value for most co-firing mixes, except for 50% co-firing with high-end feedstock prices.

Policies to support co-firing include a substantial carbon tax, redirecting coal subsidies, and promotion of biomass utilization. Improving the supply chain involves identifying biomass sources near coal mines and enhancing transportation infrastructure for a stable biomass supply.

Limitations stem from simplified input variables for potential calculations derived from literature review, with constraints in representation and data sources. Challenges emerge in logistics, pelletizing, coal input, LCOE modeling, and potential calculations. However, these constraints don't necessarily invalidate the research, as it employs dynamic approaches, presenting result ranges and considering diverse scenarios to enhance outcome validity.

To promote biomass co-firing in Indonesia's CFPP, the following recommendations are suggested: prioritize the utilization of agricultural residues like palm kernel shells, rice husks, and sawdust residues; stabilize biomass fuel prices through domestic market obligations similar to coal; introduce pre-treatment of biomass before transportation to enhance efficiency; and provide electricity tariffs for CFPPs co-firing above 50% to meet national BPP and encourage greater adoption of renewable energy. Implementing these measures strategically could significantly enhance the integration of sustainable biomass co-firing practices in Indonesia's energy sector.

Contents

Nomenclature

List of Abbreviations

ASTM American Society for Testing and Materials

BPP Biaya Pokok Produksi

CFB Circulating Fluidised Bed

CFPP Coal-Fired Power Plant

CHP Combined Heat and Power

CSI Case Study 1

CSII Case Study 2

DMO Domestic Market Obligation

GIS Geographic Information System

HGI Hardgrove Grindability Index

HTI Industrial Forest Plantations

IEA International Energy Agency

IESR Institute for Essential Services Reform

IPP Independent Power Producers

IRENA International Renewable Energy Agency

JIS Japanese Industrial Standards

LCOE Levelised Cost of Electricity

MEMR Ministry of Energy and Mineral Resources

MSW Municipal Solid Waste

NRE New and Renewable Energy

O&M Operation and Maintainence

PC Pulverised Coal

PKS Palm Kernel Shell

PLN Perusahan Listrik Negara

PPA Power Purchase Agreements

ROC Renewable Obligation Credits

RUPTL Rencana Usaha Penyediaan Tenaga Listrik

SDE Sustainable Energy Production and Climate Transition Subsidy Scheme

SRF Solid Recovered Fuel

UK United Kingdom

US United States

List of Symbols

α Availability Factor (-)

β Co-firing mix (-)

η Thermal Efficiency (-)

ϕ Consumption in kWh/kg

ρ by-product density (tons/m^3)

C Cost ($)

c crop by-product ratio (-)

Ce Cost per kWh ($/kWh)

CF Capacity Factor (-)

Cl Cost per litre ($/litre)

Ct Fuel Cost per ton ($/ton)

Cy Cost per year ($)

D Travel Distance (km)

E Energy Production (MWh/year)

F Fuel Cost ($/year)

FE Fuel Economy (km/litre)

I Investment Cost ($)

k wood by-product ratio (-)

LHV Lower Heating Value (MJ/ton)

M Maintenance Cost ($/year)

Mw Moisture Content (-)

N Number (-)

OH	Operational Hours (hours)
P	Annual Resource Production (tons, m^3)
P	Fuel Quantity (ton/year)
PC	Plant Capacity (MW)
Q	Biomass Potential (MJ)
r	Discount Rate (-)
r	wood by-product ratio (-)
S	Wage ($/month)
V	Consumption rate in litre/day
Xd	Capacity (ton/day)
Xt	Capacity (ton)

List of Subscripts

A	Available
AC	Agriculture
b	Biomass
c	Coal
co	Co-firing
d	Diesel
E	Technical
el	Electricity
F	Forestry
L	Logistics
M	Machine
O	Operational
P	Pre-treatment
R	Raw Feedstock
RT	Round Trip
S	Personnel
T	Theoretical
$trans$	Transshipment
v	Truck
var	variable
W	Waste

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1
Introduction

1.1. Current Renewable Energy Situation in Indonesia

The energy sector is responsible for around three-quarters of today's global greenhouse gas emissions. Indonesia is the twelfth largest energy consumer and the ninth largest emitter of CO_2 from fuel combustion in the world. With the expected economic growth over the next decades, it is projected that the country's energy consumption will rise by 3.5% per year (IRENA, 2022). Coal energy represents 50% of the total installed capacity for electricity generation, with a production of 32 EJ per year and 3 kton CO_2/ kton coal emitted (IEA, 2019; Damayanti and Khaerunissa, 2018). Moreover, Indonesia is one of the largest coal producers worldwide and the largest in the Association of Southeast Asian Nations region. Nevertheless, Indonesia remains committed to its goal to become net zero by 2060 and reduce 29% of its carbon emissions by 2030 (IRENA, 2022).

Additionally, biomass energy has been utilised in Indonesia traditionally as wood burning for cooking in households. Although, it has recently increased its share in the NRE sector as sustainable biofuel and biogas (IRENA, 2022). Indonesia - with a surface area size of 1.9 million square meters, has a vast land area for biomass materials which include palm kernel shells, wood pellets, waste, etc. Moreover, the biomass potential is expected to be 32.6 GW (Primadita et al., 2020). Currently, there have been several pilot projects that convert coal plants to co-firing biomass undergone by PLN which has a monopoly on electric power distribution in Indonesia and generates the majority of the country's electrical power (IRENA, 2022).

However, co-firing still includes a percentage of coal being combusted, which is not ambitious enough to meet the net zero emission target. Only two projects have been conducted in which 100% biomass has been used which was described as High Co-Firing (Prakoso, 2022). Nonetheless, such projects exhibit the motivation of Indonesia to substitute non-renewable primary energy sources such as coal for NRE.

1.2. Background of Technology

Biomass co-firing refers to the simultaneous combustion of biomass and fossil fuels in a power plant. The process involves the addition of a certain percentage of biomass, such as wood chips, agricultural residues, or dedicated energy crops, to the fuel mix that is typically made of fossil fuels, such as coal or natural gas. The percentage of biomass that is co-fired with fossil fuels can vary. The report from IRENA (2022) identified that existing co-firing programs in Indonesia have a thermal mix range of 5% - 20 % biomass. Co-firing can be achieved through various methods, such as blending the biomass with the fossil fuel before combustion, or by feeding the biomass directly into the power plant's boiler alongside the fossil fuel. The schematic of co-firing can be seen in Figure 1.1. In this report, co-firing is discussed in terms of thermal mixing ratios.

Additionally, the biomass can undergo **pre-treatment options** to further decrease moisture content and increase its bulk density. This allows for convenient transport and storage of biomass, as well as enhances the fuel quality when burning. In Indonesia, the current pre-treatment options include pelletizing, pyrolysis, gasification, and hydrothermal treatment (Aktawan et al., 2020).

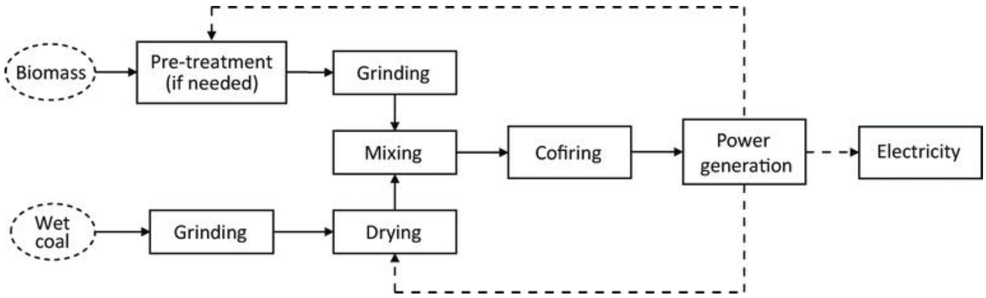


Figure 1.1: Schematic of biomass co-firing retrieved from Darmawan et al. (2018)

Retrofitting coal plants refers to the process of modifying existing CFPPs to allow for the simultaneous combustion of biomass and coal. The process of retrofitting typically involves modifying the plant's boiler, fuel handling & storage systems, and emission control equipment to accommodate the new fuel source (Hansson et al., 2009). Additionally, co-firing can also provide a market for agricultural and forest residues, which can help to reduce waste and support rural economies. Furthermore, the availability and cost of biomass, the technical compatibility of the biomass with the power plant, and the potential for increased emissions of pollutants must be considered (IEA, 2012).

Moreover, the study focuses on assessing technical and economic potential and therefore, the definitions will be outlined to ensure clarity. According to Blok and Nieuwlaar (2016), **theoretical potential** refers to the potential that is restricted by physical constraints such as natural energy flows and available reserves. **Technical potential** is the contribution that could be made by the technologies assumed to be available in a certain year. To determine the technical potential, practical constraints are taken into account, such as the thermal efficiency of a conversion technology. **Economic potential** is defined as the part of the technical potential that is economically attractive from a social perspective. In this study, the economic potential will include calculating the LCOE, which will be described in further detail in Chapter 7. The relation between the three types of potential for biomass energy is depicted in Figure 1.2.

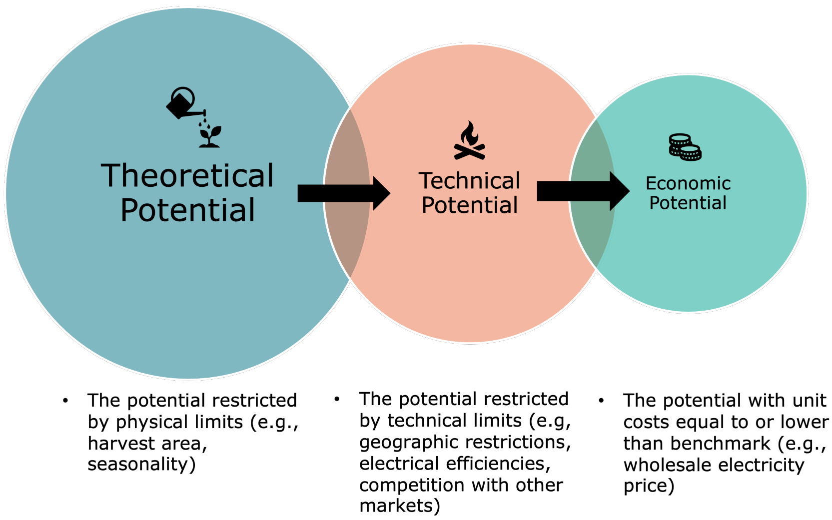


Figure 1.2: Three types of potential for biomass energy

1.3. Problem Statement and Research Questions

The initial literature review identified the current situation of Indonesia's co-firing plan. There has been lack of research on the feasibility of co-firing more than 20% and the economic potential of such projects. Additionally, there has been limited studies which identifies the locations of biomass waste and the transport options to CFPPs in Indonesia. A more broad knowledge gap identification will be provided in the next chapter. Nevertheless, the identified knowledge gaps has led to the formulation of the main research question:

Main Research Question 1

What is the techno-economic potential for retrofitting pulverized coal boiler plants to incorporate second-generation biomass co-firing in Indonesia?

Subsequently, sub research questions were constructed to address specific aspects of the main research question. The four sub-questions can be seen below.

Sub Research Question 1

What is the availability of second generation biomass for co-firing in Indonesia?

Sub Research Question 2

What is the technical potential of co-firing in Indonesia?

Sub Research Question 3

What are the economic perspectives of retrofitting coal plants for biomass co-firing in Indonesia?

Sub Research Question 4

What are the current policies and regulations in place to support biomass co-firing in existing coal plants in Indonesia, and what new policy recommendations could be made to enhance its economic potential?

1.4. Scope and Structure of the Report

This report aims to fill a critical knowledge gap hindering the advancement of biomass co-firing practices in Indonesia. The objective is to assess the techno-economic potential of retrofitting existing CFPPs for biomass co-firing, providing valuable insights into its feasibility as a sustainable energy solution. The findings have the potential to shape policy decisions and the future of biomass utilization in Indonesia's energy sector.

The structure of the report is as follows. A Literature Review is conducted focusing on the biomass potential, co-firing technology, economics of co-firing, and policies and regulations related to biomass energy nationally (Chapter 2) and internationally (Chapter 3).

Chapter 5 introduces the Technical Potential Analysis Methodology section which covers the criteria for biomass selection, input parameters, and calculations for determining biomass potential. Chapter 6 presents the results of the Technical Potential Analysis, including the technical biomass potential, and potential solutions for co-firing technical challenges. Chapter 7 focuses on the Economic Potential Methodology, explaining the input data and assumptions for the LCOE cost components. The Economic Potential Results are then presented in Chapter 8, including retrofit costs, LCOE calculation results, and sensitivity analysis. In Chapter 9, the Policy Analysis Methodology is presented and Chapter 10 includes the Policy Analysis Results, where Indonesia's co-firing policy and regulations are reviewed with recommendations presented at the end.

Moving to the Discussion and Conclusion section, Chapter 11 provides an extensive discussion of the findings, highlighting any limitations in the methods used. It also presents recommendations based on the research outcomes. Finally, Chapter 12 concludes the report by answering the main research questions and closing remarks, summarizing the key points and emphasizing the significance of the research.

Part I

Literature Review

2

Biomass Co-firing in Indonesia

In this chapter, a literature assessment on the current status of biomass co-firing in Indonesia will be performed. The purpose of the review is to identify the current co-firing and retrofitting projects and the technical and economic gaps the country is faced with. Section 2.1 describes the literature selection procedure in detail, the results of the review are then presented in Section 2.2

2.1. Literature Selection

The selection process is explained in this section. The libraries used to look for literature were the TU Delft online library, Google Scholar and Scopus. Moreover, the keywords used for the research and its synonyms are listed in Table 2.1.

Table 2.1: Keywords used and their synonyms for the literature search

Keywords	Synonyms
Indonesia	Java, Sumatra, Sulawesei, Kallimantan, Papua
Biomass	Bioenergy, Biowaste, Bioresidue
Potential	-
Retrofit	-
Co-firing	Cofiring, Cofire, Co-combustion
Economic	-
Technical	-
Policy	Regulation

Additionally, further filtering was undergone in which publication year was limited, starting from 2005. The type of publications were also bounded to Journals, Reports, Conference proceedings, databases and Books in English. The search results once filtered resulted to 600+ papers where further filtering was conducted after an abstract scan. Table 2.2 displays the keyword search results.

Table 2.2: Literature Results from the keyword search on TU Delft Online Library and Scopus database

Database	Keywords	Search Result	Reviewed	Filtered
Scopus	Biomass, Potential, Indonesia	591	45	22
TU Delft Library	Biomass, Retrofit, Indonesia	6	1	1
TU Delft Library	Biomass, Co-firing, Indonesia	51	14	7
Scopus	Biomass, Co-firing, Economic, Indonesia	2	2	2
Scopus	Biomass, Co-firing, Policy, Indonesia	5	3	1

From Table 2.2 it can be seen that the search results for biomass potential in Indonesia appear to execute the most amount of papers. However, when narrowing down the terms to co-firing, there appears to be limited knowledge on such technology. Furthermore, the literature search resulted in reviewing 63 papers in which 33 were concluded to be most relevant to the thesis objective.

2.2. Literature Review Results

In this section, the results of the literature review will be discussed. The papers of most significance will be analysed to understand the current status of biomass co-firing in Indonesia. Table 2.3 displays the key insights from the selected literature.

The first paper by Hambali and Rivai (2017) delves into the palm oil industry in Indonesia. The insight is that in Palm Oil Mills, the fresh fruit bunches get processed into (1) crude palm oil and (2) palm kernel oil. From this process, 24% of the fresh fruit bunches yield crude palm oil while 2.4% yields palm kernel oil. The remaining by-products are empty fruit bunches (21%), mesocarp fiber (14%) and Palm Kernel Shells (PKS) (6.4%). The total national empty fruit bunch production in 2015 was 30.6 million tons. With the current production rate, the study expects the production of empty fruit bunch in 2030 to increase to 54 million tons, making it abundant. Therefore, this insight quantifies the biomass waste empty fruit bunch which could be a potential feedstock in retrofitted CFPPs in Indonesia.

The second insight from Arifin et al. (2023) is related to the co-firing status in Indonesia. It has been identified that the Indonesian energy mix in the electricity generation sector is still dominated by coal firing. The capacity of CFPPs are about 32.8 GW, in which 16 GW of CFPP is connected to the Jawa-Madura-Bali through a high-voltage grid system. Furthermore, the Indonesian government, through PLN, has planned to implement co-firing for CFPPs with a total capacity of around 18000 MWe and an average percentage of co-firing of 10%. The aforementioned total capacity is dominated by Pulverized Coal (PC) boilers with a percentage of 86%, followed by Circulating Fluidized Boilers (CFB) and Stoker boilers with a percentage of 13% and 1%, respectively.

The third study gives insights into the technical potential of co-firing with hydrothermally treated empty fruit bunches as feedstock in existing power plants. Darmawan et al. (2017) propose that the pre-treatment of empty fruit bunches are essential because co-firing requires biofuels with a uniform quality and high energy density to allow for processing in the fuel handling and combustion equipment of existing CFPP. Moreover, a sensitivity analysis of biomass composition was conducted, revealing that the optimal composition of hydrothermally treated empty fruit bunches was between 10-25%. Higher compositions may lead to higher outlet temperature and blockage in the pipe due to the high ash composition.22

The fourth paper gives insight into the benefit-cost ratio of biomass co-firing in a CFPP. There are 114 CFPP units owned by PLN that can facilitate biomass co-firing. This would require 9 million tons of biomass per year. However, Sugiyono et al. (2022) determines that appropriate incentives are required for co-firing to be economically feasible. The study determines that the biomass price must be able to compete at a price 15% cheaper than the price of coal and the investment cost for implementing biomass co-firing technology in coal power plants ranges from 50-300 USD($)/kW. Furthermore, incentives for processing biomass from municipal waste are recommended to aid in achieving co-firing targets.

The fifth study explores the utilisation of biomass residue in Indonesia. Rhofita et al. (2022) determines the residue that has the highest potential in Indonesia as well as models the availability of all residues in Indonesia by island. The study determined that rice, corn and palm oil ranked in the first three places of agricultural products, respectively. Moreover, logging residues from the plant Accacia sp. generate over 90% of forestry residue potential.

The last study by Simangunsong et al. (2017) gives insights into wood residues in Indonesia. The estimated production cost of wood pellet was estimated about 103$/ton pellet assuming an international wood pellet export price of 135$/ton. Within the production costs, the raw material cost had the highest share at 30$/ton pellet, whereas the cost of milling equates to 55% of the wood pellet price. The raw material considered was residue from sawnwood, plywood, veneer sheets and chipwood which had a total energy potential of 65 PJ in 2013. The study concludes that raw material price appears to be the largest component of the economic value. The study deduces that due to the current feed-in tariff being low, this causes a disincentive to IPPs and thus economic value of forest biomass would be an important input to revise current government policies on the feed-in tariff and IPP incentives.

Table 2.3: Key insights of primary literature

Year	Author	Title	Key Insights
2017	E Hambali and M Rivai	The Potential of Palm Oil Waste Biomass in Indonesia in 2020 and 2030	This study determines the sources of waste that is a result of palm oil processing. The study also quantifies the production of biomass waste during palm oil processing and projects the increased amount in 2030.
2023	Z Arifin et al	Techno-Economic Analysis of Co-firing for Pulverized Coal Boilers Power Plant in Indonesia	This study discusses the current co-firing status in Indonesia that has been trialed by PLN. The content includes the existing coal plants that have undergone up to 5% co-firing without additional modifications. Moreover, the study conducts parameter analysis determining which plant variables are affected most when co-firing biomass.
2017	Darmawan et al	Retrofitting existing coal power plants through co-firing with hydrothermally treated empty fruit bunch and a novel integrated system	This study analyses co-firing behaviour of hydrothermally treated empty fruit bunches when co-fired in a drop tube furnace using computational fluid dynamics analysis. The effect of biomass co-firing compositions are studied to evaluate the potential of retrofitting existing power plants.
2022	A Sugiyono et al	Potential of biomass and coal co-firing powerplants in Indonesia: a PESTEL analysis	This study uses the PESTEL analysis (Political, Economic, Social, Technical, Environmental and Legal) to analyse the business prospects form biomass co-firing in coal plants. Government regulations and incentives are discussed in this paper. Investment costs and technical challenges are also mentioned.
2022	E Rhofita et al	Mapping analysis of biomass residue valorization as the future green energy generation in Indonesia	This study gives an in depth analysis on the utilisation of biomass residue in Indonesia. The paper includes potential calculations based on different scenarios of utilisation as well as a spatial analysis of residue availability in Indonesia.
2017	Simangunsong et al	Potential forest biomass resource as feedstock for bioenergy and its economic value in Indonesia	This study estimate the availability of Indonesia's forest biomass resource as fuel feedstock, explore its conversion technology for bioenergy and estimate its economic value for a selected conversion technology

3

Biomass Co-firing: Global Review

This chapter includes the results of a comprehensive literature review concerning biomass co-firing within a global framework. The review will primarily include topics related to the availability and characteristics of biomass (Section 3.1), the utilization of co-firing technology (Section 3.2), and the economic potential as observed in different countries where co-firing practices have been implemented (Section 3.3). The literature was sourced from libraries such as Google Scholar and Scopus.

3.1. Biomass Residues and Their Applications

The use of biomass for co-firing can be sourced from different materials. A paper by Gonzalez-Salazar et al. (2014) identified the most abundant biomass residue sources available in Colombia. The paper considers biomass residues from agricultural, forestry, animal and urban waste. It appears that forestry residues, EFB from palm oil tree, cane leaves, cane tops and cattle manure are the most available type sourced locally.

Moreover, Roni et al. (2017) reviewed co-firing in various countries and identified that wood pellets, sawdust and wood chips were commonly used and imported for co-firing in The Netherlands and Denmark. The trend in biomass resource potential differs according to the country region. For instance, the available biomass residue for co-firing in the Netherlands is limited to forestry residues. As for Denmark, the domestic market for straw residue has already been established, allowing the supply of two-thirds the annual wood chip demand. When compared to Indonesia, rice residues are used for cooking fuel in remote areas whereas other uses of residues include fertilisers and animal feed, similar to other countries reviewed (Hardhi, 2022). Table 3.1 gives an outline of biomass residues found in these three countries and its alternative uses.

Forestry residues in Colombia are used for soil replenishment, this helps to avoid soil erosion by placing residues on the top layer so that it is protected from wind and water. Moreover, the organic matter found in residues can aid in enhancing soil and nutrient quality. These residues also aid in pH regulation, supporting optimal nutrient uptake by plants. Meanwhile, agriculture residues in Denmark and the Netherlands are used in soil recovery. These residues can be utilized through methods like mulching, composting and cover cropping. By leaving residues on the field, incorporating them as green manure, and practicing crop rotation, farmers can improve soil structure, fertility, and water retention.

Moreover, the availability factor, symbolised as α, holds significance as an indicator of the availability of utilizing biomass residues for co-firing. Specifically, alternative applications for rice husk predominantly revolve around animal bedding and organic fertilizer, while the ash derived from rice husk combustion exhibits potential for soil amendment, effectively enhancing pH levels and overall soil quality (Singh, 2018). Conversely, competition arises in the utilization of sugarcane bagasse for biofuel production. An illustrative example can be found in Colombia, where sugarcane bagasse obtained from large-scale plantations is employed to generate heat and power to sustain the sugar and bioethanol industry (Gonzalez-Salazar et al., 2014). Further elaboration of the availability of biomass will be explored in Chapter 5.

In relation to the chemical properties of biomass, multiple values have been reported, stemming from variations in measurement procedures employed during proximate analysis and the geographical origin of the biomass. For instance, when examining coconut husks, those measured in Bangladesh display slightly

Table 3.1: Biomass residues and alternative uses in several countries

Country	Biomass Residues Available	Alternative Use
Colombia	Forestry Residues Cane Leaves and Tops Empty Fruit Bunch Cattle Manure	Soil Replenishment Heat, Animal Feed, CHP Heat Fertiliser
The Netherlands	Forestry Residue Animal Manure Potato Residue Sugar Beet Residue Green Maize Residue	Heat Soil Fertilisation Soil Recovery Soil Recovery Soil Recovery
Denmark	Straw from Wheat, Barley and Rape Rapeseed residue Wood residue Potato residue	Heat, Biofuel, Bedding Biodiesel Contruction, Furniture Soil Recovery
Indonesia	Forestry Residues Rice residues Sugar Residues	Heat, Particle Boards Bedding, Cooking Fuel, Fertilisers Boiler Fuel for Sugar Mills

higher moisture content but lower ash content compared to their counterparts from Ghana. Similarly, PKS sourced from Ghana exhibit lower ash content in contrast to PKS of Malaysian and Indonesian origin. These discrepancies in values can arise due to a range of factors, including the purity of the feedstock sample and the temperature at which the sample was collected. Table 3.2 details an overview of the proximate analysis results and measurement methods identified through various papers. The full proximate analysis for all biomass residues considered in this thesis will be mentioned in Chapter 5.

Table 3.2: Comparison of moisture content (MC) and ash content (AC) values of biomass residues found in different countries

Biomass Residue	Country Origin	Measurement Method	MC wt%	AC wt%	Source
Coconut Husk	Bangladesh	JIS-M8813	9.96	2.23	(Wang and Sarkar, 2018)
	Nigeria	Anderson and Ingram 1979	5.43	3.95	(Adeyi, 2010)
	Ghana	ASTM	7.5	5.3	(Windeatt et al., 2014)
Palm Kernel Shell	Malaysia	ASTM	6.33	11.75	(Ahmad et al., 2014)
	Ghana	ASTM	8.5	0.03	(Bonsu et al., 2020)
	Indonesia	ASTM	19.58	2.75	(Rusdianasari et al., 2022)

The ASTM measurement method is a standard measurement procedure employed which measures the moisture content, ash fontent, volatile matter and fixed carbon of the sample. JIS has also developed its own standards. Some of the JIS methods for proximate analysis are similar to the ASTM methods, but they may have slight variations in procedures or equipment used.

3.2. Co-firing Technology

Co-firing technology has been implemented in various countries since the early 2000's. As mentioned in Chapter 1, there are several types of co-firing technologies that are widely used in coal plants: direct, indirect and parallel co-firing. The least cost and most straightforward method is direct co-firing. This method allows the direct combustion of biomass in the same coal furnace. This technology has been implemented in several countries such as the UK, Netherlands, The US, Denmark and Japan. However, there has been challenges when implementing direct co-firing such as slagging and fouling in the boiler, lack of biomass fuel flexibility and limited co-firing thermal mix (Roni et al., 2017).

Indirect co-firing installs a separate gasifier to convert the solid biomass into synthesis gas (H_2 + CO_2). Indirect co-firing provides a number of benefits over direct co-firing. Firstly, boiler slagging can be reduced since biomass does not directly feed into the boiler. Secondly, gasification reduces gas residence time which means faster reactions and reduced emissions. Thirdly, indirect co-firing allows the flexibility to use different base fuels such as coal, oil, and natural gas.

Parallel co-firing involves the installation of a completely separate external biomass-fired boiler for the steam turbine in the CFPP. This steam generated from biomass-fired boiler is used to meet the demands of the CFPP and reduce the operational risk due to the availability of separate and dedicated biomass burners running parallel to the existing boiler unit. Parallel co-firing can increase the biomass percentage during biomass co-firing and avoid biomass-related contamination issues. However, this technology is proven more expensive than the direct co-firing approach since additional infrastructure is needed to support the system. A visualisation of the different co-firing technologies are depicted in Figure 3.1.

An overview of selected countries that have integrated co-firing practices in their CFPPs is presented in Table 3.3. The majority of the countries have implemented direct co-firing technology, predominantly utilising biomass fuel derived from wood pellets. An exception is Denmark, which has achieved 100% co-firing with straw as its fuel source. Notably, the US has emerged with the highest amount of co-firing CFPPs, though the extent of co-firing is confined to a thermal mix of 5%. (Roni et al., 2017).

When contrasting Indonesia's co-firing advancements with those of other nations, it is evident that substantial progress has been achieved. The co-firing conditions were derived from commercial co-firing plants. While there have been co-firing trials in Indonesia showcasing 100% co-firing with PKS in a 7MW plant (PLN, 2022), the majority of plants predominantly employ lower co-firing rates, typically below 20%. Therefore, there remains potential for further improvement, particularly by enhancing the co-firing proportion and expanding the number of co-firing plants.

Furthermore, pre-treatment of biomass residues before co-firing is commonly applied. The import of wood pellets for co-firing is the main source of biomass fuel for countries like The Netherlands and Denmark. The pelletizing of biomass emerges as a viable strategy due to the enhancement of bulk density, making feedstock transportation more feasible and efficient. Other pre-treatment methods such as drying aid in reducing moisture content of the biomass before combustion, which helps retain similar physical properties as coal (Irawan, 2021). A further in-depth review of co-firing technical challenges and solution will be discussed in Chapter 5.

3.3. Economics of Co-firing

The economic viability of implementing co-firing is often assessed using several cost components, including biomass prices, investment expenses, Operating and Maintenance costs (O&M), and the applicable carbon tax rate. The O&M costs includes both fixed and variable costs. Fixed expenses include maintenance, staff expenditures, and insurance premiums. Variable costs include additional maintenance, power and fuel cost.

Direct co-firing is known to be the least cost option whereas parallel co-firing requires the highest investment costs. IEA & NEA (2015) estimates the investment costs for direct co-firing to be between 700-1000$/kW, between 3300-4400$/kW for indirect co-firing and 1800-2800$/kW for parallel co-firing. Alternatively, The paper IRENA (2013) estimates the range for direct co-firing to be 430-500$/kW, 760-900$/kW for indirect

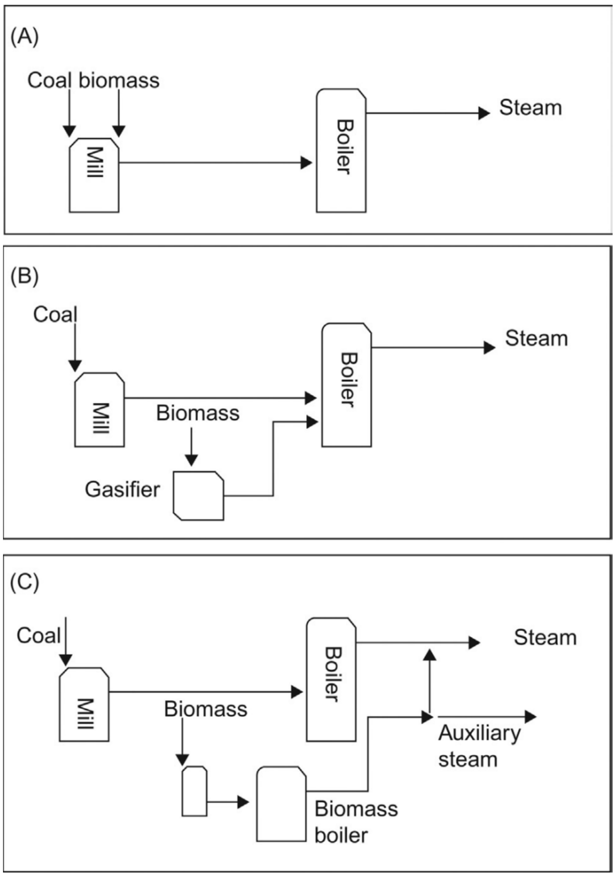


Figure 3.1: There are three choices for integrating biomass with coal in a coal-fired boiler. The first is direct co-firing, where biomass is introduced directly into the coal pulverizing mill (A). The second is indirect co-firing, involving biomass gasification and the combustion of the produced gas in the boiler (B). The third option is parallel co-firing, in which biomass is burned in a separate boiler, and the resulting steam is then supplied to the steam header (C). Diagram Retrieved from Basu (2018)

co-firing and 3000-4000$/kW for parallel co-firing. The difference between these two reports are substantial and proves that co-firing investment costs are difficult to estimate.

Furthermore, the investment costs associated with retrofitting for biomass co-firing exhibit notable variations across different countries. These cost ranges are dependent on factors such as the selected co-firing technology, mixing ratios of biomass with coal, as well as varying labor and construction expenses. An overview of the investment cost ranges can be seen in Table 3.4.

For instance, as reported by Knapp et al. (2019), Germany showcases a wide range of investment costs relative to the type of fuel utilized. The adoption of torrefied biomass incurs the least retrofit cost, while the utilization of wood chips incurs the highest cost. Additionally, the Netherlands stands out with the highest investment costs observed among the reviewed countries. These findings reflect the significance of regional disparities in retrofitting expenses, highlighting the impact of fuel choices and local economic factors on co-firing investment costs. Additionally, the retrofit costs estimated for Indonesia fall within the range observed in other countries, suggesting the potential for economically viable co-firing practices.

Table 3.3: Summary of biomass co-firing condition in some selected countries, sourced from Roni et al. (2017) and Modi (2021)

Country	No. of Co-firing Plants	Co-firing Range	Co-firing Methods	Primary Feedstock
Netherlands	10	5-80%	Direct, Indirect	Wood Pellets, PKS, Waste Wood, Cocoa Shells
Denmark	7	5-100%	Direct, Indirect	Straw, Wood Chips, Wood Pellets
UK	14	3% by heat input	Direct	Wood pellet, Miscanthus, Olive/Palm Residues
US	86	5% on energy basis	Direct	Wood Pellets, Wood Chips, Wood Waste
Japan	9	3% by mass	Direct	Wood Pellets
Indonesia	17	1-10% on energy basis	Direct	Sawdust, Rice Husk, Wood Pellets

Table 3.4: Overview of co-firing investment cost ($/kW) for selected countries

Countries	Investment Cost Co-firing ($/kW)	Source
US	305	(Picciano et al., 2022)
Germany	38-346	(Knapp et al., 2019)
Netherlands	600-650	(IEA & NEA, 2015)
Vietnam	500	(Truong et al., 2022)
Indonesia	50-300	(Sugiyono et al., 2022)

Furthermore, the economic potential of co-firing is significantly influenced by the fuel costs associated with biomass. Unlike coal, the biomass supply chain is not as well-established, giving rise to considerable cost variations in feedstock procurement. These cost fluctuations are based on multiple factors, including the origin of the biomass, biomass type, and its specific composition (such as LHV or moisture content) (IRENA, 2013).

To shed light on this aspect, a study conducted by IRENA (2012) provides feedstock data pertaining to locally available biomass resources in The US, Europe, Brazil, and India. The study indicates a diverse range of costs for different biomass sources. For instance, the cost of bagasse in Brazil and India exhibits a range of 0-11 $/MWh electricity, whereas the cost for agricultural residues in the US and Europe shows an even broader range, varying from 6-22 $/MWh electricity. These findings emphasises the necessity of considering region-specific feedstock costs when evaluating the economic feasibility of biomass co-firing projects.

Moreover, importing wood chips serves as a prevalent choice for countries whose biomass production is not sufficient to meet their co-firing supply requirements. The global market price for wood chip has reached 160 $/ton, which can be four times higher than the price of locally sourced wood chips in Indonesia, amounting to 40 $/ton (IESR, 2023).

All in all, reviewing the cost profiles of several countries offers valuable insights into the financial outlay associated with co-firing technology. Such insights serve as essential inputs for modeling the LCOE for biomass co-firing in the specific context of Indonesia. This is described in detail in Chapter 7.

4

Identifying Knowledge Gaps

Several significant knowledge gaps exist in the domain of biomass co-firing in Indonesia, which necessitate further exploration. Firstly, while co-firing trials have been conducted in some CFPPs by PLN, a broader national-scale implementation of co-firing is yet to be achieved. With only 52 CFPPs undergoing co-firing testing, there remain approximately 200 CFPPs potentially eligible for co-firing, warranting further investigation.

Secondly, the literature review indicates a scarcity of research on the complete replacement of coal with biomass in existing power plants. Though some trials have demonstrated 100% co-firing success, such as the case of PKS at the 7 MW Tembilahan CFPP (PLN, 2022), and the joint project between PLN and Mitsubishi Heavy Industries at the Suralaya CFPP (MHI, 2022), there is limited experience with co-firing above 20% in Indonesia. This thesis aims to identify the techno-economic potential of co-firing at higher thermal mixes.

Thirdly, studies exploring PT methods and transport options for biomass supply to CFPPs in Indonesia are limited. Existing information primarily focuses on the types of biomass used in co-firing trials, such as PKS, rice husks, Solid Recovered Fuel (SRF), refuse derived fuel, wood pellets, sawdust, and wood chips (Rachmatullah, 2020). In contrast, countries like the Netherlands, Denmark, and Japan rely on wood pellet imports for their co-firing biomass supply. This thesis will explore modeling options for biomass transport and pre-treatment methods.

Fourthly, academic research assessing the LCOE for co-firing biomass in Indonesia is finite. While some papers compare the LCOE of co-firing against other NRE technologies and fossil-fired plants, these analyses often assume wood chips as the biomass fuel without providing further details on transport and PT sources (IESR, 2023). Additionally, investment costs for co-firing are not extensively covered in available reports. This thesis aims to conduct a thorough analysis of investment costs and LCOE parameters to address these knowledge gaps.

Part II

Technical Potential Analysis

5
Technical Potential Methodology

In this chapter, the methodology of the Technical Potential Analysis will be described. The selection criteria and the overview of biomass residues in Indonesia can be found in Section 5.1.Section 5.2 will describe the equations for calculating the theoretical, available and technical biomass potential. Meanwhile, the significant input parameters will be stated in Section 5.3. Lastly, the methodology for reviewing the co-firing challenges and retrofit approach can be found in Section 5.4.

5.1. Biomass Selection Criteria

When discussing biomass, various resource categories are identified. First-generation biomass includes food crops, while second-generation biomass includes non-edible or lignocellulosic resources like switch-grass, fast-growing trees, and industrial by-products. Third-generation biomass involves micro and macro algae. Fourth-generation biomass emerges from bio-engineered microorganisms (microalgae, yeast, cyanobacteria) that capture CO_2 through photosynthesis. Fourth-generation technologies also integrates solar-to-fuel, using sunlight to capture CO_2 for biofuel production, and pyrolysis, a process breaking down biomass into bio-oils and biochar in the abscense of oxygen (Alalwan et al., 2019). The research will particularly concentrate on re-purposing by-products and waste from second-generation biomass as co-firing fuel. Examples of biomass generations are outlined in Table 5.1.

Table 5.1: Biomass Generations and their Examples retrieved from Alalwan et al. (2019)

Biomass Generation	Classification	Examples
1st	Edible	Sugarbeet Sugarcane Wheat Corn Oil Crops
2nd	Non-edible	Wood Grass Straw Waste by-product
3rd	Algal Biomass	Macroalgae Microalgae
4th	Breakthrough	Genetically Modified Organisms Pyrolysis Solar to Fuel

Indonesia possesses an abundant supply of biomass residues originating from agricultural, forestry, and urban waste sources. The residue flow diagram depicted in Figure 5.1 illustrates the various types of residues found in Indonesia and their biomass origins. For the purpose of this study, the focus was on agricultural and forest residues that hold potential as energy sources. Agriculture products, including rice, corn, cassava, groundnut, and soybeans, as well as plantation crops like sugarcane, coconut, palm oil, coffee, and cocoa, are widely available commodities across different regions of Indonesia throughout the year. Forest residues, on the other hand, originate from natural forest harvesting (e.g., Acacia sp., Eucalyptus sp., Tectona grandis LF, Meliaceae, and Albizzia falcataria), industrial forest plantations (e.g., Shorea spp, Mixed forest, Intsia bijuga, and Dipterocarpus borneensis), and wood processing mill residues (Koopmans and Koppejan, 1997; Rhofita et al., 2022).

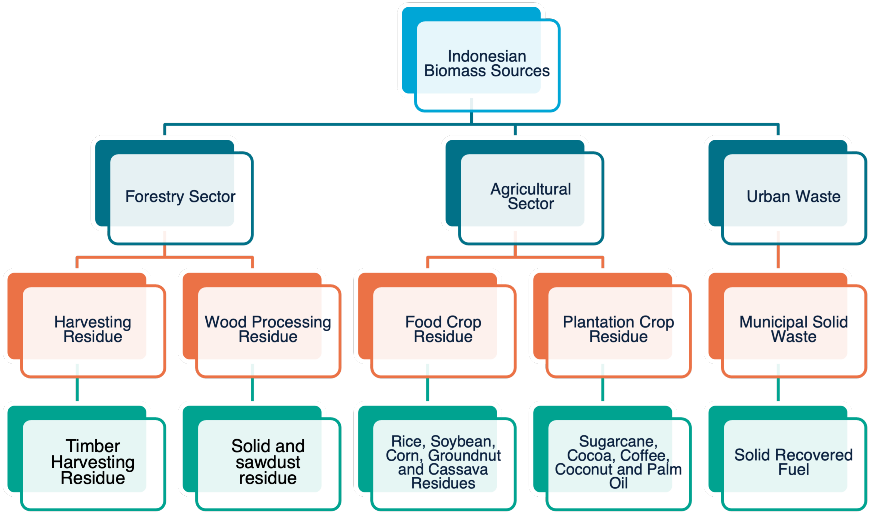


Figure 5.1: Available Biomass Residue Flow Chart in Indonesia

Forestry production in Indonesia is further broken down into subsections (see Figure 5.2). Log Production Harvesting consists of forestry from natural production forests, Industrial Forest Plantations (HTI), timber utilisation permits for forest areas, private forest company Perum Perhutani and HTI land preparations. The by-products derived from these are considered timber harvesting residues. Wood processing consists of solid and sawdust residue derived from the processing of sawnwood, plywood, chipwood, pulpwood and sawlog (Koopmans and Koppejan, 1997; Simangunsong et al., 2017).

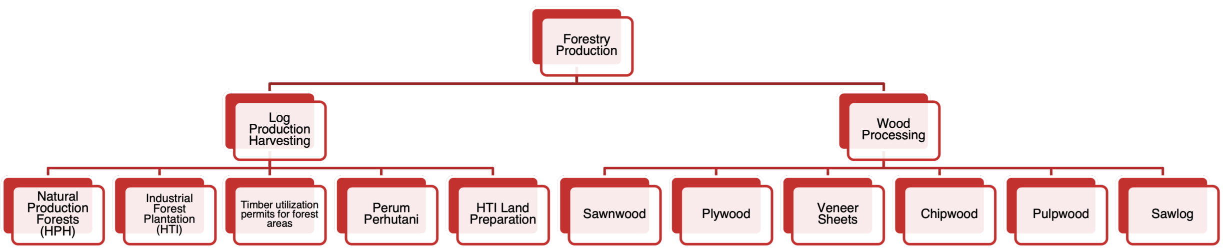


Figure 5.2: Breakdown of Forestry Residue Flow Chart in Indonesia

Furthermore, SRF is a subset of Refuse Derived Fuels and is produced from non-hazardous waste streams that has met the classification and specification for fuel for national standards (IPEN, 2022). A breakdown of MSW composition in Indonesia is presented in Figure 5.3, retrieved from SIPSN (2022). RDF is processed from wood, paper, plastics and fabrics waste allowing the use of 45.3% of MSW composition.

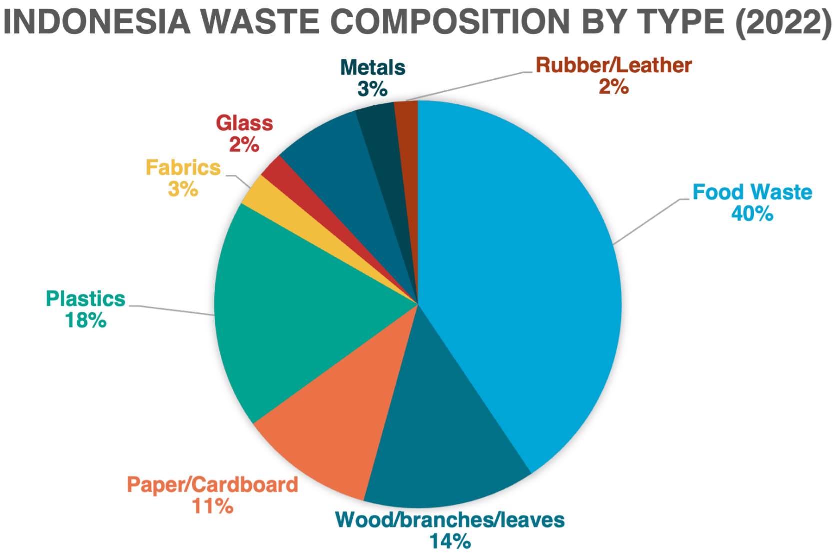


Figure 5.3: Breakdown of MSW Composition in Indonesia, retrieved from SIPSN (2022)

5.2. Biomass Potential Calculations

The biomass potential calculations are based on the paper Gonzalez-Salazar et al. (2014). The Theoretical Biomass Potential, Q_T is the sum of the potential from agricultural residue (Q_{AC}), forestry residue (Q_F) and urban waste (Q_W). The equations to calculate these residues are given below (see Equation 5.1a - Equation 5.1c).

$$Q_{AC}\ (\text{MJ}) = P\ (\text{ton}) \times k\ (-) \times (1 - M_w)\ (-) \times LHV_b\ (\text{MJ(dry)/ton}) \tag{5.1a}$$

$$Q_F\ (\text{MJ}) = P\ (\text{m}^3) \times c\ (-) \times \rho\ (\text{ton(dry)/m}^3) \times LHV_b\ (\text{MJ(dry)/ton}) \tag{5.1b}$$

$$Q_W\ (\text{MJ}) = P\ (\text{ton}) \times s\ (-) \times (1 - M_w)\ (-) \times LHV_b\ (\text{MJ(dry)/ton}) \tag{5.1c}$$

$$Q_T\ (\text{MJ}) = Q_{AC} + Q_F + Q_W \tag{5.1d}$$

Where:

$P =$ Resource Production in a year (tons or m^3)
$c =$ wood by-product to product ratio (-)
$k =$ crop by-product to product ratio (-)
$s =$ share of waste appropriate for fuel (-)
$M_w =$ Moisture content (-)
$\rho =$ by-product density (tons(dry)/m^3)
$LHV_b =$ Lower Heating Value of biomass (MJ(dry)/ton)

Wood density refers to the weight of dry wood per unit volume. It's measured after removing any water content. Additionally, the Lower Heating Value (LHV$_b$) of biomass is indicated on a dry-basis. The moisture content (Mw) is calculated by the difference in weight of the sample after drying over the initial weight multiplied by 100.

Available Biomass Potential, Q_A is the biomass potential taking into account the availability factor, α which determines if the residue is available for feed stock use. The alternative uses has been mentioned in the literature review (Section 3.1 and further elaboration will be made in Chapter 6 and Chapter 11. The equation for available biomass potential can be expressed as:

$$Q_A\ (\text{MJ}) = Q_T\ (\text{MJ}) \times \alpha\ (-) \tag{5.2}$$

The Technical Biomass Potential, (Q_E) can also be calculated by converting available biomass potential from Joules to Watt-Hour. This enables the biomass potential to be quantified as a value of electricity generated.

$$Q_E\ (\text{MWh}) = \frac{Q_{AC}\ (\text{MJ})}{3600\ (\text{MJ/MWh})} \tag{5.3}$$

5.3. Biomass Input Parameters

The input parameters for the biomass potential equations were collected from numerous sources. However, the priority of literature was given in order of relevance: Indonesian government websites, literature papers and general websites.

The MC and LHV were determined based on proximate analysis literature (Rhofita et al., 2022; Koopmans and Koppejan, 1997; Zhang et al., 2012; Rusdianasari et al., 2022; Danish et al., 2015). The annual production of crop/resource were retrieved from the Food and Agriculture Organization of the United Nations and Indonesian Central Bureau of Statistics for the year 2021. The by-product ratio and availability factor were acquired from Rhofita et al. (2022); Koopmans and Koppejan (1997). The wood densities and production were obtained from Redaksi (2022); WolrdAgroForestry (nd); Rhofita et al. (2022). MSW production was taken from SIPSN (2022), while the residue by product was estimated from SIPSN (2022). All the necessary input variables for potential calculations are presented in Table 5.2.

5.4. Co-firing Technical Challenges

The technical challenges of co-firing will be explored by doing a literature review on co-firing technology. The primary objective of this literature review is to identify and analyze the challenges associated with co-firing technology in the context of biomass co-firing with existing CFPP. The review aims to gain insights into the existing knowledge gaps, technical hurdles, and potential limitations related to the successful implementation of co-firing technology. The results of the literature review will be mentioned and technical solutions for the challenges will be outlined.

The literature review will be conducted using electronic search strategy. databases such as Google Scholar, Scopus, TU Delft Library, and relevant academic journals will be utilized to collect peer-reviewed articles, conference papers, reports, and relevant publications. The search will involve an extensive set of keywords and phrases, covering areas such as ”biomass co-firing,” ”challenges in co-firing technology,” ”retrofitting coal power plants,” and related terms. Additionally, a specific focus will be placed on literature addressing the influence of biomass organic content on boiler performance. Relevant indices, including slagging and fouling index, as well as hardgrove grindability index, will also be explored in the process.

To ensure the relevance and quality of the selected literature, specific inclusion and exclusion criteria will be applied. The selected literature must focus on co-firing technology challenges and their practical implications in the context of retrofitting existing coal-fired power plants.

Upon the completion of the literature search, data from the selected sources will be extracted and organized for systematic analysis. The identified challenges related to biomass co-firing will be classified and grouped based on common themes, such as technical barriers associated with biomass composition and equipment.

Throughout the literature review process, potential knowledge gaps and areas requiring further research will be identified. These gaps will be documented, and recommendations for retrofitting CFPPs in Indonesia will stated.

Table 5.2: Input Parameters of Biomass Residues retrieved from various sources mentioned in Section 5.3

Biomass Type	Biomass Source	Biomass Residue	ρ (kg/m^3)	P (Mton/year)	P (m^3/year)	c, k, s (-)	Mw (-)	LHV (MJ/kg)	avg. α (-)
Agriculture	Cassava	Stalk	-	17.7	-	0.23	0.175	15.1	0.5
Agriculture	Cocoa	Pods	-	0.7	-	0.97	0.45	13.9	0.4
Agriculture	Coconut	Shell	-	17.2		0.21	0.12	18.3	0.3
Agriculture	Coconut	Husk	-	17.2	-	0.42	0.105	15.5	0.5
Agriculture	Coffee	Husk	-	0.8	-	1.16	0.11	10.9	0.4
Agriculture	Ground nut	Shell	-	0.8	-	1.25	0.09	13.8	0.3
Agriculture	Maize	Stalk	-	20	-	2.14	0.159	9.2	0.4
Agriculture	Maize	Corncob	-	20	-	0.27	0.064	16.5	0.4
Agriculture	Palm Oil	Empty Fruit bunch	-	256.6	-	0.21	0.137	15.5	0.3
Agriculture	Palm Oil	PKS	-	256.6	-	0.06	0.196	19.3	0.3
Agriculture	Rice	Straw	-	54.4	-	1.1	0.125	15.0	0.525
Agriculture	Rice	Husk	-	54.4	-	0.2	0.09	14.5	0.525
Agriculture	Soybeans	Straw	-	0.3	-	2.13	0.135	17.2	0.5
Agriculture	Sugarcane	Bagasse	-	32.2	-	0.31	0.25	14.3	0.35
Agriculture	Sugarcane	Top and Leaves	-	32.2	-	0.19	0.565	13.4	0.5
Forestry	Chipwood	Solid and sawdust residue	380	0.7	1788000	0.5	-	10.5	0.475
Forestry	Industrial Forest Plantation (HTI)	Timber Harvesting Residue	606	28.1	46400000	0.5	-	8	0.605
Forestry	Mixed Tropical Hardwood	Timber Harvesting Residue	711.8	4.3	6055524	0.5	-	8	0.605
Forestry	Plywood	Solid and sawdust residue	660	3	4507154	0.5	-	15.4	0.475
Forestry	Sawlog	Solid and sawdust residue	600	19.9	33114000	0.5	-	16.5	0.475
Forestry	Sawnwood	Solid and sawdust residue	470	1.2	2576790	0.5	-	12	0.475
Forestry	Veneer Sheets	Solid and sawdust residue	440	0.7	1594401	0.5	-	12	0.475
Forestry	Timber Utilisation Permits for Forest Areas	Timber Harvesting Residue	658.9	0.8	1240000	0.5	-	8	0.605
Forestry	Perum Perhutani	Timber Harvesting Residue	658.9	0.7	988708	0.5	-	8	0.605
Forestry	HTI Land Preparation	Timber Harvesting Residue	606	0.4	597046	0.5	-	8	0.605
Forestry	Pulpwood	Solid and sawdust residue	450	22.5	49896723	0.5	-	18.4	0.475
Urban Waste	MSW	Solid Recovered Fuel	-	70.8	-	0.45	0.5	19.5	0.7

6

Technical Potential Results

This chapter provides the results of the Technical Potential Analysis. Specifically, Section 6.1 presents the theoretical biomass potential calculations, while Section 6.2 focuses on the available biomass potential calculations. Additionally, Section 6.3 showcases the overall technical potential results. Furthermore, Section 6.4 reveals the findings from the co-firing technical challenges literature review, offering potential solutions and proposing various scenarios for co-firing potential in Indonesia.

6.1. Theoretical Biomass Potential

The theoretical biomass potential was calculated using Equation 5.1 and the input parameters in Table 5.2. The results are presented in Table 6.2. The biomass waste with the highest theoretical potential is rice straw (0.79 EJ), followed by empty fruit bunch (0.72 EJ) and corn stalk (0.33 EJ). The residue with the least theoretical potential is forestry residues from HTI land preparation, Perum Perhutani, timber utilisation permits for forest areas and agricultural wastes from coffee, soybean, cocoa and groundnut.

Additionally, the results of the theoretical biomass potential can be displayed in a pie chart where the biomass residues are grouped by the biomass source (Figure 6.1). When doing so, a shift in largest potential is observed. The largest potential comes from palm oil residue (28.4%) and rice residues (27.4%) whereas wood processing residues and maize residues both exhibit the third largest potential with a 11.6% share in overall biomass residue potential. Overall, the agriculture sector produces the highest biomass residue potential at a 76% share in theoretical biomass potential, followed by forestry (15%) and MSW (9%).

The theoretical biomass potential results reveals the maximum biomass residue potential in Indonesia. However, not all of the potential can be utilised for co-firing. This may be due to alternative uses of the residue that has been established in the market. Therefore, the next section will analyse the biomass residues available for use in co-firing.

Table 6.1: Results of the Theoretical Potential (EJ) of Biomass Residues

Biomass Type	Biomass Source	Biomass Residue	Theoretical Potential, Q_T (EJ)
Agriculture	Cassava	Stalk	0.051
Agriculture	Cocoa	Pods	0.005
Agriculture	Coconut	Shell	0.058
Agriculture	Coconut	Husk	0.1
Agriculture	Coffee	Husk	0.009
Agriculture	Ground nut	Shell	0.012
Agriculture	Maize	Stalk	0.333
Agriculture	Maize	Corncob	0.084
Agriculture	Palm Oil	Empty Fruit bunch	0.721
Agriculture	Palm Oil	PKS	0.254
Agriculture	Rice	Straw	0.788
Agriculture	Rice	Husk	0.144
Agriculture	Soybeans	Straw	0.011
Agriculture	Sugarcane	Bagasse	0.107
Agriculture	Sugarcane	Top and Leaves	0.036
Forestry	Chipwood	Solid and Sawdust Residue	0.004
Forestry	Industrial Forest Plantation (HTI)	Timber Harvesting Residue	0.112
Forestry	Mixed Tropical Hardwood	Timber Harvesting Residue	0.017
Forestry	Plywood	Solid and Sawdust Residue	0.023
Forestry	Sawlog	Solid and Sawdust Residue	0.164
Forestry	Sawnwood	Solid and Sawdust Residue	0.007
Forestry	Veneer Sheets	Solid and Sawdust Residue	0.004
Forestry	Timber Utilisation Permits for Forest Areas	Timber Harvesting Residue	0.003
Forestry	Perum Perhutani	Timber Harvesting Residue	0.003
Forestry	HTI Land Preparation	Timber Harvesting Residue	0.001
Forestry	Pulpwood	Solid and Sawdust Residue	0.206
Urban Waste	MSW	SRF	0.313
Total			**3.57**

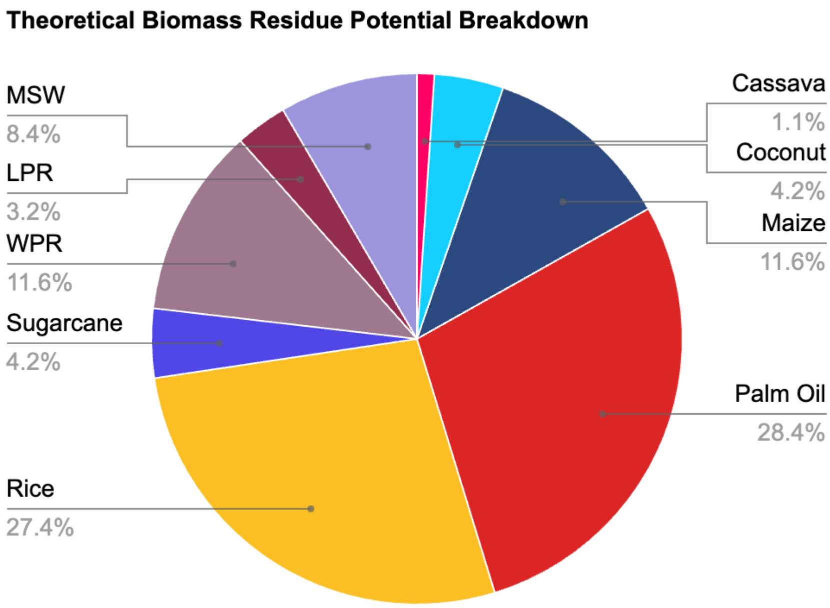


Figure 6.1: Theoretical Biomass Potential Breakdown (Total = 3.57EJ). Note: WPR = Wood Processing Residues, LPR = Log Processing Residues.

6.2. Available Biomass Potential

As mentioned in Section 5.3. The availability of biomass residues in Indonesia for feedstock use has been reviewed and the results are visualised in Figure 6.2. The Sankey diagram presented offers a visualization of the theoretical biomass potential distribution among various alternative uses. The diagram showcases the diverse pathways through which biomass residues can be utilized, including livestock feed and bedding, mulch and fertilisers, conventional cooking fuel and boiler fuel for sugar factories. Moreover, the lack of waste management for MSW has also hindered the availability of waste to be utilised.

As the biomass residues are channeled into these alternative uses, their availability for feedstock purposes decreases accordingly. Consequently, the diagram highlights that the available biomass potential for biomass feed stock is currently estimated to be 45% of the theoretical biomass potential.

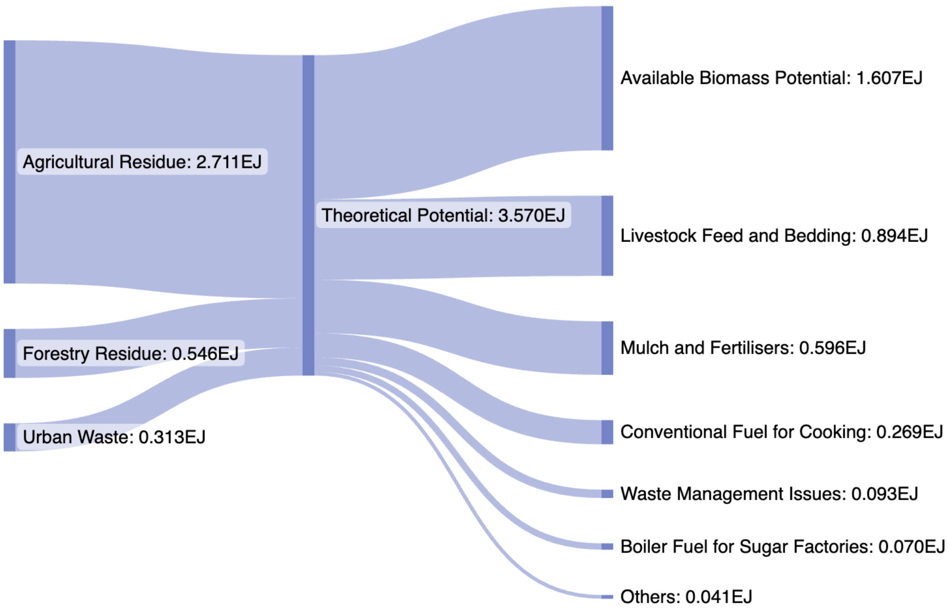


Figure 6.2: Sankey Diagram of Available Biomass Potential and Alternative Uses of Biomass Residues in Indonesia.

Furthermore, the available biomass potential for each type of residue was computed using Equation 5.2, and a detailed breakdown of these results is presented in Table 6.2. Notably, there has been a shift in the ranking of residues: rice straw remains the highest available potential amounting to 0.41 EJ. However, MSW takes the second position with 0.219 EJ, and empty fruit bunch secures the third place, accounting for 0.216 EJ.

In Figure 6.3, the distribution of available biomass potential is visualized based on biomass sources. A notable shift in the distribution is evident when compared to the Theoretical Biomass Potential. Specifically, there is a higher proportion of rice residues available for feedstock use, comprising 31.3% of the total. This surpasses palm oil, which has moved to the second-largest potential source at 18.8%. Additionally, the share of MSW residue has increased, positioning it as the third-largest source. Following this, wood processing residues constitute the fourth-largest share at 12.5%, while maize residues constitute the fifth-largest share at 10.4%.

Table 6.2: Results for Available Potential (EJ) of Biomass Residues

Biomass Type	Biomass Source	Biomass Residue	Availability Factor		Available Energy Potential (EJ)	
			range (%)	average (-)	range	average
Agriculture	Cassava	Stalk	20-80	0.5	0.01014-0.04055	0.025
Agriculture	Cocoa	Pods	20-60	0.4	0.00109-0.00325	0.002
Agriculture	Coconut	Shell	20-40	0.3	0.01162-0.02324	0.017
Agriculture	Coconut	Husk	40-60	0.5	0.03992-0.05988	0.05
Agriculture	Coffee	Husk	20-60	0.4	0.00173-0.00517	0.003
Agriculture	Ground nut	Shell	20-40	0.3	0.00239-0.00477	0.004
Agriculture	Maize	Stalk	20-60	0.4	0.06656-0.19966	0.133
Agriculture	Maize	Corncob	20-60	0.4	0.01683-0.05048	0.034
Agriculture	Palm Oil	EFB	10-50	0.3	0.07207-0.36033	0.216
Agriculture	Palm Oil	PKS	10-50	0.3	0.02544-0.12718	0.076
Agriculture	Rice	Straw	25-80	0.525	0.19693-0.63018	0.414
Agriculture	Rice	Husk	25-80	0.525	0.03591-0.11491	0.075
Agriculture	Soybeans	Straw	40-60	0.5	0.0044-0.0066	0.005
Agriculture	Sugarcane	Bagasse	20-50	0.35	0.0214-0.0535	0.037
Agriculture	Sugarcane	Top and Leaves	20-80	0.5	0.00714-0.02856	0.018
Forestry	Chipwood	Solid and Sawdust Residue	25-70	0.475	0.0009-0.0025	0.002
Forestry	Industrial Forest Plantation (HTI)	Timber Harvesting Residue	42-79	0.605	0.04725-0.08886	0.068
Forestry	Mixed Tropical Hardwood	Timber Harvesting Residue	42-79	0.605	0.00725-0.01363	0.010
Forestry	Plywood	Solid and Sawdust Residue	25-70	0.475	0.00573-0.01604	0.011
Forestry	Sawlog	Solid and Sawdust Residue	25-70	0.475	0.04108-0.11502	0.078
Forestry	Sawnwood	Solid and Sawdust Residue	25-70	0.475	0.00182-0.00509	0.003
Forestry	Veneer Sheets	Solid and Sawdust Residue	25-70	0.475	0.00106-0.00295	0.002
Forestry	Timber Utilisation Permits for forest areas	Timber Harvesting Residue	42-79	0.605	0.00138-0.00259	0.002
Forestry	Perum Perhutani	Timber Harvesting Residue	42-79	0.605	0.0011-0.00206	0.002
Forestry	HTI Land Preparation	Timber Harvesting Residue	42-79	0.605	0.00061-0.00115	0.001
Forestry	Pulpwood	Solid and Sawdust Residue	25-70	0.475	0.05159-0.14445	0.098
Urban Waste	MSW	Solid Recovered Fuel	50-90	0.7	0.15638-0.28148	0.219
Total					**0.829-2.384**	**1.607**

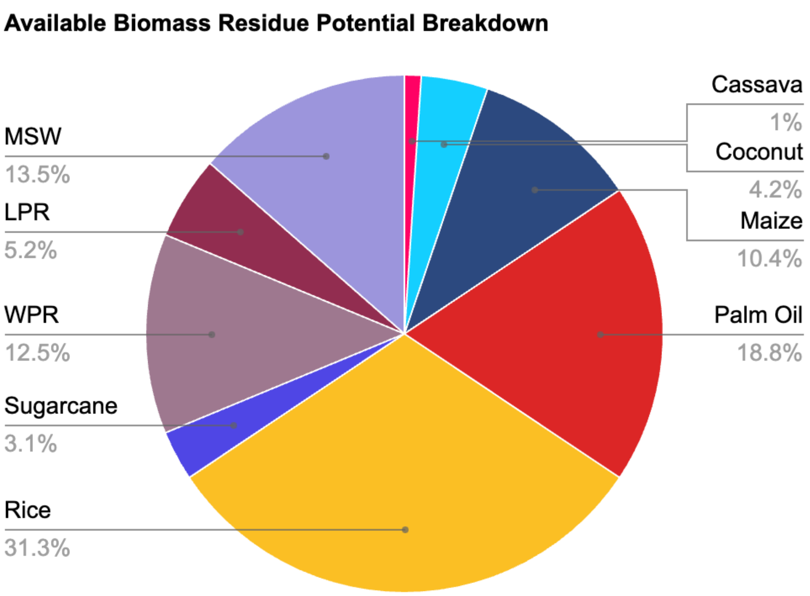


Figure 6.3: Available Biomass Potential Breakdown (Total = 1.607EJ). Note: WPR = Wood Processing Residues, LPR = Log Processing Residues.

6.3. Technical Biomass Potential

The technical biomass potential is the available biomass potential expressed in terawatt-hours (TWh), allowing for a comprehensive examination of the biomass residues within the context of electricity generation.

The graphical representation in Figure 6.4 illustrates the observed technical potential of the biomass residues investigated in this study, which amounts to a total of 450 TWh. Specifically, the rice residues in Indonesia exhibit the potential to generate 135 TWh of electricity, while palm oil residues, MSW, and wood processing residues have the capability to produce 81 TWh, 61 TWh, and 54 TWh of energy, respectively.

In 2020, Indonesia's final electricity consumption was reported to be 268 TWh (IEA, 2020a) and the projected electricity demand in 2030 is estimated to be 445 TWh (PLN, 2021). Based on the technical potential results, biomass residue potential is able to supply the electricity demand, exceeding by 5 TWh.

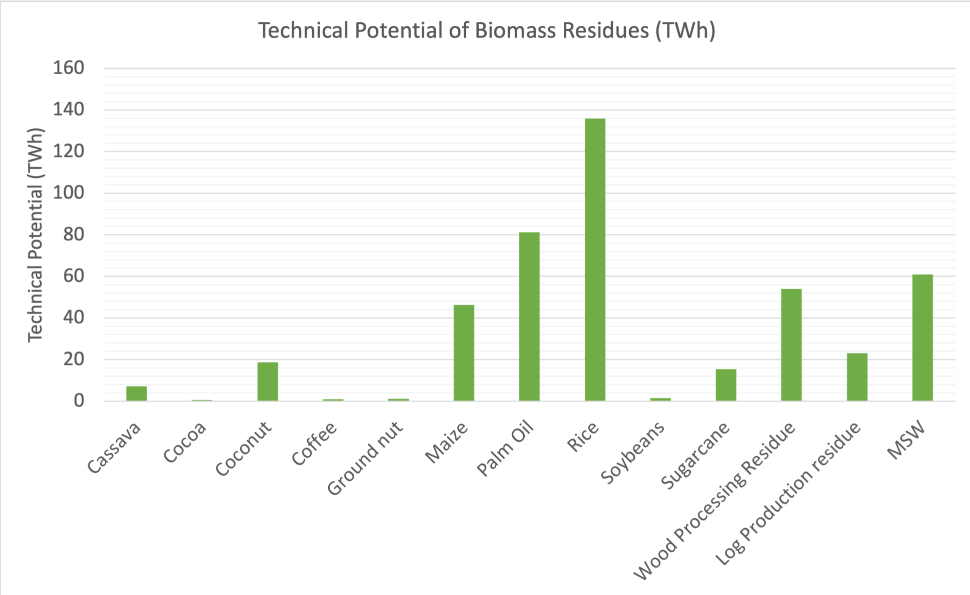


Figure 6.4: Technical Potential (TWh) of Biomass Residues in Indonesia

6.4. Co-firing Technical Challenges Results

In this section, a literature review on the technical challenges associated with co-firing will be presented. Firstly, an overview of co-firing technology will be provided, highlighting its key aspects and functionalities. Subsequently, the technical challenges encountered during co-firing operations will be examined in detail. Various obstacles and complexities that arise in the process of co-firing will be discussed. Furthermore, potential solutions and strategies to overcome these challenges will be explored and analyzed. Finally, the section will conclude with the development of co-firing scenarios specific for Indonesia, which will be used for the economic potential modelling.

6.4.1. Co-firing Technology Overview

The three main conversion technologies available in Indonesia are PC, CFB and Stoker combustion (BRIN, 2023). The total capacity of Indonesia's CFPPs are dominated by PC boiler with a percentage of 86%, followed by CFB and Stoker with a percentage of 13% and 1%, respectively (Arifin et al., 2023). The technical differences between these technologies affect the feasibility of biomass combustion and the range of material accepted. An overview of the co-firing range and biomass compatibility can be seen in Table 6.3. Overall, equipping CFB in the combustion unit allows larger particle sizes than the other two. However, CFB requires high maintenance and costly primary air pressure for circulating the bed material.

Contrasting, PC is the most widely used technology for utility-scale power generation. The downside of using PC is that smaller particles sizes (fine shavings <2mm) are tolerated in the system. This narrows down the biomass fuel flexibility (Roni et al., 2017).

Meanwhile, stoker boilers come in either chain-grate or spreader stoker boiler. chain-grate stokers have a moving chain or grate that carries the fuel for combustion, while spreader stokers evenly distribute the fuel on the combustion bed. Spreader stokers offer better fuel control, higher combustion efficiency, and can handle a wider range of fuel types, making them suitable for larger industrial facilities and power plants (Elie Tawil, 2013). Chain-grate stokers are used in smaller applications.

Table 6.3: Overview Co-firing Technologies Specifications mentioned in Roni et al. (2017); Karampinis et al. (2014); Tillman et al. (2012)

Pulverised Coal	**Circulating Fluidised Bed**	**Stoker**
• 1-40% cofiring mix • Particle size <2mm (Pulversied coal particle size ranges from 18-224um) • Moisture content <20wt% • Suitable for Coal, sawdust and fine shavings • PC boilers have a narrower range of tolerance for fuel properties.	• 60-95.3% cofiring mix • Particle size <40mm • Suitable for various fuels, woody biomass • Suitable for fuel mixtures that are less reactive and require long residence time for full conversion • High maintenance needed for the refractory in the bed • Bed technology requires costly primary air pressure.	• Chain-grate or spreader • 5-10% co-firing mix • Particle size between 6-25mm • Suitable for various fuels, woodchips, waste.

6.4.2. Co-firing Technical Challenges

The technical challenges of co-firing were reviewed and the key challenges are described below.

1. **Boiler Corrosion:** According to Karampinis et al. (2014), the utilization of biomass in direct co-firing scenarios, especially when exceeding a 20% mixture, can lead to challenges like increased slagging and fouling issues, mainly attributed to higher ash and inorganic content levels. Additionally, the combustion of biomass in certain cases, like CFB systems, can result in soot formation. The elevated ash content in biomass, compared to coal, could potentially contribute to boiler corrosion. Moreover, specific types of biomass containing elevated levels of potassium or chlorine can expedite the corrosion of boiler components. High moisture content in biomass impacts its combustion properties by lowering the maximum combustion temperature and extending the required residence time in the combustion chamber. This can lead to incomplete combustion and higher emissions.

   Additionally, the proximate analysis in Figure 6.5 reveals biomass residues generally have higher volatile content and lower fixed carbon than bituminous coal. However, some biomass fuels, like Kemper wood and sawdust, have lower ash content than coal. Others, such as rice husks and PKS, have higher ash and volatiles. Moreover, biomass ash composition varies due to the chemical components essential for plant growth. Biomass ash generally contains more inorganic material than coal ash. This discrepancy impacts ash handling, disposal, and may necessitate additional plant modifications.

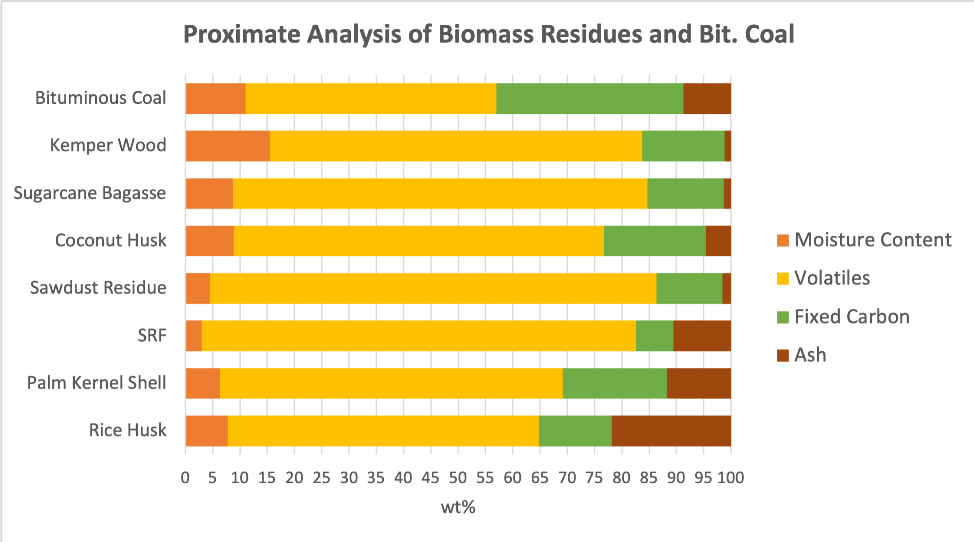


Figure 6.5: Proximate Analysis of selected Biomass Residues and Bituminous Coal in wt%

2. **System Flexibility:** The ability to utilize different types of biomass in a system is advantageous as less transport costs are required to transport biomass fuel if there is a possibility for it to be sourced locally. Generally, biomass has lower bulk densities, particle densities and heating values than coal (Baxter and Koppejan, 2005). However, the boilers observed in CFPPs may have limited flexibility. PC boilers have limitations concerning moisture content and particle size requirements, despite it being the most used boiler type in Indonesia.

   Furthermore, the co-milling of biomass and coal has the potential to result in a reduction of system efficiency. Although the practice of blending these two materials on the belt is feasible, it is subject to inherent limitations with a capacity in the range of 5% to 10% based on mass input identified, predominantly due to operational challenges encountered within the coal mills. Notably, the Naantali-3 T-fired boiler located in Naantali, Finland, serves as an illustrative example, revealing that the introduction of biomass alongside coal led to compromised mill fineness and the identification of biomass accumulation within the mill (Tillman et al., 2012).
3. **Crop Availability:** The availability of biomass feedstock from agriculture and forestry residues is dependent on the crop yield. This results in an unpredictable stock of biomass, making it challenging to maintain a consistent and reliable supply for the system (Roni et al., 2017).
4. **Generation and Accumulation of Dust:** The generation and accumulation of dust can be a concern in biomass systems, as it can swell and lead to mould growth Maciejewska et al. (2006).
5. **Fuel Conversion and Particle Size:** The size and density of biomass particles are essential factors affecting fuel conversion efficiency. Larger biomass particles, when not efficiently converted during combustion, may end up in the bottom ash with minimal conversion, leading to decreased overall system performance (Karampinis et al., 2014) .

6.4.3. Solutions to Technical Challenges

One effective solution to address the challenges of co-firing biomass is through indirect co-firing. This approach involves using two separate burners for the biomass before it enters the main boiler, as advised in Maciejewska et al. (2006); Livingston (2013) By doing so, the biomass can be better handled, leading to improved combustion efficiency and reduced operational issues. Indirect co-firing allows for more controlled and optimized burning of the biomass, minimizing potential problems associated with direct mixing of biomass and coal in the boiler.

Another valuable strategy to overcome co-firing challenges is pre-treatment of the biomass before combustion. One form of pre-treatment is pelletizing. Pelletizing biomass residues can be a viable solution to tackle high moisture content and low density issues (IEA, 2016). This process transforms the biomass into densified pellets, making long-haul transport more feasible and efficient. Additionally, the torrefaction of biomass can yield materials with physical and chemical properties similar to bituminous coal. This opens up the opportunity for high substitution ratios of biomass in existing coal-fired boilers without significant modifications.

Furthermore, ash from biomass co-firing can potentially serve as fertilizers due to its magnesium and calcium content. Fly ash from fluidized bed biomass gasification, with high energy content and unburned carbon, can be used as fuel for power generation Tumuluru et al. (2011).

To ensure the biomass is suitable for the combustion process, on-site pre-treatment processes can include reception hopper grids and cyclones to remove large and small materials, respectively. Magnets can also be employed to separate ferrous materials. Furthermore, milling the biomass before it enters the boiler can significantly reduce particle size to 50-90 μm, making it suitable for PC furnaces (Livingston, 2013).To mitigate the risks of dust generation and accumulation, implementing measures such as explosion vents and fire suppression systems can help manage the potential hazards (Maciejewska et al., 2006; Karampinis et al., 2014).

As reviewed by Tortosa-Masiá et al. (2005), improving slagging and fouling monitoring involves establishing a comprehensive database that encompasses key biomass fuel characteristics, including alkali, alkaline earth, silica, sulfur, ash melting point and chlorine content. This data set serves as a foundation for modeling the heat transfer and transport dynamics within the boiler. By integrating sensors capable of analyzing real-time combustion conditions, the prediction of slagging and fouling tendencies can be enhanced.

Furthermore, effective on-site storage facilities are essential in dealing with co-firing challenges related to biomass availability and seasonality. Storing biomass in bales or piles not only reduces the area required for storage but also minimizes physical and biological decomposition (Karampinis et al., 2014). This mitigates the risk of resource seasonal availability and ensures a steady supply of biomass for co-firing operations. Proper storage facilities contribute to the overall stability and reliability of the co-firing system, allowing for continuous operation and optimizing the use of available biomass resources.

6.4.4. Co-firing Scenario Development

Based on the co-firing technology review, several retrofit scenarios can be outlined for different co-firing ranges.

A feasible approach for co-firing below 10% involves co-milling, where biomass and coal are mixed before entering the mill system. This method requires adjustments to handling and storage systems. However, a concern is the potential biomass particle accumulation in the mill. Biomass sorting can be based on the Hardgrove Grindability Index (HGI), which measures grinding ease. A higher HGI implies easier grinding, while a lower value suggests resistance. For example, sub-bituminous coal possesses an HGI of 50, while wood pellets exhibit values ranging from 16 to 18, and raw empty fruit bunches have an HGI of 12. (Tymoszuk et al., 2019). Additionally, it is crucial to avoid direct contact between dry biomass and the hot primary air within the mill to prevent the premature release of volatile combustibles from the biomass.

When considering co-firing levels between 10% and 50%, a dedicated milling equipment for biomass becomes a more practical option. Implementing such equipment can enhance the thermal share of biomass in the overall combustion process. To achieve desired particle sizes, the installation of hammer mills specifically developed for biomass fuels may be necessary (IEA, 2016). Furthermore, it is recommended to establish a separate on-site storage facility dedicated to storing biomass, ensuring proper handling and logistics.

Co-firing at levels exceeding 50% necessitates significant modifications to the existing boiler setup. Specifically, for pulverized fuel-fired boilers, replacing the bottom with a new bubbling fluid bed type bottom could allow better handling of biomass fuels with moisture content ranging between 50% to 60%. Furthermore, adjustments to the air to fuel ratio and ignition flame may be required to accommodate the characteristics of biomass as the predominant fuel source in the combustion process (Karampinis et al., 2014). A summary of the proposed scenarios can be visualised in Figure 6.6.

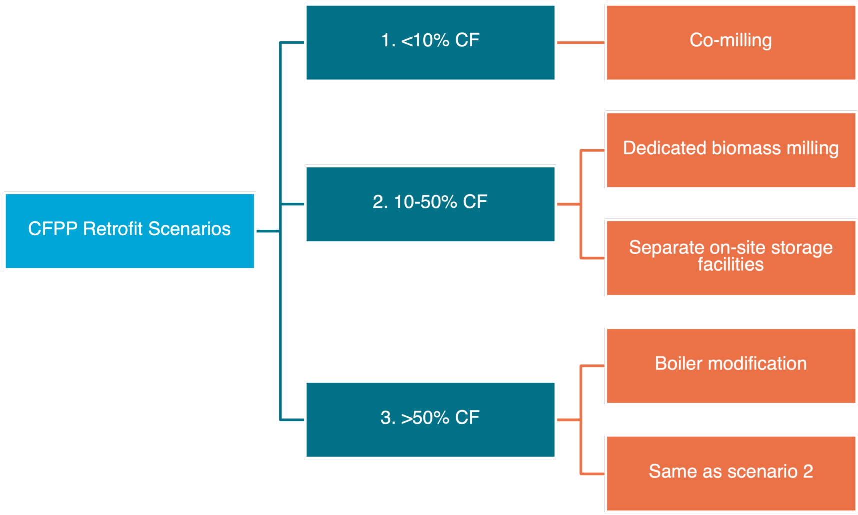


Figure 6.6: Proposed retrofit strategies for various co-firing scenarios within Indonesia's CFPPs, considering the precondition that the biomass undergoes pelletization before being introduced into the system.

In summary, the theoretical potential of biomass residues in Indonesia is calculated to be 3.57 EJ. Rice straw has the highest theoretical potential (0.79 EJ), followed by empty fruit bunch (0.72 EJ), and corn stalk (0.33 EJ). The available biomass potential is dominated by agricultural by-products (70%), followed by forestry residues (17%) and Municipal Solid Waste (MSW) (13%). Among agricultural residues, rice and palm oil residues lead with potentials of 0.49 EJ and 0.29 EJ respectively. For forestry residues, solid and sawdust residues contribute 0.098 EJ and 0.078 EJ respectively. The total available biomass residues amount to 1.607 EJ. The estimated technical potential for co-firing is 450 TWh.

Part III

Economic Potential Analysis

7
Economic Potential Methodology

In this chapter, the methodology for the economic potential analysis is described. Section 7.1 will include the equation used for calculating LCOE, key assumptions of the model and Indonesia's system for electricity selling. Section 7.2 will discuss the input parameters taken into account for the LCOE calculation.

7.1. Economic Potential Calculation

LCOE is the measure of the average total cost of generating electricity over the lifetime of a power plant. It takes into account the costs of building and operating the power plant. This includes the cost of financing the project, fuel, maintenance, and decommissioning. it is defined as the cost of electricity generated per unit of energy and can have the unit of price per kWh. The formula for LCOE, obtained from Abdelhady et al. (2018) can be seen below:

$$\text{LCOE} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \tag{7.1}$$

Where:

$I_t =$ Investment cost in year t
$M_t =$ operation and maintenance cost in year t
$F_t =$ Fuel cost in year t
$n =$ Expected asset lifetime
$r =$ real discount rate
$E_t =$ Energy production in year t

The investment cost is expected to have low impact compared to the fuel cost since the study intends to utilise existing infrastructure from steam power plants. The retrofitting cost will include additional equipment required proposed in Section 6.4.4 for biomass co-firing in which these costs would be included in investment and maintenance.

Moreover, Indonesia's CFPP is majorly situated in the western side of Indonesia Figure 7.1 presents the location of all operating CFPP in Indonesia. The coordinates of the CFPP were retrieved from Global Energy Monitor database and the map was generated using QGI, a free and open-source cross-platform desktop geographic information system application that supports various geospatial tasks (QGIS, 2023). As observed in Figure 7.1, the islands of Java, Sumatra and Sulawesi comprises the highest amount of CFPP, with a capacity of 25 GW, 5.8 GW and 6.2 GW, respectively.

Furthermore, the key assumptions are specified below:

1. **Location**: The economic potential model will focus on two case studies. Case study 1 (CSI) will

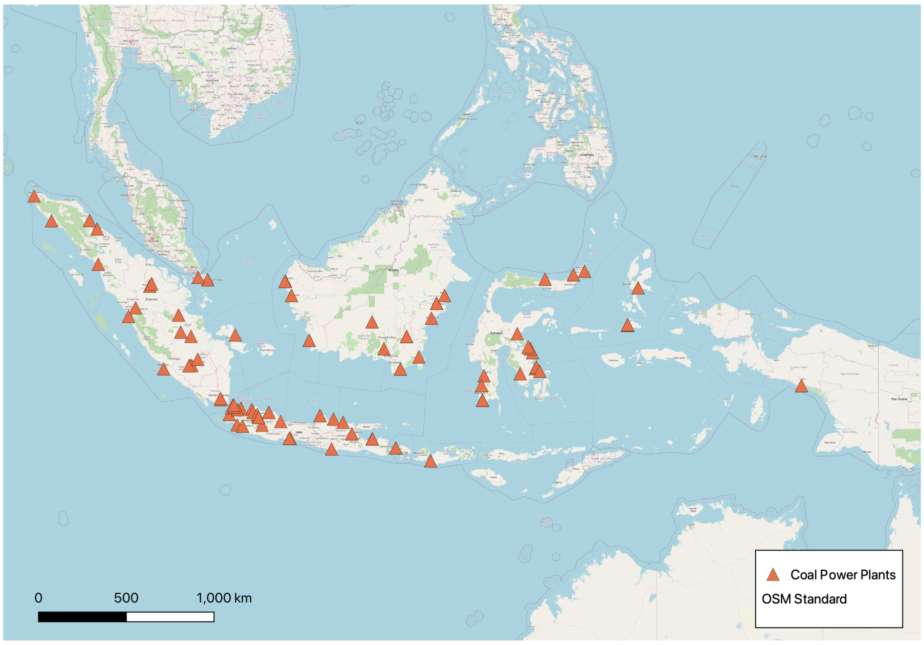
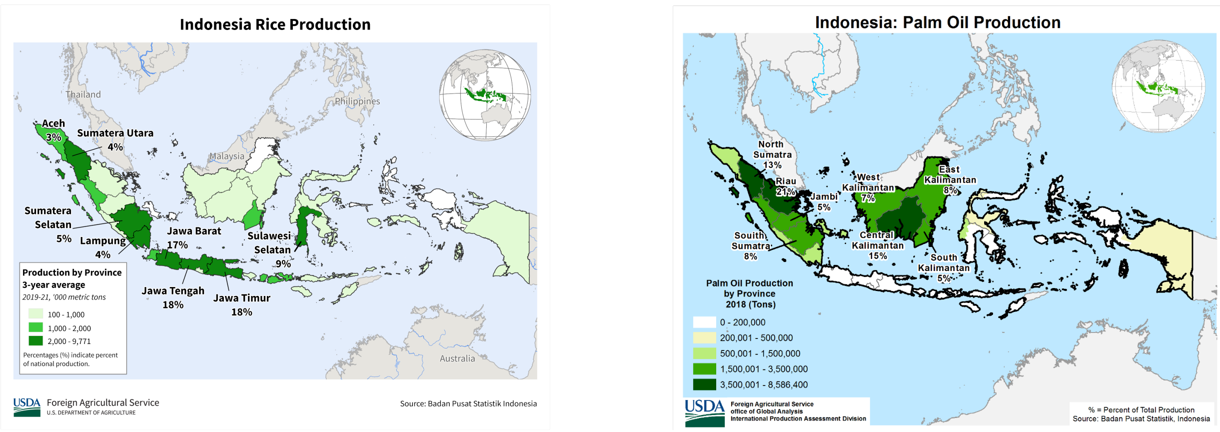


Figure 7.1: Map of operating CFPP in Indonesia, retrieved form GEM (2023)

model the 200 MW Kalbar-1 CFPP in West Kalimantan and Case study 2 (CSII) will model the 600MW Suralaya CFPP in West Java. The first location was selected based on the high availability of PKS biomass resources in the Kalimantan island (see Figure 7.2b). The decision to model the West Java CFPP is primarily driven by the fact that the island of Java houses over 56% of Indonesia's population (Statista, 2020), resulting in substantial electricity demand in the region.

2. **Biomass Type**: As mentioned earlier, the biomass source chosen for CSI is PKS. PKS exhibits high calorific value and low moisture content which makes its an attractive feedstock for combustion. Additionally, the residue has also been used in co-firing trials by PLN (Rachmatullah, 2020). As for CSII, RH was considered based on the high availability of RH in Java (see Figure 7.2a). By utilising biomass sources available in the same island, the costs for transporting the material may be reduced.



(a) Map of Rice Production in Indonesia, retrieved from USDA (2023b)

(b) Map of Palm Oil Production in Indonesia, retrieved from USDA (2023a)

Figure 7.2: Map of Palm Oil and Rice Husk production in Indonesia, retrieved from USDA (2023b,a)

3. **Co-firing Technology**: The co-firing technology was chosen based on the results of the Technical Potential Analysis. According to Sugiyono et al. (2022), Indonesian CFPPs predominantly utilize

PC combustion as their primary combustion technology. Moreover, the direct co-firing requires the least modifications and most straightforward co-combustion technique. Since the thesis focuses on modelling co-firing in a national scale, the choice of technology is chosen based on the most available.

4. **Capacity Factor**: This is the unitless ratio of actual electrical energy output over a given period of time to the theoretical maximum electrical energy output over that period. The capacity factor of CFPP's in Indonesia is approximated to be 53% based on data retrieved from GEM (2023).
5. **Discount Rate**: A 7% discount rate was applied for this model. This was chosen based on the rationale that co-firing projects are relatively lower risk. Additionally, the existence of previous trials and investments in similar projects provided further support for this decision.
6. **Asset Lifetime**: Asset lifetime has been assumed to be 10-15 years. This is approximately half the lifetime of an average CFPP. This is based on if co-firing was adapted halfway through the plant's lifetime due to the increasing commitment to transition from fossil fuels to RE over the past decade.

The LCOE calculation results will be compared with the National BPP and it will demonstrate on which conditions the retrofitted coal plants is higher, lower or equal to the BPP.

7.2. LCOE Input Data

In this section, assumptions of the input parameters for the LCOE calculation will be explained.

7.2.1. Calculating Energy Production

The energy production is based on the plant capacity, capacity factor and operational hours. The plant capacity for CSI and CSII is 200MW and 600MW, respectfully. The typical coal power plant in Indonesia operates in condensing mode, with no district heat production (Directorate General Electricity, 2021). Therefore, E can be interchanging with 'electricity' in this case. The capacity factor is assumed to be 53% for both plants. The plant is assumed to operate continuously for 365 days a year thus the operational hours is set at 8760 hours.

$$E = CF \times OH \times PC \tag{7.2}$$

Where:

$E =$ Energy produced in a year (MWh)
$CF =$ Capacity Factor (-)
$OH =$ Operational Hours (h)
$PC =$ Plant Capacity (MW)

7.2.2. Calculating Fuel Cost

The second component of the LCOE that will be discussed is the fuel cost (F), which can be broken down as follows:

$$F = Ct_b + P_b + Ct_c + P_c \tag{7.3a}$$
$$Ct_c = Ct_{R,c} + Ct_{L,c} \tag{7.3b}$$
$$Ct_b = Ct_{R,b} + Ct_{L,b} + Ct_{P,b} \tag{7.3c}$$

Ct represent the cost per ton ($/ton) of the subscripts c, b, R, L, P representing coal, biomass, Raw feedstock, Logistics and Pre-treatment, respectively. P represent the fuel quantity in ton/year for coal (c) and biomass (b).

The fuel cost for biomass (Ct_b) is sum of the cost of raw feedstock, logistics and pre-treatment costs. The fuel cost for coal (Ct_c) follows the same equations, except the pre-treatment cost is excluded in the fuel price.

Fuel Quantity

The coal fuel quantity is the amount of coal required for combustion in a year. This was determined based on the following equations:

$$P_c = \frac{(1 - \beta_{co}) \times E}{LHV_c \times 0.001 \times \eta} \tag{7.4}$$

The same can be followed for the biomass fuel quantity:

$$P_b = \frac{(1 - \beta_{co}) \times E}{LHV_b \times 0.001 \times \eta} \tag{7.5}$$

Where β_{co} is the fraction of co-firing (-).The symbol η represents the average thermal efficiency of sub-critical CFPPs in Indonesia, standing at 36% as per Directorate General Electricity (2021). Moreover, the range for η within Indonesia's CFPP spans from 29% to 45%, implying potential for adjustments in this parameter.

Feedstock Price

The biomass feed stock price, ($Ct_{R,b}$) is the price of the raw biomass residue. The buying price of the residues were found through reviewing several PLN documents, as well as general websites. The outcome of this research resulted in the prices noted in Table 7.1. The lower prices for rice husks and PKS were derived from PLN's co-firing document (Rachmatullah, 2020), referencing the "price of biomass for co-firing trial." The higher prices for rice husks are also sourced from this document, obtained through farmer surveys for co-firing implementation. Additionally, the higher price for PKS is based on the international market price retireved from palmkernelshell.id (2023).

The residues that were chosen in the model were based on the results of the technical potential. As concluded in Section 6.2, the analysis concludes that the two most available biomass residues are derived from rice and palm oil sources. Among the two rice residues, although rice straw exhibits higher availability, rice husks showcase superior characteristics such as lower moisture content and reduced chlorine and alkaline content. Simultaneously, PKS were favored over empty fruit bunches, primarily due to their higher calorific value and lower ash content.

Additionally, the third most available residue arises from SRF sourced from MSW. However, the economic viability of utilizing SRF as feedstock is challenged by its high price, which is noted as $301 per ton according to a reference by PLN (Rachmatullah, 2020). This cost consideration renders SRF uneconomical and less attractive as a feasible fuel option.

Table 7.1: Low and High Prices of Raw Biomass Residues ($Ct_{R,b}$)

Biomass Residue	Low Price ($/ton)	High Price ($/ton)	Source
PKS	40	100	(Rachmatullah, 2020; palmkernelshell.id, 2023)
Rice Husks	35	60	(Rachmatullah, 2020)

Meanwhile, the price of raw coal ($Ct_{R,c}$) was set based on the buying price of PLN, which is equivalent to 30$/ton (Rachmatullah, 2020).

Modelling Logistics

The biomass logistics cost, $Ct_{L,b}$ is the cost of transporting the biomass from the source to the CFPP. The logistics modelling assumptions differs per case study. CSI assumes a transport route from palm oil mills in West Kalimantan to the Kalbar-1 power station. CSII assumes a transport route from rice paddies in West Java region to the Suralaya power station. however, both case studies assume transport by truck via road.

Additionally, the values for truck price, truck capacity and fuel economy were retrieved from Purwanto et al. (2022). The personnel wage was estimated from salaryexplorer (2023b). The diesel price was assumed from current diesel prices in Indonesia as of June 2023 (Pertamina, 2023). The model assumptions for the two case studies can be seen in Table 7.2

Table 7.2: Biomass Logistics Model Assumptions

Inputs	logistics Model Assumptions	Source
Biomass Source	Case Study I: Palm Oil Mills in West Kalimantan Case Study II: Rice Paddies in West Java	Own Assumption
Truck Price, C_V	\$70,000	Purwanto et al. (2022)
Truck Capacity, Xt_V	10 tons	Purwanto et al. (2022)
Drivers per Truck, $N_{S,L}$	2	Purwanto et al. (2022)
Fuel Economy, FE	5 km/litre	Purwanto et al. (2022)
Personnel wage, S_L	400 \$/month	salaryexplorer (2023b)
Diesel Price, Cl_d	0.9045 \$/litre	Pertamina (2023)

Meanwhile, the assumption for transport distance was determined by two methods. The first method involved utilizing QGIS. The distance between the palm oil mills and Kalbar-1 power station in West Kalimantan was determined using the Network Analysis toolbox function ”Shortest Path (point to point)” within QGIS. The coordinates and the capacity of the palm oil mills were retrieved from Heinimann (2020). The number of palm oil mills required can be calculated by dividing the fuel quantity of biomass needed per day and the PKS output from the palm oil mills per day. From this, the amount of palm oil mills are determined when co-firing at a specific percentage and thus the transport distance range can be calculated.

Furthemore, the second method assumes that rice husk are sourced from plantations in three provinces: Banten, Jakarta and West Java. The rice paddy production per province was taken from Indonesian Central Bureau of Statistics (BPS, 2023). The supply of rice husk is then determined by multiplying the by-product to product ratio and the availability factor. the full list of regions and their rice husk production can be seen in in the appendix (Table A.1). After calculating the supply of rice husk per province, the furthest travel distance can be estimated. Once the transport distances are established, the total operating cost can be computed using the specified parameters from Table 7.2 and the given transport distance.

$$N_V = \frac{P_b}{365 \times C_V \times N_{RT}} \tag{7.6a}$$

$$V_d = \frac{D}{FE} \times N_{RT} \times N_V \tag{7.6b}$$

$$Cy_d = Cl_d \times V_d \times 365 \tag{7.6c}$$

$$Cy_{S,L} = N_{S,L} \times S_L \times 12 \tag{7.6d}$$

$$Cy_{O,L} = Cy_d + Cy_{S,L} \tag{7.6e}$$

$$Ct_{L,b} = \frac{Cy_{O,L}}{P_b} \tag{7.6f}$$

Where N represents the count of items (-), with subscript V denoting trucks and RT indicating round trips, variables such as D stand for travel distance in kilometers (km), V_d represents the daily diesel consumption rate in liters (litre/day), and Cy pertains to the annual cost (\$/year) associated with subscripts d (diesel), S (Personnel), L (Logistics), and O (Operation).

The coal logistics cost, $Ct_{L,c}$ was determined differently for the two case studies. For CSI, the coal is assumed to be transported by barge from Ida Manggala coal mine in South Kalimantan via the PT Tapin Coal Terminal. The shipping rate for coal transport via this route was reported to be 4 \$/ton (Widhi, 2022).

However, the coal transport for CSII was assumed to be from the Bukit Asam Coal Mine in Muara Enim, South Sumatra. The logistics model assumes multimodal transport route of rail and barge transport. The rail transport occurs from the coal mine to the Port of Palembang which covers a distance of 154km (see Figure 7.3a). This method is already been used in practice and rail infrastructure was constructed in the 1940’s. The barge transport assumes the use of a tug boat and barge combination from the Port of Palembang to the Suralaya coal terminal with a distance of 441 nautical miles (see Figure 7.3b). Figure 7.3 depicts the route for rail and barge.

The cost of transport by rail and barge were determined based on data from Hardian (2011), which modelled the coal transport economics in South Sumatra. The paper states that for the transport mode of railway and barge, the costs are 0.005-0.001 \$/ton-miles and 0.020-0.023 \$/ton-miles, respectfully. Therefore, the costs per ton can be calculated by converting the distance to miles unit and adjusting for inflation. Also, according to the Decree of the MEMR Number 18.K/HK.02/MEM.B/2022 Year 2022 document, the maximum transshipment cost for coal is 4 \$/ton (MEMR, 2022).

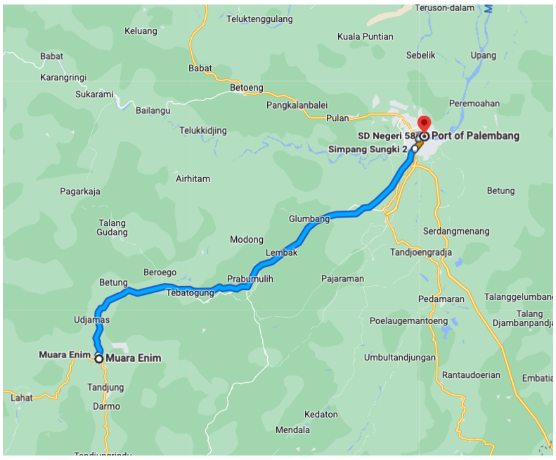
$$C_{rail}\ \text{\$/ton} = \frac{154\ \text{km}}{1.6\ \text{km/miles}} \times 0.023\ (\text{\$/ton-miles}) \tag{7.7a}$$

$$C_{barge}\ \text{\$/ton} = \frac{441\ \text{nm}}{0.87\ \text{nm/miles}} \times 0.01\ (\text{\$/ton-miles}) \tag{7.7b}$$

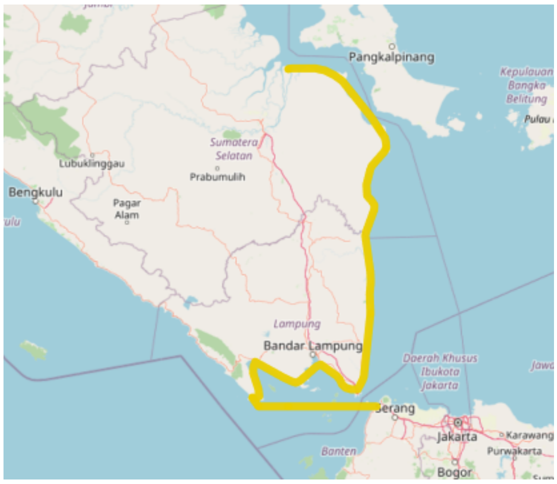
$$C_{trans}\ \text{\$/ton} = 4\ \text{\$/ton} \tag{7.7c}$$

$$Ct_{L,c}\ \text{\$/ton} = C_{rail} + C_{barge} + C_{trans}\ \text{\$/ton} \tag{7.7d}$$

Where C_{rail}, C_{barge}, C_{trans} is the cost of rail, barge and transshipment in \$/ton, respectively.



(a) Railway transport from Coal Mine to Port



(b) Barge Transport from Port in Sumatra to CFPP Coal Terminal

Figure 7.3: Coal Transport Multi-Modal Route for CSII

Modelling Pre-treatment

The pre-treatment cost for biomass, $Ct_{P,b}$ is the cost of pelletizing the raw biomass. The choice of pelletizing as a pre-treatment option was chosen based on the technical potential results. The pre-treatment of biomass is assumed to be performed prior to transport from the source of pickup. The values for equipment price and capacity, electricity consumption and price, and personnel per machine were derived from Purwanto et al. (2022). The personnel wage was assumed based on average salaries for factory workers in Indonesia (salaryexplorer, 2023a).The key assumptions for the pelletizing model can be seen in Table 7.3.

Furthermore, the cost of pre-treatment can be calculated with the input parameters in Table 7.3 and the biomass fuel quantity.

$$N_M = \frac{P_b}{365 \times Xd_M} \tag{7.8a}$$

$$Cy_{S,P} = N_M \times N_{S,P} \times S_P \times 12 \tag{7.8b}$$

$$Cy_{el} = P_b \times \phi_{el} \times Ce_{el} \tag{7.8c}$$

$$Cy_{O,P} = Cy_{S,P} + Cy_{el} \tag{7.8d}$$

$$Ct_{P,b} = \frac{Cy_{O,P}}{P_b} \tag{7.8e}$$

Table 7.3: Biomass Pelletizing Model Assumptions

Inputs	**Pelletizing Model Assumptions**	**Source**
Location	Case Study I: situated in palm oil mills Case Study II: situated in Rice Processing Facilities	Own Assumption
Equipment Price, C_M	$50,000 per unit	Purwanto et al. (2022)
Equipment capacity, Xd_M	20 ton/day	Purwanto et al. (2022)
Personnel per machine, $N_{S,P}$	5	Purwanto et al. (2022)
Personnel wage, S_P	600 $/month	salaryexplorer (2023a)
Electricity Consumption, ϕ_{el}	0.1375 kWh/kg	Purwanto et al. (2022)
Electricity Price, Ce_{el}	0.07 $/kWh	Purwanto et al. (2022)

Where N_M is the number of machines required, Cy is the cost per year ($/year) of the subscripts el (electricity), S (Personnel), P (Pelletizing) and O (Operation).

7.2.3. Calculating Investment and O&M Cost

The Investment cost, I includes the additional expenses related to the construction, equipment, materials, labor, and other costs needed to facilitate co-firing. The type of modifications has been determined based on the technical potential results. As there is no known data regarding the retrofit costs for CFPP's in Indonesia, the values were derived based on thorough literature search from other papers.

The paper by Abdelhady et al. (2018) conducts a techno-economic analysis for designing biomass power plants in Egypt. The study estimates direct capital costs for specific equipment required, with the fuel handling equipment estimated at 182 $/kW and the boiler at 500 $/kW. Based on the paper's estimates, the investment costs for retrofitting CFPP were determined to be 200 $/kW for fuel handling and 200 $/kW for boiler upgrading/modification. The slightly higher price chosen for fuel handling is attributed to inflation, as the paper was written two years ago. Meanwhile, the lower cost chosen for the boiler is because the retrofit assumes the use of the existing boiler with necessary upgrades.

Additionally, the investment cost also includes the truck and the pelletizing equipment costs, I_L and I_{PT} respectively. These values can be calculated based on the previous parameters defined:

$$I_L = C_V \times N_V \tag{7.9}$$
$$I_P = C_M \times N_M \tag{7.10}$$

Moreover, the O&M costs, M includes the additional cost for labor, electricity, insurance, utilities, planned and unplanned maintenance. The O&M costs are assumed to be 3% of the additional investment costs for retrofitting.

Six scenarios have been outlined determining the degree of additional equipment and modifications. The first three scenarios do not include the initial investment cost of the CFPP whereas the last three scenarios do. The investment (I_C), fixed O&M (M_F) and variable O&M (M_V) costs for CFPP were retrieved from IESR (2023). The scenarios are outlined in Table 7.4.

Meanwhile, the investment costs for each scenario can be expressed:

$$I_{1A} = I_L + I_{PT} \tag{7.11a}$$
$$I_{2A} = I_{FH} + I_L + I_{PT} \tag{7.11b}$$
$$I_{3A} = I_{FH} + I_{BM} + I_L + I_{PT} \tag{7.11c}$$
$$I_{1B} = I_C + I_{1A} \tag{7.11d}$$
$$I_{2B} = I_C + I_{2A} \tag{7.11e}$$
$$I_{3B} = I_C + I_{3A} \tag{7.11f}$$

Table 7.4: LCOE Investment and O&M cost scenarios

Scnearios	Co-firing Mix	Investment	O&M
1A	10%	Logistics and Pelletizing Equipment	3% of Investment Cost Scenario 1A 3% Investment Cost for Fuel Handling & Storage
1B		Scenario 1A plus CFPP Initial Investment Cost included	3% of Investment Cost Scenario 1B 3% Investment Cost for Fuel Handling & Storage
2A	20%	Logistics and Pelletizing Equipment Fuel Handling & Storage	3% of Investment Cost Scenario 2A
2B		Scenario 2A plus CFPP Initial Investment Cost included	3% of Investment Cost Scenario 2B
3A	50%	Logistics and Pelletizing Equipment Fuel Handling & Storage Boiler Modification	3% of Investment Cost Scenario 3A
3B		Scenario 3A plus CFPP Initial Investment Cost included	3% of Investment Cost Scenario 3B

Also, the maintenance costs for each scenario can be expressed as a function of the Investment costs.

$$M_c = M_{\text{fixed}} + M_{\text{var}} \tag{7.12a}$$
$$M_{1A} = 0.03 \times (I_{1A} + I_{FH}) \tag{7.12b}$$
$$M_{2A} = 0.03 \times I_{2A} \tag{7.12c}$$
$$M_{3A} = 0.03 \times I_{3A} \tag{7.12d}$$
$$M_{1B} = 0.03 \times (I_{1A} + I_{FH}) + M_c \tag{7.12e}$$
$$M_{2B} = 0.03 \times I_{2A} + M_c \tag{7.12f}$$
$$M_{3B} = 0.03 \times I_{3A} + M_c \tag{7.12g}$$

Once the initial LCOE results are calculated, a sensitivity analysis will be performed in which the parameters η, LHV, D and $\text{Ct}_{R,b}$ will be subject to a ± 10% variation in default values for both case studies. A schematic for the case study model is depicted in Figure 7.4

Additionally, the LCOE of different CFPP plant sizes available in Indonesia will be determined based on CSII model. The plant size will be varied from 30-1000MW and the variables taken from CSII will be the feedstock type (rice husk), logistics model for the coal and biomass and the pelletizing model for the biomass. The efficiency and capacity factor will follow the previous assumptions (36% and 53%, respectively). Three scenarios will be discussed, A B and C. The investment and O&M criterion mentioned in Table 7.4 will be used for scenarios A and B with additional requirement in which Scenario A will use low-end feedstock cost (34.5 $/ton) whereas scenario B uses the high-end feedstock cost (60 $/ton). An additional scenario was created as a middle-end LCOE output (scenario C) in which the investment and O&M costs follow from scenario B but the feedstock costs used is within the mid-range of 50 $/ton and the plant lifetime is set to 20 years.

Furthermore, a comparison of the LCOEs of varying energy generation technologies in Indonesia will be done. The input parameters for other NRE technologies used in the comparison of LCOE with other technologies can be found in the appendix (see Table A.3 and Table A.2). As for the co-firing model, the parameters will be based on the economic analysis results.

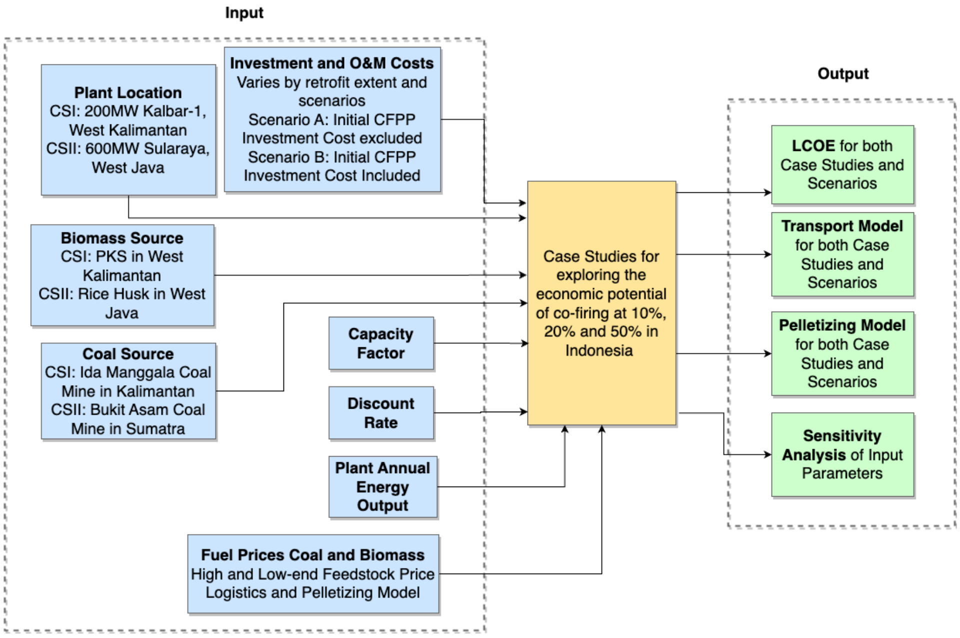


Figure 7.4: Schematic of economic potential input and output variables for the two case studies

7.2.4. Chapter Summary

This chapter provided a comprehensive overview of the input parameters utilized in the calculation of the LCOE. The essential variables required for determining fuel cost, investment cost, maintenance cost, and energy production have been thoroughly explained, and the underlying assumptions have been clarified. Subsequently, the LCOE methodology, employed to assess the economic potential, will be subjected to a detailed analysis in the results section. The anticipated outcome of this analysis is to compare the two case studies and investigate the impact of factors such as fuel cost, location, and plant size on the LCOE. Furthermore, a sensitivity analysis is conducted to identify the variables with the most significant influence on the LCOE value when subjected to a $\pm 10\%$ variation. The results of the LCOE assessment also contribute to the determination of which co-firing CFPP in Indonesia meet the national BPP. Lastly, a comparative evaluation will be made between the LCOE of co-firing CFPPs and other NRE technologies to observe its level of competitiveness in the energy market.

8

Economic Potential Results

In this chapter, the results of the Economic Potential Analysis is presented. Firstly, the results of the input parameters that were modelled are exhibited in Section 8.1. Secondly, the LCOE results of both case studies will be shown in Section 8.2 along with a sensitivity analysis of input parameters and the comparison of the co-firing model to other RE technologies.

8.1. Input Variable Results

The results of the fuel quantity of coal and biomass (P_c and P_b) were calculated using Equation 7.4 and Equation 7.5. The values are presented in Table 8.1. Overall, the larger plant size (CSII) requires higher amount of biomass fuel. At 50% co-firing, the amount of rice husk required is close to 1000 kton/year, this amounts to around 17% of the available rice husk potential in Indonesia per year. As for CSI, the the required PKS quantity for 50% co-firing equates to roughly 5% of total PKS potential in Indonesia.

Moreover, the results of transport distance (D) estimation were calculated using QGIS. The shortest path toolbox was used and the distance from 10 of the closest palm oil mills were calculated (see Figure 8.1). For CSI, it can be seen that the maximum distance for 50% co-firing was found to be 160km and the minimum distance was 19km for 10% co-firing.

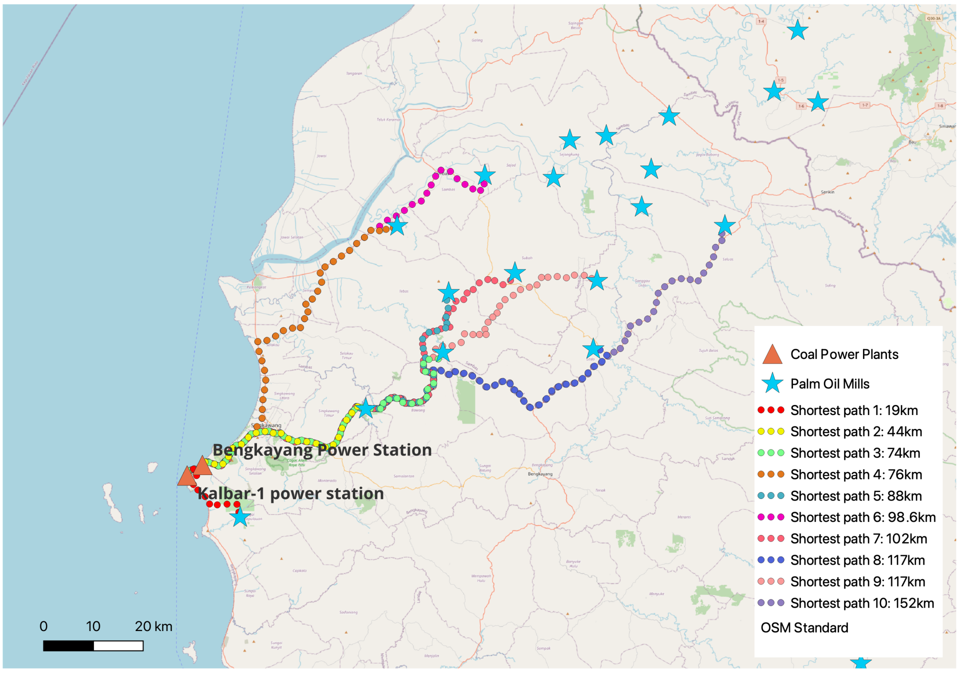


Figure 8.1: Map of Travel Distances between Kalbar-1 Power Station and palm oil mills in West Kalimantan

For CSII, the furthest distance was estimated based on the quantity of rice husk required at 50% co-firing. The furthest area to obtain the rice husk from was found to be the sub-province of Indramayu, 320km away from the power plant. As for 10% co-firing, the rice husk production from the province of Banten and Jakarta were sufficient to supply the co-firing. For 20% co-firing, rice husks from sub-provinces of Karawang and Sukabumi were required to supply the co-firing operation. A diagram was drawn in QGIS to visualise the rice husk collection distances based on a radii (see Figure 8.2).

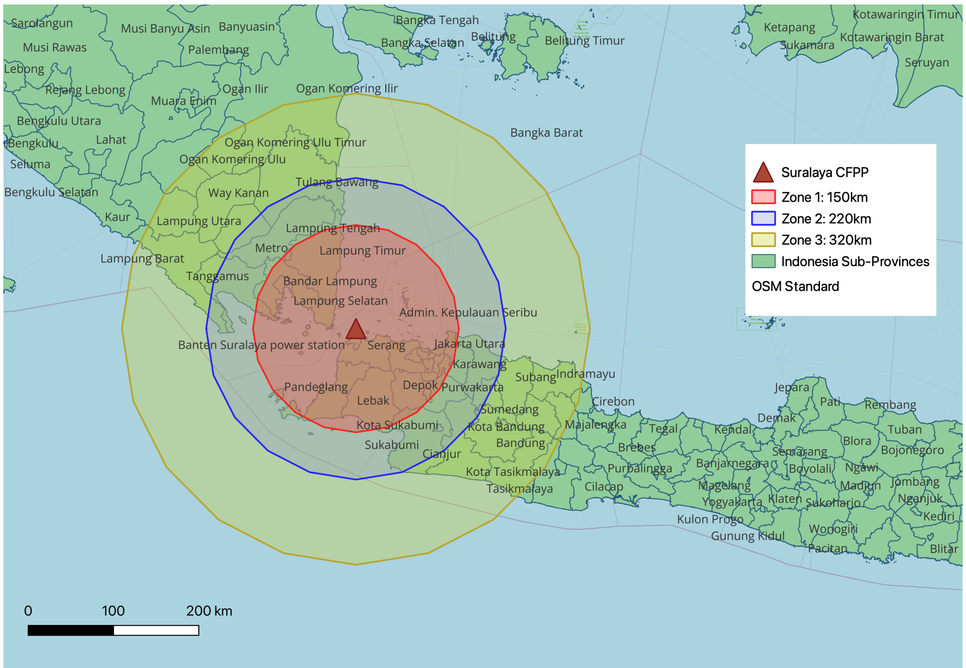


Figure 8.2: Map of Travel Radii between Suralaya Power Station and sub-provinces in Western Java with rice husk supply potential.

Once the transport distances are estimated, the biomass transport costs were calculated using the results of the fuel quantity and Equation 7.6. The results can be seen in Table 8.1. The biomass transport cost for CSI equated to a range of 3.31-7.1 $/ton whereas CSII resulted in a higher range of 7.2-13.3 $/ton. This is expected as the travel distance (D) for CSII was larger and therefore the diesel consumption directly affects the transport cost.

As for the coal transport, the multi-modal transport model (Equation 7.7) for CSII was used to determine the transport cost for coal transport from Bukit Asam Coal Mine to the Suralaya CFPP. The results of the model exhibit a transport cost of 14 $/ton in which rail, barge and transshipment costs were 3$/ton, 7 $/ton and 4 $/ton, respectively. The total cost is 3.5 times higher than coal transport in CSI. This is expected as the multi-modal transport incurs higher cost which could be derived from the transshipment costs.

The pelletizing model is assumed to be the same for both case studies. The results were determined using Equation 7.8 and biomass fuel quantities. The values are presented in Table 8.1. The pre-treatment costs of both case studies were nearly identical, however, CSI exhibited a slightly higher average.

The raw feedstock costs and the total cost of biomass and coal per ton were presented in Table 8.2. The lowest cost of biomass per ton is achieved when using low-end price of rice husks in CSII at 10% co-firing (56 $/ton) and the highest cost was obtained when using high-end PKS price at 50% co-firing in CSI (121 $/ton). The highest biomass cost per ton in all cases is around 3 times higher than the cost of coal per ton, this makes biomass resides a less attractive source of fuel for combustion at CFPPs.

Furthermore, a breakdown of the biomass fuel cost per ton in percentage of the components can be seen in Figure 8.3. It appears that the raw feedstock cost ($Ct_{R,b}$) has the largest share of the fuel cost in both low-end and high-end cases. However, the graph suggests that there is a higher influence of feedstock

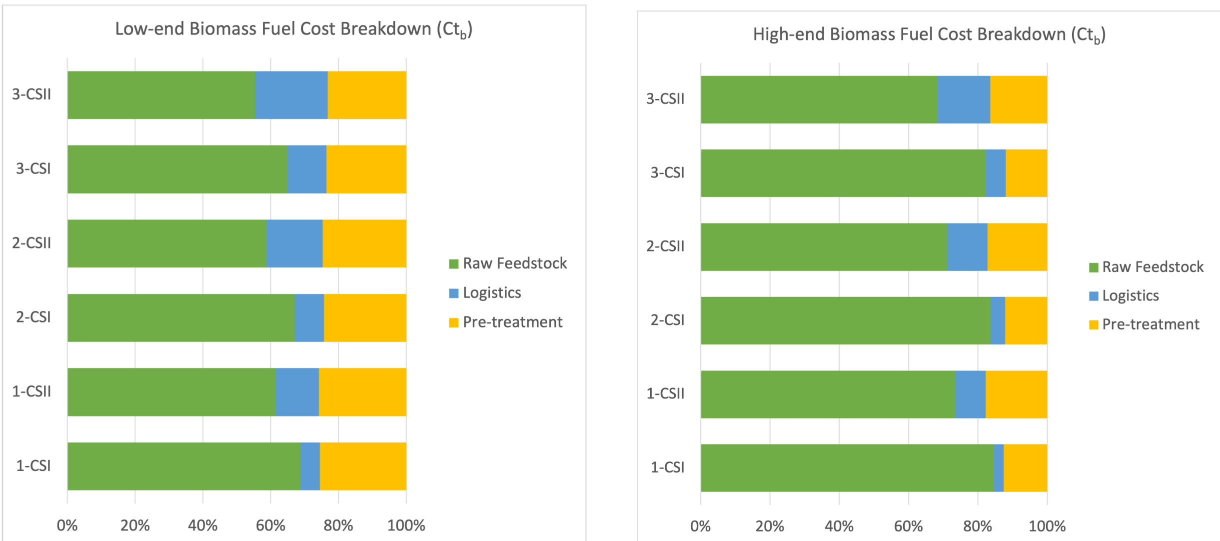
Table 8.1: Results of the Economic Potential Input Variable Model Part 1

Scenarios	Case Study	P_c (kton/year)	P_b (kton/year)	D (km)	$Ct_{L,c}$ ($/ton)	$Ct_{L,b}$ ($/ton)	$Ct_{P,b}$ ($/ton)
1	CSI	483.625	48.17	50	4	3.31	14.6
	CSII	1450.88	191.94	150	14	7.2	14.5
2	CSI	429.88	96.35	100	4	5.09	14.6
	CSII	1289.66	383.88	220	14	9.78	14.5
3	CSI	268.7	240.86	160	4	7.1	14.6
	CSII	2208	959.7	320	14	13.3	14.5

Table 8.2: Results of the Economic Potential Input Variable Model Part 2

Scenarios	Case Study	$Ct_{R,b}$ ($/ton)		$Ct_{R,c}$ ($/ton)	Ct_b ($/ton)		Ct_c ($/ton)
		Low	High		Low	High	
1	CSI	40	100	30	58.16	118.16	34
	CSII	34.5	60	30	56.2	81.7	44
2	CSI	40	100	30	59.57	119.57	34
	CSII	34.5	60	30	58.78	84.28	44
3	CSI	40	100	30	61.65	121.65	34
	CSII	34.5	60	30	62.26	87.76	44

cost in CSI than CSII for all scenarios. Additionally, at lower co-firing rates, the share of raw feedstock cost in the overall biomass fuel cost is the highest for both case studies. Meanwhile, the pelletizing costs have the second largest share and transport cost is observed to have the least share in the total biomass fuel cost per ton for all cases.



(a) Low-end Ct_b Breakdown (%)

(b) High-end Ct_b Breakdown (%)

Figure 8.3: Low and High-end Ct_b Breakdown (%) for CSI and CSII at all scenarios

Furthermore, the investment costs for the logistics and pelletizing model were calculated using Equation 7.9 and Equation 7.10. The Investment and O&M costs were calculated using Equation 7.11 and Equation 7.12. The values are presented in Table 8.3.

Table 8.3: Results of the Economic Potential Input Variable Model Part 3

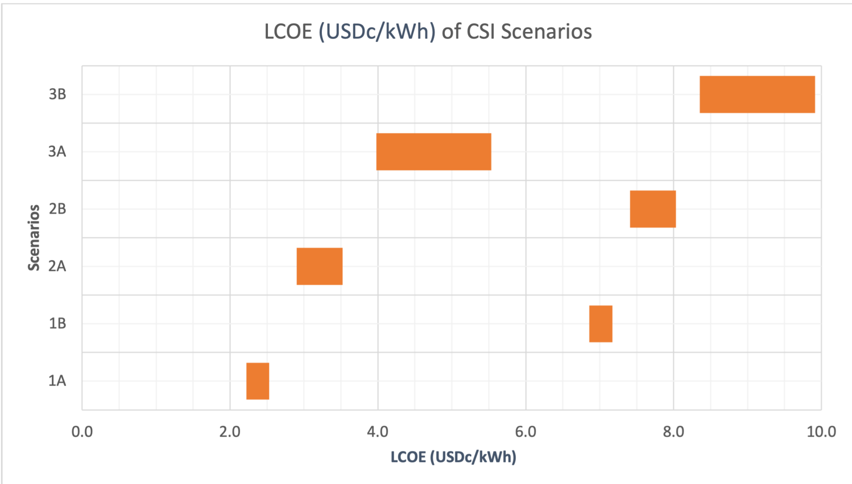
Scenarios	Case Study	I_L (\$)	I_P (\$)	I (\$)	M (\$/year)	M_c (\$/year)	F (\$/year)	
							low	high
1A	CSI	490	324	814	1256	0	19256	22146
	CSII	2473	1289	3763	3768	0	74764	79658
1B	CSI	490	324	340814	12660	11404	19256	22146
	CSII	2473	1289	603763	24391	20623	74764	79658
2A	CSI	980	647	43487	1256	0	20365	26146
	CSII	4947	2578	133195	3768	0	79430	89219
2B	CSI	980	647	383487	12660	11404	20365	26146
	CSII	4947	2578	733105	24391	20623	79430	89219
3A	CSI	2310	1617	85788	2456	0	23993	38445
	CSII	12273	6444	264298	7368	0	95326	119799
3B	CSI	2310	1617	425788	13860	11404	23993	38445
	CSII	12273	6444	864298	27991	20623	95326	119799

8.2. LCOE Calculation Results

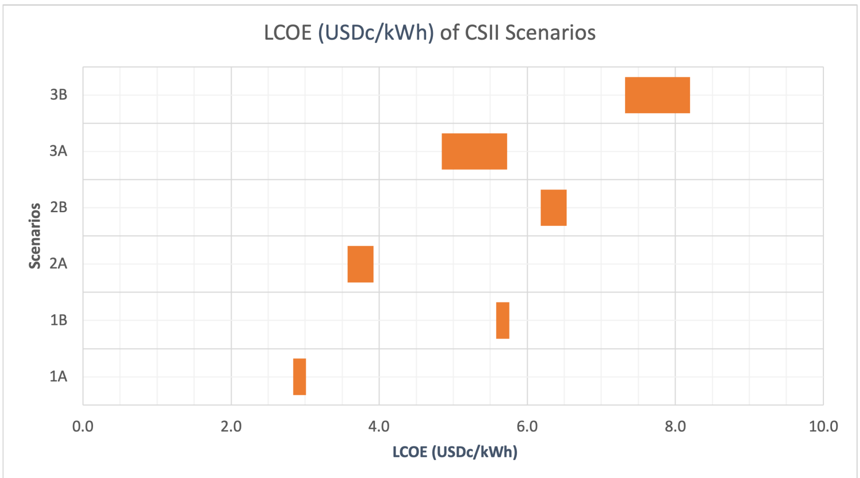
The LCOE results for CSI and CSII were calculated using Equation 7.1. and values from Section 8.1. The results are presented in Figure 8.4. The figure illustrates that the LCOE values for scenario A is lower than scenario B for both case studies, with the cheapest LCOE at 2.2 $/kWh for scenario 1A, CSI. Furthermore, the most expensive LCOE is calculated for scenario 3B, CSI with value of approximately 10 $/kWh.

Moreover, the change in LCOE when applied low and high-end raw feedstock costs appear to have varying results. The highest change in LCOE is observed in Scenarios 3A and 3B for both cause studies (at 50% co-firing) when fuel quantity is highest. In contrast, the smallest change is observed in Scenarios 1A and 1B (at 10% co-firing).

The findings indicate that LCOE is lower for CSI than CSII with scenario A, but the reverse is true for scenario B. This is evident in Figure 8.5 and Figure 8.6. In Figure 8.5, low-end LCOE results are compared for both case studies and scenarios. Similar trends are seen in the high-end LCOE results in Figure 8.6. Additionally, the change in LCOE for 10% co-firing plants remains insignificantly affected by low or high-end feedstock prices. However, for 50% co-firing, the change in LCOE significantly increases. This is due to rising investment costs for equipment modifications and substantially higher biomass fuel costs in the high-end scenario, which are at least double the cost of coal.

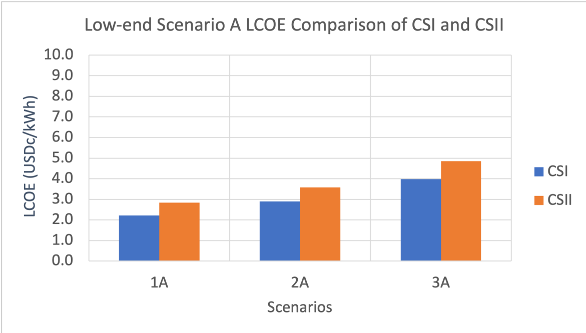


(a) LCOE results of CSI for all scenarios

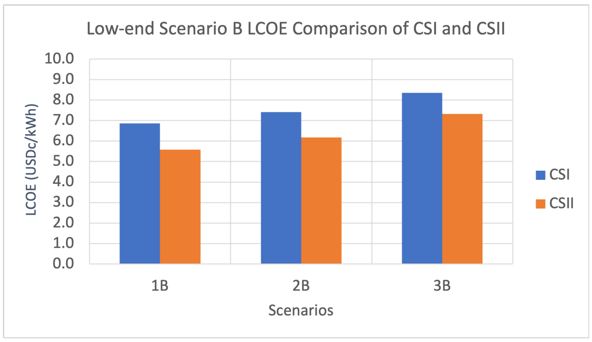


(b) LCOE results of CSII for all scenarios

Figure 8.4: LCOE results for CSI and CSII in $c/kWh for all scenarios

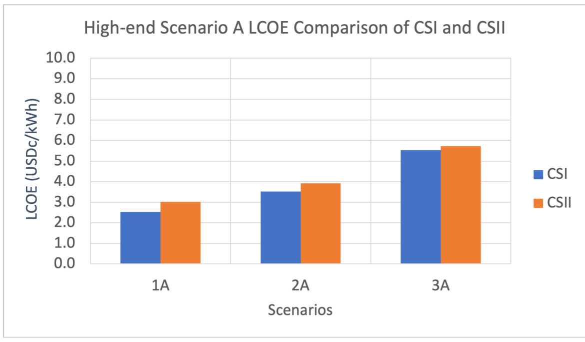


(a) Low-end LCOE results for Scenario A

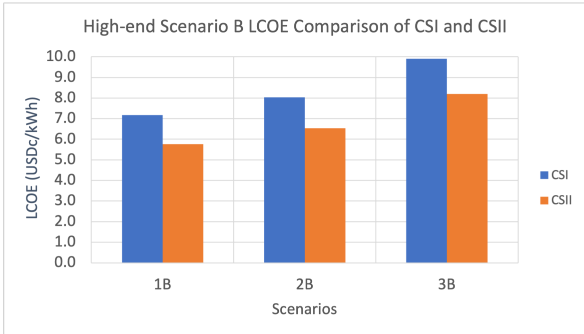


(b) Low-end LCOE results for Scenario B

Figure 8.5: Low-end LCOE results for CSI & CSII



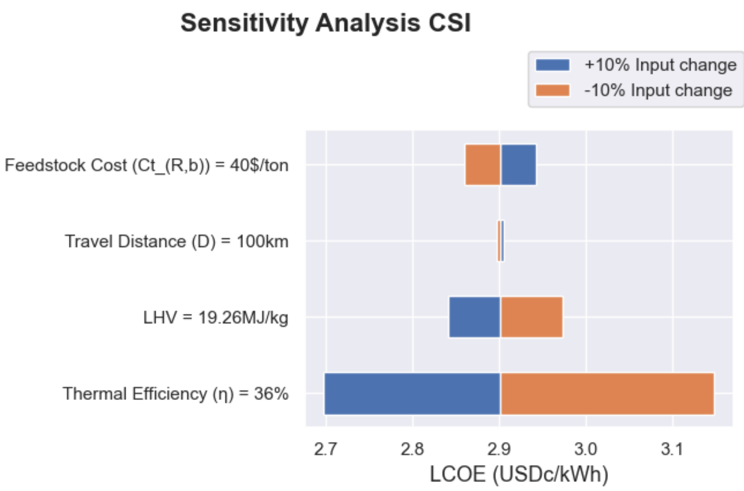
(a) High-end LCOE results for Scenario A



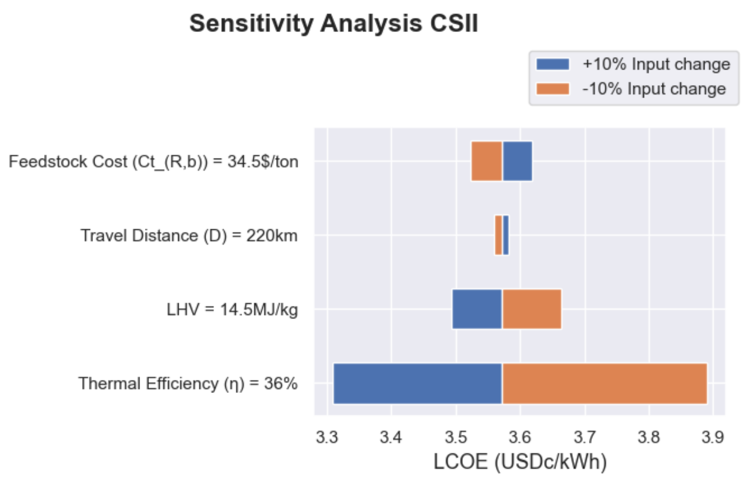
(b) High-end LCOE results for Scenario B

Figure 8.6: High-end LCOE results for CSI & CSII

A sensitivity analysis was conducted where the model adapts scenario 2A (co-firing at 20% without initial CFPP investment and maintainence costs) and with the following parameters subject to a 10% increase/decrease of value: Thermal Efficiency η (%), LHV$_b$ (MJ/kg), Travel Distance D (km) and Raw Feedstock Price Ct$_{R,b}$ (\$/ton). The results for both case studies are seen in Figure 8.7.



(a) Sensitivity Analysis CSI



(b) Sensitivity Analysis CSII

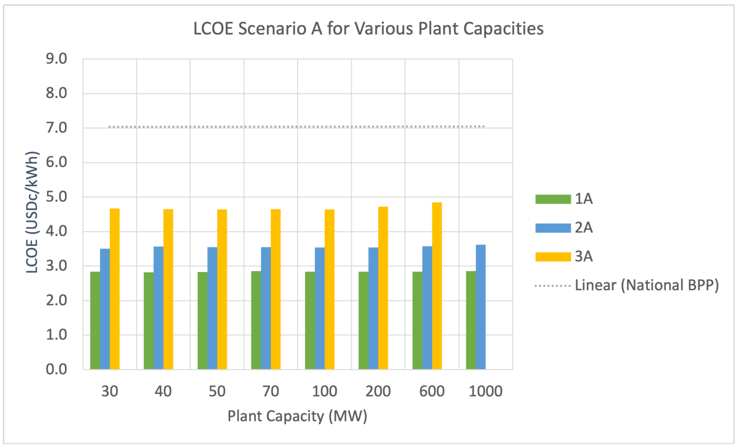
Figure 8.7: Sensitivity Analysis of input variables subject to $\pm 10\%$ change

From the sub-figures, it seems evident that the plant thermal efficiency (η) has the highest influence in the LCOE change, followed by the biomass LHV. The findings indicate an inverse relationship between thermal efficiency and LHV with the LCOE value, while feedstock price and travel distance exhibit a direct relationship.

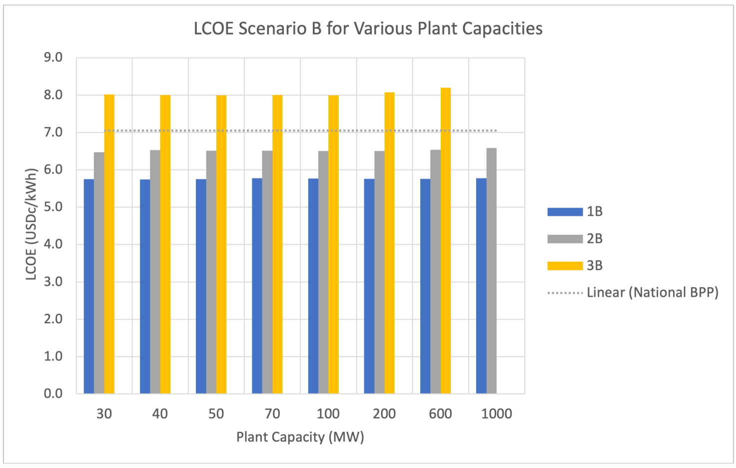
Despite the results observing the influence of thermal efficiency, which represents a fixed parameter impervious to alterations, it is important to acknowledge the potential for optimizing biomass's calorific content. This optimization hinges on factors such as biomass residue's chemical properties and the pre-treatment approaches adopted before combustion. This underscores the significance of selecting the right biomass feedstock to enhance co-firing efficiency.

Moreover, the LCOE model was used to calculate the various LCOE's for different plant capacities found in Indonesia. This model used rice husk at a price of 34.5$/ton for Scenario A, 50$/ton for Scenario C and 60$/ton for Scenario B. The results are shown for different co-firing ranges in Figure 8.8. The value for 3B at 1000MW was not calculated due to the assumption that the biomass fuel quantity required for 50% co-firing requires a greater travel distance than 320 km and therefore is not practically feasible to transport daily by truck due to time constraints in the day. This is emphasised in IESR (2022) in which the feedstock distance is limited to 360km in Java to meet the economic equivalent for coal transport. Alternative methods of transport should be explored.

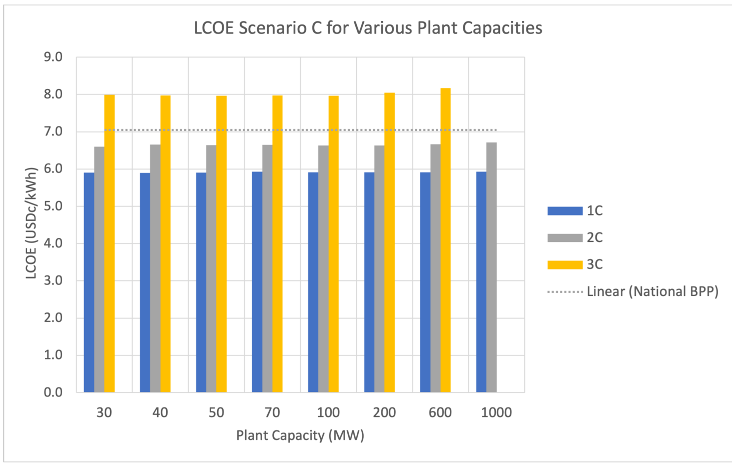
When looking at the results for scenario A, the LCOE of all plant capacities are below the national BPP of 7.05 $/kWh, with the highest LCOE for the 600 MW plant to be 4.85 $/kWh. As for scenario B, all plant sizes in the 1B and 2B cases exhibit LCOE values lower than the national BPP. However, the 3B case results in LCOE values higher than the BPP, with an average of 8.04 $/kWh. Moreover, scenario C results in similar values as scenario B, with a slightly lower 3C average of 8.01 $/kWh. Therefore, it can be concluded that when taking into account the initial investment costs of the CFPP, and with high-end biomass feedstock prices, the LCOE of coal plants co-firing at 50% thermal mix are not economic feasible as it results to an LCOE above the national BPP.



(a) LCOE Output of Scenario A for various plant capacities



(b) LCOE Output of Scenario B for various plant capacities



(c) LCOE Output of Scenario C for various plant capacities

Figure 8.8: LCOE Output of All Scenarios for various plant capacities

Lastly, a comparison of the LCOE model for co-firing to various NRE technologies advancing in Indonesia was done. The parameters used are from Table 8.4 for the co-firing plants and Tables A.2-A.3 for other

NRE technologies. Figure 8.9 presents the output.

Table 8.4: Low-end and High-end Technical and Financial Parameters for co-firing plant LCOE calculation in Figure 8.9

Technology	Technical parameters							
	Technical Lifetime (years)		Fuel Efficiency (%)		Capacity Factor (%)		Plant Size (MW)	
	Low	High	low	High	Low	High	Low	High
Co-firing 10%	40	25	37	29	73	53	1000	70
Co-firing 20%	40	25	37	29	73	53	1000	70
Co-firing 50%	40	25	37	29	73	53	1000	70
Technology	**Financial parameters**							
	Investment Cost ($/kW)		Fix O&M ($/kW/year)		Var. O&M ($/MWh)		Fuel Cost ($/year)	
	Low	High	low	High	Low	High	Low (38.8 $/ton)	High (110 $/ton)
Co-firing 10%	1005	1705	40.279	62.789	0.09	0.16	131419	10027
Co-firing 20%	1219	1919	40.279	62.789	0.09	0.16	140258	12111
Co-firing 50%	1435	2119	46.279	68.879	0.09	0.16	166898	18324

As observed in Figure 8.9, the LCOE range for several NRE technologies have larger ranges than others. Agricultural biomass experiences a wide range of fuel supply uncertainty and dependence on import prices. Additionally, it entails high plant investment costs, amounting to $2250/kW. Wind onshore technology exhibits high investment costs, especially for small installed capacity, reaching up to 70MW. Moreover, the biomass co-firing plants falls within the range of the LCOE for coal-fired power plants, making it a competitive energy generation technology.

The cheapest generation technology is large hydropower, at 2.027 $/kWh. This is achieved for a 2000 MW plant with an investment cost of 1650 $/kW, technical lifetime of 90 years, fuel efficiency of 97% and capacity factor of 95%. In contrast, the highest LCOE is for a 1000 kW Biomass Agriculture plant (18.76 $/kWh) with an investment cost of 2250 $/kW, technical lifetime of 19 years, fuel efficiency of 25% and capacity factor of 70%.

As for the co-firing plants, the lowest LCOE is achieved at 10% co-firing (4.58 $/kWh) for a 1000 MW plant with a feedstock price of 38.8 $/ton and capacity factor of 73%. Meanwhile, the highest LCOE value (13 $/kWh) occurs with a 70 MW co-firing plant at 50% co-firing, feedstock price of 110 $/ton and capacity factor of 53%.

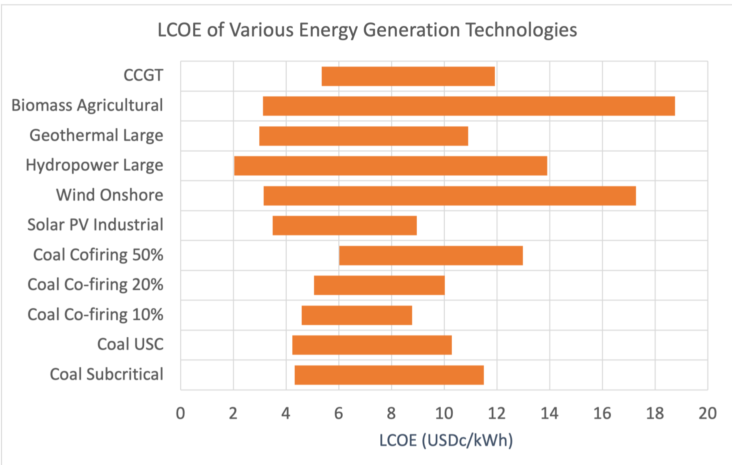


Figure 8.9: LCOE Comparison of various NRE generation technologies in Indonesia with co-firing plant modelled in this research using values from Table 8.4. Note: CCGT = Comnbined Cycle Gas Turbine, PV = photovoltaic, USC = Ultra Super Critical

8.3. Concluding Remarks

In this chapter, the LCOE has been meticulously computed, considering an in-house logistics and pelletizing model as the basis. Interestingly, a comparative assessment between a 600MW plant in Java utilizing rice husk and a 200MW plant in Kalimantan utilizing PKS under scenario A indicates a higher LCOE for the former. Conversely, under scenario B, the outcome is reversed. Conducting a sensitivity analysis reveals that thermal efficiency and calorific content demonstrate the most significant influence on LCOE when subject to a 10% variance in inputs.

For plant sizes ranging from 30 to 1000MW, the LCOE consistently remains below the national BPP value for all co-firing thermal mixes, assuming a low-end feedstock price and excluding initial coal plant investment cost. However, upon considering high-end feedstock prices and initial coal plant investment, the LCOE of all plants co-firing at 50% exceeds the national BPP value, necessitating additional tariffs for electricity generation from such plants.

Part IV

Policy Analysis

9

Policy Analysis Methodology

In this chapter, the methodology for the policy analysis is described. The policy analysis will discuss the regulations and frameworks that are put in place to support co-firing program in Indonesia. The aim is to provide an overview of the challenges faced within the policy sector and subsequently yield recommendations to improve the deployment of co-firing schemes.

9.1. Literature Review

The methodology for the co-firing policy analysis involved conducting a comprehensive literature review to examine the current policy schemes for co-firing both in Indonesia and in other countries with successful co-firing implementations. The primary objective of the literature review was twofold:

1. Reviewing the Current Policy Scheme in Indonesia: The first part of the literature review focused on outlining the existing policy framework in Indonesia concerning co-firing. The review aimed to identify relevant policies deployed by the government, including subsidies, regulatory frameworks, and other incentives that have contributed to making co-firing economically attractive and feasible in the country.
2. Evaluating Policy Schemes in Countries with Successful Co-firing Implementations: The second part of the literature review involved investigating policy schemes and regulations related to co-firing in other countries known for their successful co-firing implementations. The goal was to identify effective strategies and approaches adopted by these countries that have contributed to the successful integration of co-firing technologies.

A systematic approach was adopted for data collection. Google Scholar, Scopus, and the TU Delft library were utilized as primary sources for conducting the literature search. The search terms employed included ”Co-firing Policies,” ”Co-firing Regulations,” and ”Co-firing Subsidies,” along with additional related terms specific to the countries of interest, namely ”Indonesia,” ”Denmark,” ”Netherlands,” and the ”United Kingdom (UK).”

The selection of relevant literature was governed by specific inclusion and exclusion criteria. Priority was given to peer-reviewed papers and government reports. Non-peer-reviewed sources and articles that lacked substantial empirical evidence were excluded from the analysis.

Following the literature search, relevant data from the selected sources were extracted and organized for systematic analysis. The identified policies and regulations for co-firing in Indonesia and other countries were classified based on common themes and key factors contributing to the success of co-firing initiatives. During the literature review process, various potential knowledge gaps and areas in need of further research were identified. These gaps were documented to guide the subsequent phase of the analysis. The review resulted in the formulation of specific policy and regulatory recommendations aimed at maximizing the economic and technical potential of co-firing in Indonesia.

10

Policy Analysis Results

This chapter includes the results of the co-firing policy analysis literature review. Section 10.1 will contain the review on Indonesia's co-firing policies, Section 10.2 will incorporate the co-firing policy review of other countries with successful co-firing schemes. Lastly, Section 10.3 will provide policy recommendations to further enhance the techno-economic potential of co-firing in Indonesia.

10.1. Current policy scheme Indonesia review

In pursuit of achieving a 23% NRE mix, biomass co-firing has been incorporated into the latest RUPTL (Rencana Usaha Penyediaan Tenaga Listrik or Specific Investment Plan for PLN) 2021-2030. The RUPTL strategically aims to mitigate the impact of BPP by emphasizing the prioritization of the most cost-effective NRE sources (PLN, 2021). Concurrently, the plan endeavors to stimulate the adoption of economically feasible solar photovoltaic plants and co-firing technologies to foster a sustainable and diversified energy generation landscape (PLN, 2021).

Moreover, a paper by Dani and Wibawa (2018) outlined the evolution of policies related to biomass in Indonesia. The highlights are found in Table 10.1. Presidential Regulation No. 112/2022 is notable as it aims to defer the pricing regulation from the BPP value, which has previously forced NREs to compete with the cost of generation of fossil fuel technologies. Another interesting policy is Ministerial regulation No. 27/2014 which aims to increase the electricity tariff from biomass fueled power plants.

Table 10.1: Evolution of Polices related to Biomass and Co-firing in Indonesia

No	Title	Purpose
1	MEMR Regulation No. 50/2017	• Regional Government is required to provide land and regulations regarding long-term fuel prices of biomass • PLN is required to purchase electricity produced from renewable energy generators, provided that the electricity generated does not disturb PLN's demand–supply balance
2	MEMR Regulation No. 49/2017 and no.10/2018	• PLN can receive electricity from IPP's through PPA • PLN is responsible for supplying electricity to consumers either through itself or subsidiaries
3	Energy Law No. 30 of 2007	• To regulate renewable energy development and energy efficiency policy, particularly by increasing the utilization of renewable energy and provide incentives for renewable energy developers for a certain period of time
5	Presidential Regulation No. 61/2015	• Assigning the Palm Oil Plantation Fund Management Agency to collect, develop and use the Palm Oil Plantation Fund for the benefit of the oil palm industry

Continued on next page

Table 10.1: Evolution of Polices related to Biomass and Co-firing in Indonesia (Continued)

6	Presidential Regulation No. 112/2022	• New pricing regulation does not depend on BPP. Instead, all types of renewable energy projects will be given ceiling prices, which takes locational factors into account to encourage renewable development and investment.
7	Presidential Regulation No. 98/2021	• Emission trading system has been trialed, carbon pricing for tax purposes and carbon trading will be fully implemented by 2025 • Foundation to regulate carbon trading, carbon market and the implementation of Carbon Economic Value concept to support the national targets as stated in the Nationally Determined Contribution document for controlling climate change • To be able to mobilize more green financing and investments that have an impact on reducing greenhouse gas emissions involving various stakeholders from the central government, local governments, business actors, and the local community.
8	Ministerial regulation No. 4/2012	• To set the Feed in Tariff for electricity generated from biomass
9	Ministerial regulation No. 27/2014	• Increase the portion of renewable energy to at least 23% by 2025 and 31% by 2050 • Utilization of biomass is focused for electricity and transportation • Using feed-in-tariff for NRE • To encourage government and private companies in using biomass and biogas as fuel of power plant • To increase the electricity tariff from biomass fueled power plant

10.1.1. PLN Director Regulation No. 001/2020

The report ”PLN Director Regulation No. 001/2020: Guidelines for Co-firing of Coal-fired Power Plants with Biomass Fuel” encompasses comprehensive guidelines governing the purchase price of biomass fuel, with the highest price being determined based on three crucial factors. Firstly, the average coal price from the previous three months, including transport costs, forms a significant determinant. Secondly, a correction factor of 0.85 is applied to account for the costs associated with modifying or adding infrastructure for the handling and pre-treatment of biomass, with this factor being calculated as 0.85 of the purchase price of coal (PLN, 2020).

Furthermore, the calorific value of the biomass plays a vital role in the pricing mechanism. A correction factor is introduced based on the ratio of the calorific value of biomass to the calorific value of coal (calorific value biomass / calorific value coal). Under the co-firing program, the purchase price of biomass by the relevant coal power plant is set at a maximum of 85% of the coal price, with the calorific value of biomass aligning with that of coal (PLN, 2020).

In terms of biomass content specification, certain criteria must be met to ensure compatibility and efficiency in co-firing. The moisture content of the biomass should not exceed 20%, while the calorific value should be greater than 3400 kcal/kg. Additionally, the organic material composition must exceed 95%.and exclude any hazardous and toxic materials and chloride materials to maintain safety and environmental standards.

Additionally, the report mentions the responsibility for acquiring biomass fuel is assumed by the main unit of PLN and/or Subsidiaries managing the CFPP, using the coal fuel procurement budget.

10.1.2. Policy on Subsidies

Regarding the policies on subsidies, the primary business potential for biomass energy generation in Indonesia lies in the domain of IPPs. IPPs operate as private developers and financiers, engaging in the sale of electricity to PLN, under long-term PPAs that extend up to 30 years. These contractual arrangements enable IPPs to establish a stable and reliable revenue stream from their biomass energy projects (IRENA, 2022).

In this context, the bench marking of biomass energy projects is conducted based on PLN's average electricity generation unit. It is noteworthy that the pricing of electricity generation is notably influenced by coal plants due to the Domestic Market Obligation (DMO). This policy sets a cap on the price of coal at USD 70 per ton, thereby exerting downward pressure on average electricity generation unit costs (IESR, 2022).

Moreover, Indonesia continues to adhere to a cheapest price policy, wherein the pricing of electricity from renewable energy sources is compelled to compete with that of electricity derived from fossil fuels (IESR, 2022). Consequently, the pricing dynamics presents a challenge for renewable energy projects, including biomass energy generation, in their pursuit of economic viability and competitiveness in the market.

10.1.3. Carbon Policy

Concerning carbon policies in Indonesia, the prevailing Carbon Pricing stands at 30,000 Indonesia Rupiah per ton of CO_2 equivalent (2$/ton of CO_2eq), a rate regarded as relatively low. Moreover, the existing emissions cap, varying between 0.911 and 1.297 tons of CO_2 equivalent per megawatt-hour (tCO_2eq/MWh), closely aligns with the technical assumption of the maximum CO_2 emissions factor stated in IESR (2023) report, which is set at 1.34 tCO_2eq/MWh. This proximity between the current emissions cap and the technical assumption renders the carbon policy comparatively ineffective in mitigating emissions.

10.1.4. Biomass Supply Chain Policy

Regarding the biomass supply chain, the government has taken measures to cater to the co-firing demand by engaging state-owned enterprises associated with biomass suppliers, although specific details remain undisclosed.

In this context, P.T. Energi Primer Indonesia has entered into a memorandum of understanding with PT Energy Management Indonesia and PT Alpha Rizki Teknologi. The collaboration aims to facilitate the development and management of biomass resources while strengthening the overall supply chain for co-firing initiatives (IEA, 2023).

At present, within biomass plantation areas, farm roads serve for in-plant transportation requirements. However, these roads are only sporadically connected to district arterial roads (Hardhi, 2022).

10.1.5. Co-firing Policy Knowledge Gaps

Knowledge gaps related to co-firing policies in Indonesia have been identified, presenting crucial areas for further investigation and policy development.

Firstly, to ensure the feasibility of co-firing schemes, addressing biomass supply security, stable biomass prices, and securing additional investment funding for coal plant retrofitting are essential. These aspects require examination to establish robust policies and mechanisms that enable a seamless integration of biomass co-firing within the existing energy landscape.

Furthermore, PLN seeks regulatory and policy support from the Indonesian government to sustain biomass supply and maintain competitive tariffs. A well-defined policy framework in this regard is crucial for fostering the stability and long-term viability of biomass co-firing projects.

Considering IPPs, adjustments to PPAs become imperative to accommodate the procurement of biomass fuel supply and address heat rate differences between coal and biomass fuel. A thorough understanding of these technical intricacies is vital for developing PPAs that strike a balance between cost-efficiency and effective utilization of both coal and biomass resources.

Moreover, the lack of transparency in PPAs and auctions for renewable energy from PLN has emerged as a significant concern, leading to uncertainty and instability in investments for NRE projects (IRENA, 2022). Addressing this knowledge gap is pivotal to ensure a more predictable and conducive environment for RE project developers, encouraging greater investments in sustainable energy initiatives.

10.2. Current policy scheme other countries review

In this section, the co-firing policy of selected countries with successful implementation over the last decade will be reviewed.

10.2.1. Netherlands

Co-firing in the Netherlands utilises direct and indirect co-firing of wood pellets and coal. In total, 8 plants have used co-firing with different fuel handling and combustion choices (Roni et al., 2017).

Policies and regulations in the Netherlands have been designed to incetivize the adoption of renewable energy sources. Tradable green certificates, introduced in 2001, exempt buyers from paying energy tax on the electricity represented by these certificates, thereby encouraging the use of green energy. Another measure is the zero tariff for green electricity, where utility companies are not taxed on energy generated from renewable sources if a specific 'green' contract exists between the energy company and the consumer (Kwant, 2003).

Support schemes play a significant role, with green funds, accelerated depreciation, and tax credits combining to provide substantial subsidies of 25-35% of the investment. The Dutch MEP (later SDE) subsidy scheme offers a fixed premium on top of the wholesale electricity price for domestic producers and CHP plants, applicable to co-firing projects before 2009. Different feedstock types receive varying subsidies, such as 6.5 c/kWh for wood pellets, 3.8 c/kWh for agro-residues, and 3.8 c/kWh for mixed biomass feedstock (Roni et al., 2017).

To control subsidies, the Dutch Energy Accord limits the subsidy to an energy output of 25 PJ per year (approximately 3.5 million mega ton of wood pellets). The government has set aside $4 billion funds for co-firing wood pellets with coal, with each power company being eligible for a share of the allocation (Roni et al., 2017).

10.2.2. Denmark

Denmark has had 5 power plants which initiated co-firing using straw, wood chips and wood pellets using a mix of combustion technologies. Moreover, Denmark has achieved 100% co-firing with parallel firing of straw (Roni et al., 2017).

Policies and regulations in Denmark are aimed at supporting the development of renewable energy sources. The Public Service Obligation serves as a funding source, with consumers contributing through their electricity bills. The Public Service Obligation funds subsidies for CHP plants, energy research, and other development costs in the electricity system. Additionally, the Renewable Energy Act provides a subsidy of 2 euro cents per kWh, applicable to installations using biomass or a combination of biomass with other fuels. A quota-obligation scheme is also in place to encourage utilities to utilize biomass (Roni et al., 2017).

However, Denmark faces challenges in the global biomass market as a price taker due to reliance on imports, which could result in price volatility. Another challenge involves potential loss in tax revenue from the energy market as more efficient large-scale CHP biomass power plants are introduced, potentially phasing out smaller-scale CHP plants.

10.2.3. The UK

In the UK, all major coal pants have adopted biomass co-firing at 3% biomass by energy basis. Biomass fuel is sourced form agriculture residue, energy crops and forestry residues.

Several policies have been implemented to promote renewable energy development. The Non-Fossil Fuel Obligation evolved into the Renewable Obligation scheme, which played a crucial role in encouraging renewable energy growth. Under this scheme, qualified renewable energy generators received Renewable Obligation Credits (ROC) based on the percentage of their power sourced from renewable sources (see Table 10.2. The proportion started at 2% in 2003 and progressively increased to 48.4% in 2019-2020. These ROCs are tradable to energy suppliers, further supporting the renewable energy sector (Roni et al., 2017).

Additionally, the Energy Crop Scheme provides grants to farmers for establishing energy crops such as short rotation coppice and miscanthus, contributing to the expansion of sustainable energy sources in the UK.

10.3. Recommendations of policy review based on LCOE

Based on the review of policies implemented by countries with successful co-firing practices, financial subsidies have emerged as a key aspect that significantly influences co-firing adoption. For instance, in

Table 10.2: Support Level given for co-firing implementation in the UK, retrieved from Roni et al. (2017)

Band	Co-firing range in a unit	Support level (ROC/MWh)
low-range (SCF)	50% CF	0.5
mid-range (ECF-mid)	50%-85% CF	0.6
high range (ECF high)	85%-100% CF	0.7
Biomass conversion	100% biomass use	1

the Netherlands, the government's provision of subsidies based on the electricity output from biomass co-firing played a crucial role in adopting co-firing practices. Similarly, the UK's rewarding of Renewable Obligation Certificates served as an incentive for power plants to adopt co-firing.

Implementing similar policies and regulations in Indonesia could potentially foster the widespread adoption of co-firing on a national level. These policies, which offer direct financial support and incentives to power producers, may prove to be more beneficial in promoting co-firing compared to implementing carbon taxes and feedstock pricing, which are market-based regulations. By providing financial assistance and rewards, the government can create a encourage environment for the expansion of renewable energy sources like co-firing and accelerate the country's transition to a more sustainable energy mix.

Drawing from the policy analysis conducted in Indonesia and other nations, it becomes possible to formulate a set of recommendations that address specific subject.

To increase the co-firing thermal mixes:

1. In order to curtail coal consumption and facilitate the transition towards renewable energy sources, the implementation of a substantial carbon tax becomes imperative. As demonstrated in a study by IESR (2023), an evaluation of the LCOE for coal plants after a carbon tax of US$10/tCO2eq revealed an LCOE escalation of 20% to 7.6 c$/kWh. Furthermore, the LCOE saw a surge of 101% to 12.89$c/kWh with a carbon tax of US$54/tCO2eq. The removal of coal subsidies and the incorporation of pollution taxes on fossil fuels could enhance the attractiveness of co-firing investments. This is underscored by the observation that the LCOE for 50% co-firing can decrease to below 10 $c/kWh in a high-end scenario. These findings potentially advocate for economic incentives to prompt industries to transition away from coal-dependent energy sources.
2. Introducing compensatory mechanisms to manage biomass consumption can effectively enhance the sustainability of the biomass supply chain. The adoption of banded ROCs, inspired by the UK's model, offers a promising strategy to incentivize biomass utilization and its integration within the energy matrix. Furthermore, given the present gaps in the biomass supply chain or information deficit, ROCs could play a pivotal role in engaging suppliers to provide biomass resources to CFPPs. Another avenue for consideration is the re-evaluation of the DMO subsidy, which currently caps coal prices in Indonesia at 70$/ton (IESR, 2023). By eliminating this subsidy or introducing a similar incentive for biomass, the feasibility of increasing co-firing ratios could be bolstered.
3. Promoting the adoption of NRE technologies by private institutions hinges on the provision of appealing incentives to facilitate co-firing with economically viable solutions. Given that IPPs constitute key players in co-firing initiatives, offering financial assistance or tax advantages could considerably boost their investments in co-firing projects. Financial incentives, such as subsidizing electricity rates when they surpass the BPP for higher co-firing ratios, as indicated by LCOE findings, could be a strategic measure. Moreover, ensuring that PPAs are integrated into the RUPTL and enhancing transaction transparency can significantly enhance the attractiveness of the investment.

On the supply chain of biomass:

1. The biomass logistics model revealed increasing truck transport costs when gathering larger quantities of PKS and Rice Husks, thereby increasing the retrofit investment costs. Nonetheless, a potential enhancement in efficiency arises if the biomass retrieval process aligns with the existing coal supply chain to the plant. This synchronization necessitates the identification of biomass sources and harvest zones located in close proximity to coal mines. This strategic proximity could optimize the biomass transport route, thus potentially mitigating investment expenses and improving efficiency.

2. To ensure the smooth incorporation of biomass into the energy supply, it is crucial to establish supplementary infrastructure, with a focus on constructing roads suitable for trucks. These roads will play a pivotal role for the direct transport of biomass residues from plantations to power plants. The responsibility for developing this infrastructure is shared between national and local governments. Presently, the transportation model assumes the use of trucks to transport rice husks in the western part of Java, covering a distance of 320 kilometers one way for 50% co-firing scenario. Exploring the feasibility of utilizing barge or rail transport in the Java region could reduce the transportation time.
3. Establishing interconnected routes would enable more seamless transport of biomass feedstock to a centralized refinery location. Such infrastructural enhancements will significantly contribute to streamlining the biomass supply chain, optimizing resource utilization, and ultimately promoting efficient co-firing practices.
4. Farmers' limited understanding of effectively utilizing biomass by-products is a challenge that requires enhancement and eventual enforcement. For instance, empty fruit bunch's are often burned and disposed of in landfills, releasing toxic emissions (Cifriadi et al., 2017). Addressing this issue would pave the way for the widespread adoption of biomass pre-treatment. This could involve establishing a standard practice of pre-treating biomass, either directly at the farm site or within a centralized facility dedicated to processing residues in the region. Research institutions have a pivotal role to play in educating and guiding farmers in the adoption of methods that harmonize with the prerequisites of biomass collection, thereby fostering a resilient and efficiently organized biomass supply network.

On biomass feedstock allocation:

1. According to the findings from IESR (2023), the most significant obstacles to expediting the adoption of NREs within Indonesia's power sector are the subsidies provided to fossil fuels. As mentioned in Section 10.1.2, the "cheapest price policy," forces the cost of electricity generated from renewable sources to compete with that generated from fossil fuels. Shifting the focus of these fossil fuel subsidies towards initiatives that support clean energy is a key measure in advancing the transition to sustainable energy sources. By doing so, governments can establish a more equitable playing field for the advancement of renewable energy and stimulate its expansion. Setting distinct pricing targets for electricity generated from NREs and increasing Feed in Tariffs to ensure that the selling prices of electricity remain below the BPP can significantly contribute to achieving these goals.
2. The attractiveness of exporting biomass due to higher selling prices compared to domestic rates can lead to a competitive scenario for biomass residues. This dynamic is reflected in the premium price of biomass found in Table 7.1. The high-end cost of $100 per ton of PKS was drawn from the global market price, while the low-end price of $40 per ton was based on local suppliers' selling price for PLN's co-firing trials.
   To ensure a consistent and secure supply of biomass for co-firing purposes, a combination of government intervention and market mechanisms is essential. These interventions might encompass regulatory measures, the establishment of transparent markets, or the introduction of incentives that prioritize the domestic utilization of biomass for clean energy production, akin to the DMO policy applied to coal.

Part V

Discussion and Conclusion

11
Discussion

In this chapter, the discussion of the techno-economic analysis will be mentioned. The technical and economic results will be compared with other literature in Section 11.1. Following after, the limitations to the model will be explained in Section 11.2. Lastly, recommendations for future research is presented in Section 11.3.

11.1. Comparison with other literature

As previously described, the results of the theoretical biomass potential discovered that rice straw, empty fruit bunch and corn stalk comprise the top three highest theoretical biomass potential found in Indonesia. The combined potential of the three residues contribute to 52% of the total theoretical biomass potential. Moreover, the results of the available biomass potential found a shift of the largest potential available. This time, the rice straw remains the highest MSW took over second place and empty fruit bunch got pushed down to third place. The overall contribution of the three potentials is 28% of the available biomass potential.

The paper by Rhofita et al. (2022) found the total agricultural residue potential at more than 300MJ. The paper deduces that rice and corn residues have the highest available potential in food crop sector whereas palm oil and coconut residues have the highest available potential in the plantation sector. When compared to the results obtained in this research, it appears that there are similarities with the highest potential being rice and palm oil in their respective sectors. However, cassava and sugarcane residues take second largest available potential in food and plantation sector, respectively. The difference in values may arise from the input sources used. The paper obtained annual crop production and harvested area from the BPS for the year 2020 whereas this research obtained production quantity data from the Food and Agriculture Organization of the United Nations database for the year 2021. Differences in production values in these two years, and the information on production quantities may have led to the differences in residue potential.

Furthermore, this study discovered that solid and sawdust residue and timber harvesting residue resulted in 0.19 EJ and 0.08 EJ available potential, respectively. The top three forestry residues were derived from (1) pulpwood, (2) sawlog and (3) HTI. The results can be compared to a study by Simangunsong et al. (2017). Their study identified that the highest forest residue potential in 2013 came from HTI, followed by sawnwood and chipwood. It appears that the LHV values employed in this research differed from those presented in the referenced paper. In this research, the LHV of timber harvesting residues was taken as 8 MJ/kg whereas the LHV in Simangunsong et al. (2017) was between 18.2-19.7 MJ/kg, which is over twice as high.

Moreover, the retrofit scenarios proposed in this research implies little to no modifications required when co-firing up to 10%, requiring dedicated biomass milling and separate on-site storage facilities when co-firing between 10-50% and additional boiler modification when co-firing at 50%.

Additionally, the parameter α denotes the availability factor, signifying the portion of biomass residue accessible for co-firing, which is essentially the estimated quantity not allocated for other applications. It's important to emphasize that the values assigned to α vary across different types of residues and encompass a wide range. Notably, this factor is not a fixed constant but rather contingent upon factors such as prevailing market conditions, harvesting methodologies, and the significance of the specific biomass for alternative purposes.

For example, the availability of sugarcane bagasse spans a range of 20-50%, considering that it is commonly utilized as boiler fuel in sugar factories. On the other hand, chipwood residues exhibit an availability range of 25-70%, with a significant portion primarily serving as cooking fuel in rural communities. Interestingly, the latter scenario presents an opportunity for these chipwood residues to be repurposed as co-firing fuel, as this application might offer enhanced efficiency compared to its current use for cooking purposes. This underscores the dynamic nature of α and how it can be influenced by diverse factors and contexts.

The scenario for 10% can be comparable with PLN's statement which mentions no additional investment costs were used and only an increase in operational costs were added when co-firing at the specific mix (Wahyudi, 2023). Moreover, the paper by Karampinis et al. (2016) mentions that due to the negative impact on efficiency when co-milling, it is recommended to switch to dedicated biomass milling equipment for higher co-firing thermal mixes. This is also recommended by IEA (2020b) which mentions that co-firing in PC boilers without modifications can reach up to 10-30%, and additional maintenance and capital expenditure will be required at higher rates.

Furthermore, this research found that the LCOE of co-firing in Indonesia has a range of 2.2-13 $c/kWh depending on the plant location, plant size, investment cost, fuel type and co-firing mix. These values can be compared to the LCOE reported in IESR (2023). The report calculates an LCOE between 6-16 $c/kWh for co-firing using wood pellets at varying feedstock price, co-firing mixes and CFPP type.

Differences in the methods were observed, the IESR report opted for the annuity method which calculates the cost of capital using the weighted average cost of capital. This is estimated through surveys and interviews with related stakeholders over the value and cost of debt and equity. Meanwhile, the LCOE method opted in this report is the discounted method. In this method, a discount factor is used and the cash flows are discounted to their present value using a discount rate to account for the time value of money. Ultimately, the discounted method may provide a more realistic LCOE calculation compared to the annuity method as the time value of money is considered.

Furthermore, the economic potential analysis models the logistics and pelletizing costs of biomass fuel for co-firing. The available literature regarding this topic is limited and this research finding may contribute to exiting body in the sense that a more detailed analysis was done on the contribution of variables to the biomass fuel cost. The model discovered that the raw feedstock costs contribute to 55-84% of total biomass fuel cost, with logistics and pelletizing contributing to 3-20% and 12-25%, respectively. These values show a wide range due to the variation in plant size, location, co-firing range, biomass fuel source and price. A report by IESR (2022) states that the fuel breakdown composition was 63.4% feed stock price, 25.9% processing costs and 10.4% for transport costs estimated by the centre for energy studies at Gadjah Mada University. The values demonstrate comparable results, supporting the validity of the model developed in this study.

Moreover. IRENA (2013) mentions that biomass fuel costs can be fluctuating based on raw feed stock costs. However, the sensitivity analysis that was performed in this research discovered that calorific content displays higher influence to LCOE than feedstock cost. However, the LHV can influence the feedstock price, as a higher LHV signify lower MC and better combustion characteristics, which may make the biomass more valuable in the market.

11.2. Limitations to method

Input Variables for Potential Calculations - To simplify the analysis, not all agriculture and wood species present in Indonesia were included, which may have led to some degree of under-representation in the results. Additionally, the input parameters employed in the analysis were obtained through a literature search, and as a consequence, there is a possibility that these values may not precisely correspond to the actual biomass characteristics found in Indonesia. Furthermore, the availability factors used in the calculation were derived from Rhofita et al. (2022), but upon further investigation, it was discovered that the values utilized in that paper were originally sourced from a study focused on biomass in Thailand. Similarly, estimations for the by-product uses were based on information extracted from various literature sources. These limitations should be taken into consideration when interpreting the findings and generalizing the results to the specific context of biomass co-firing in Indonesia.

However, considering that this research is based on qualitative data gathered from literature reviews, it's important to acknowledge that the precision of the availability factor's accuracy is confined to papers specifically focused on biomass residue availability within Indonesia. However, for a more precise determination of biomass potential, an improved approach involves integrating current availability data sourced directly from market conditions and engaging in interviews with local farmers to gain insights into their harvesting practices.

Although literature data was utilized for input parameters such as by-product utilization, LHV, and the availability factor, the validity of the available biomass potential results remains intact. This is due to the meticulous research conducted to estimate these values to the best extent possible within the context of qualitative research. The outcomes generated by the research provide a range of values, along with an average, effectively portraying both the upper and lower boundaries of the results. As a result, the approach undertaken not only acknowledges the inherent limitations of using literature-derived data but also ensures a comprehensive representation of the potential biomass availability.

Logistics Modelling - The travel distance between biomass residue collection sites and co-firing plants could be limited by time constraints that are crucial for day-to-day operations, particularly when dealing with larger distances of 200-300 km one way. Furthermore, the utilization of road transport for larger plant capacities, which typically range from 600 to 1000 MW, might introduce inefficiencies in the primary biomass transportation process. However, while these considerations hold weight, it's important to note that transport expenses account for a relatively minor portion of the overall biomass fuel costs, constituting less than 10% on average according to the calculations. This relatively small share of transport costs would not necessarily invalidate the results, as it remains a fraction of the total costs incurred.

Pelletizing Modelling - One limitation within the pelletizing model approach revolves around the assumption concerning the location of pellet factories. The model presumes that these factories are conveniently situated near Palm Oil Mills or rice production sites to simplify travel routes. However, it's worth acknowledging that in practical scenarios, a centralized pelletizing facility might exist where trucks pause for biomass collection and transportation. This variance from the simplified model could impact the efficiency of logistics and transportation costs. Nevertheless, it's worth reiterating that, as previously mentioned, transport costs constitute a relatively minor component of the overall expenses. As such, this particular limitation would not, by itself, invalidate the model's findings.

Simplification of Coal Input - A simplification in the coal input pertains to the use of a fixed feedstock price retrieved from Rachmatullah (2020), indicating a buying price of 30 USD/ton. However, it should be noted that this price may not necessarily remain constant, as fluctuations up to 70 USD/ton could potentially occur in actual market scenarios. Such variability in coal prices could significantly impact the LCOE output, potentially leading to higher costs for co-firing projects. This limitation highlights the need for a more dynamic approach in considering varying coal prices to yield a more accurate and comprehensive assessment of the economic feasibility of biomass co-firing initiatives.

Input Variables LCOE Model - A few limitations pertain to the input variables used in calculating the LCOE. Firstly, the availability of literature on additional investment costs for co-firing projects was rather limited, necessitating the use of assumptions based on other relevant papers. It is important to note that these extra costs are not factored into real-world scenarios. This aligns with the statement by PLN, which states that co-firing required no added investment expenses, but instead led to an increase in operational costs. As a result, the LCOE results presented in this research could potentially be higher than the co-firing BPP in practical situations.

Additionally, the model for calculating the LCOE for different plant sizes relied on data from CSII. However, this approach may not fully capture the diverse scenarios encountered in reality, as co-firing plants are dispersed across different islands in Indonesia, each with distinct biomass fuel sources. As a result, this simplification may not fully encompass the variations in plant size, location, and biomass availability, potentially affecting the accuracy of the LCOE calculations.

Another limitation is not accounting the potential increase in the biomass LHV after pelletizing. Given that LHV has a signifcant influence on the LCOE output based on the sensitivty analysis, it may be prudent to conduct further investigations to account for the effects of pelletization on biomass LHV and its impact on the overall analysis.

The simplifications employed in calculating the technical and economic potential introduce the possibility of invalidating the findings. Notably, the estimations regarding retrofit investment costs and the calorific content of biomass residues significantly impact the LCOE output, as they directly influence the input parameters I and F. Therefore, it is crucial to place greater emphasis on researching and obtaining accurate data for these parameters to enhance the reliability and robustness of the results.

11.3. Recommendations

This chapter provides a brief overview of the primary recommendations for the future continuation of this research project.

1. **Technical Potential** - To enhance the accuracy of technical potential calculations, it is suggested to seek comprehensive data on the LHV and moisture content of biomass residues in Indonesia. Collaborating with research centers or universities in Indonesia to obtain this data could be beneficial. Also, incorporating a range of LHV's instead of using a single value could enable the calculation of a broader range of potentials for each biomass residue. Additionally, further research on the growth rate of biomass residues and projecting their availability over the next 10 years would provide valuable insights into the feasibility of co-firing within the upcoming years.
2. **Economic Potential** - Due to limited data availability, specific areas require attention. Obtaining more comprehensive data on raw feed stock prices, investment costs, and transport costs would significantly improve the accuracy of economic potential assessments. Exploring other transportation modes such as rail or waterways could enhance logistics and potentially reduce time constraints. Additionally, it is recommended to conduct further analysis on co-firing thermal mixes ranging between 20-50% to identify the maximum co-firing rate that remains below the national BPP value.
3. **Including CO_2 emission calculation** -To strengthen the argument for the adoption of co-firing as an effective means for accelerating the energy transition, it is essential to include calculations comparing CO_2 emissions from co-firing versus coal combustion. This analysis would highlight the environmental benefits of co-firing and further emphasize its potential role in transitioning to a sustainable energy future.
4. **Pelletizing Model** - The pelletizing process was included in the model, encompassing the costs related to biomass densification. However, the expenses associated with drying biomass before densification were not incorporated due to the wide range of available biomass fuels and the assumption of moisture content being below 10%, which is the acceptable content for densifying the residue (Stelte et al., 2012). This assumption holds true for rice husks, as indicated in Table 5.2. However, in the case of PKS, it's important to account for additional drying costs. The cost of drying is expected to influence operational expenses, given that it can consume up to 70% of the electricity in the process (Stelte et al., 2012). In this study, electricity consumption contributes to 65% of pelletizing costs, potentially resulting in an underestimation for CSI. Nonetheless, pelletizing costs constitute a maximum of 25% of the overall biomass expenses, with raw feedstock prices holding the largest share. Therefore, the impact of drying costs remains constrained. For future research, there's potential to explore modeling drying expenses and assess their implications on the overall LCOE.

12
Conclusion

The primary objective of this study was to assess the techno-economic viability of retrofitting coal plants for co-firing in Indonesia. To address this objective, specific research questions were formulated. In the following section, both the sub-research questions and the main research questions will be addressed and answered (see Section 12.1). Finally, the concluding remarks will be presented in Section 12.2.

12.1. Answer to the Research Questions

Sub-Question 1: What is the availability of second generation biomass for co-firing in Indonesia?

In this research, second generation biomass was limited to by-products and waste derived from agricultural, forestry and urban waste in Indonesia. The availability was determined by calculating the biomass potential available in Indonesia. This required input parameters such as annual production quantity of the respective first-generation biomass, by product to product ratio, Lower Heating Value (LHV) dry basis, moisture content and dry density. Moreover, the availability of the residues was quantified by the availability factor, α which estimates the amount of biomass obtainable for co-firing. Incorporating this variable enables the assessment of available residue for co-firing applications, considering its utilization in other contexts.

The findings indicated agricultural by-product as the most available second generation biomass for co-firing with a share of 70%, followed by forestry residue (17%) and Municipal Solid Waste (13%). Among the agricultural residues, rice and palm oil residues observe the top two highest potentials, at 0.49 EJ and 0.29 EJ, respectively. As for forestry residues, solid and sawdust residues derived from pulpwood and sawnwood have the highest share with a potential of 0.098 EJ and 0.078 EJ, respectively.

Sub-Question 2: What is the technical potential of co-firing in Indonesia?

To address this question, the technical potential of co-firing can be determined by calculating the available biomass potential expressed in TWh. The comprehensive analysis revealed that the overall biomass technical potential in Indonesia amounts to 450 TWh, representing the total electricity that could be generated from second-generation biomass sources. Notably, this value is about the electricity demand for Indonesia in 2030 which has been estimated by PLN as 445 TWh. However, to practically assess the feasibility of co-firing implementation in Indonesia's coal-fired power plants (CFPP), further investigation is required. A thorough literature review on the technical challenges associated with co-firing was conducted, and potential solutions for these challenges were outlined. Based on this review, scenario development was proposed to guide the retrofitting of Indonesia's CFPP for co-firing.

The proposed scenarios assume the pre-treatment of biomass fuel in the form of drying and pelletizing prior to combustion in the plant. With this in mind, the scenarios are outlined as follows: For co-firing up to 10%, minimal modifications are needed, and the biomass can be co-milled with coal, as it has a negligible impact on boiler efficiency. For co-firing between 20-50%, dedicated biomass milling and separate on-site storage facilities are recommended, considering the potential reduced efficiency of milling equipment at higher biomass mixes. For co-firing at 50% or higher, in addition to the retrofits mentioned for the middle case, further boiler modifications should be incorporated due to the increased risk of fouling and slagging in the boiler. This happens due to the higher inorganic content including chlorine and alkali metals of biomass fuels compared to coal.

Sub-Question 3: What are the economic perspectives of retrofitting coal plants for biomass co-firing in Indonesia?

The economic potential was calculated using the LCOE discounted method. The fuel costs included a model for the logistics and pelletizing costs, which - for Indonesia - had a lack of knowledge of in literature. Two case studies were examined: one for a 200 MW CFPP in West Kalimantan using Palm Kernel Shells (PKS) and the other for a 600 MW CFPP in West Java using rice husks. Two scenarios were also modeled: Scenario A in which the initial CFPP investment cost was assumed to be paid off and Scenario B where the investment and O&M costs of the CFPP were included. The LCOE is then calculated for the two case studies and scenarios. From this model, the LCOEs for varying plant sizes found in Indonesia were extracted and compared to the national cost of producing electricity (BPP).

The economic potential results obtained in this research found that the LCOE of co-firing in Indonesia has a range of 2.2-13 $c/kWh depending on the plant location, plant size, investment cost, fuel type and co-firing mix. The lowest LCOE is observed for Scenario A and Case Study 1 (CSI) at 10% co-firing whereas the highest is observed for Scenario B and Case Study 2 (CSII). The variation in LCOE is also attributed to the fluctuating biomass fuel cost, which has not been kept standardised unlike the coal price, which is capped at 70$/ton.

Conducting a sensitivity analysis reveals that thermal efficiency and LHV demonstrate the most significant influence on LCOE when subject to a 10% variance in inputs. However, since thermal efficiency affects both the LCOE of coal-fired plants and biomass co-firing plants equally, the critical factor for selecting the optimal biomass feedstock lies in the significance of biomass LHV.

For plant sizes from 30 to 1000MW, LCOE remains below the national BPP value for all co-firing thermal mixes, assuming a low-end feedstock price and excluding initial coal plant investment cost. However, with high-end feedstock prices and initial coal plant investment considered, co-firing at 50% results in LCOE exceeding the national cost of electricity (BPP) value of 7.05 $c/kWh, necessitating additional tariffs for electricity generation from such plants.

Sub-Question 4: What are the current policies and regulations in place to support biomass co-firing in existing coal plants in Indonesia, and what new policy recommendations could be made to enhance its economic potential?

The Electricity Business Plan (RUPTL) for 2021-30 aims to achieve a 23% renewable energy mix in Indonesia through biomass co-firing as a key strategy. The PLN Director Regulation No. 001/2020 provides guidelines for co-firing CFPP with biomass fuel, including pricing factors and criteria for biomass compatibility. Subsidies in Indonesia's biomass energy sector mainly benefit Independent Power Producers (IPPs) under long-term Power Purchasing Agreements (PPA), but the cheapest price policy poses challenges for renewable energy competitiveness. Indonesia's Carbon Pricing is relatively low at 2$/ton CO_2 equivalent, and the emissions cap aligns with the technical assumption, making the current policy less effective in mitigating emissions. The biomass supply chain involves the ministry of state-owned enterprises to cater to co-firing supply, but transportation infrastructure for biomass plantation areas needs improvement.

To increase co-firing thermal mixes, implementing a substantial carbon tax, eliminating coal subsidies, and increasing pollution taxes for fossil fuels can incentives industries to shift to renewable energy sources. Regulating biomass feedstock prices and providing support for private institutions can further promote biomass utilization.

For the biomass supply chain, synchronizing it with the coal supply chain involves identifying biomass sources near coal mines and constructing additional infrastructure like rails for efficient transportation. Enhancing farming practices and implementing standardized procedures for residue collection contribute to a sustainable biomass supply chain.

In terms of biomass feed stock allocation, redirecting fossil fuel subsidies to clean energy initiatives and implementing government intervention can address competition for biomass residues, ensuring a stable and secure supply for co-firing.

Main Research Question: What is the techno-economic potential for retrofitting pulverized coal boiler plants to incorporate second-generation biomass co-firing in Indonesia?

To sum up, second-generation biomass in Indonesia, consisting of agricultural, forestry, and urban waste, was assessed for co-firing availability using key parameters like production quantity, LHV, moisture content, etc. The results observed agricultural by-products accounted for 70% of available biomass, followed by forestry residues (17%) and Municipal Solid Waste (13%).

The technical potential for co-firing was estimated at 450 TWh, which amounts to the estimated electricity demand in 2030. Practical implementation requires further investigation, after reviewing the technical challenges of co-firing, proposed CFPP retrofit scenarios were recommended, with the assumption that the biomass fuel has undergone pelletizing. For co-firing up to 10%, minimal modifications are required, allowing the biomass to co-mill with coal with negligible impact on boiler efficiency. For co-firing between 20-50%, dedicated biomass milling and separate storage are recommended to maintain boiler efficiency. Co-firing at 50% or higher requires additional boiler modifications due to increased risks of fouling and slagging.

The economic potential was explored using the LCOE method, with results ranging from 2.2-13 $c/kWh, based on two case studies modeled which varied in plant location, biomass source, plant size, co-firing mixes and investment costs. For plant sizes of 30 to 1000 MW, LCOE remained below the national BPP value for all co-firing thermal mixes, except 50% co-firing with high-end feedstock prices (>60$/ton), necessitating additional tariffs for electricity generation. The LCOEs of co-firing coal plants were also comparable to coal-fired plants, which had a range of 4.2-11.5 $c/kWh, proving its economic feasibility. Additionally, the model revealed that raw feedstock costs account for 55-84% of the total biomass fuel expenses, while logistics and pelletizing contribute 3-20% and 12-25%, respectively.

Policies to bolster co-firing include a substantial carbon tax, eliminating coal subsidies, and supporting biomass utilization. Improving the supply chain involves identifying biomass sources near coal mines and constructing transportation infrastructure. Redirecting subsidies and implementing government intervention may ensure a stable biomass supply for co-firing.

12.2. Closing Remarks

The thesis aimed to address the research question ”What is the techno-economic potential of retrofitting existing coal plants for biomass co-firing in Indonesia?” The research question was divided into four sub-research questions encompassing technical potential, economic potential, and policy review. The key findings revealed that co-firing in Indonesia remains economically viable, particularly when utilizing Palm Kernel Shells and Rice Husks at co-firing rates of 10% and 20%. Furthermore, to enhance the economic attractiveness of co-firing projects, it is recommended that Indonesia incorporates carbon taxing and biomass fuel subsidies into their policy schemes to bolster the co-firing potential.

This research contributes to filling literature gaps on biomass co-firing by developing a comprehensive model of biomass feedstock cost, including logistics and pelletizing models, which have received limited attention in existing literature. Moreover, the study on co-firing in Indonesia sheds light on the broader aspects of accelerating the energy transition, facilitating a transitional period between coal and other renewable energies. In future studies, it would be beneficial to include carbon emissions considerations when opting for co-firing technology, comparing the observed differences to coal combustion emissions.

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A

Additional Data

Table A.1: Rice Husk production (ton/day) for West Java sub-provinces, Banten province and Special Capital Region of Jakarta (DKI Jakarta) retrieved from BPS.

Province	Regency	Rice Husk Production (ton/day)
West Java	KABUPATEN BOGOR	116.18
West Java	KABUPATEN SUKABUMI	254.84
West Java	KABUPATEN CIANJUR	245.16
West Java	KABUPATEN BANDUNG	158.33
West Java	KABUPATEN GARUT	189.71
West Java	KABUPATEN TASIKMALAYA	192.81
West Java	KABUPATEN CIAMIS	103.03
West Java	KABUPATEN KUNINGAN	95.64
West Java	KABUPATEN CIREBON	145.57
West Java	KABUPATEN MAJALENGKA	176.28
West Java	KABUPATEN SUMEDANG	122.41
West Java	KABUPATEN INDRAMAYU	387.00
West Java	KABUPATEN SUBANG	292.45
West Java	KABUPATEN PURWAKARTA	60.24
West Java	KABUPATEN KARAWANG	298.10
West Java	KABUPATEN BEKASI	58.54
West Java	KABUPATEN BANDUNG BARAT	75.88
West Java	KABUPATEN PANGANDARAN	46.44
West Java	KOTA BOGOR	0.75
West Java	KOTA SUKABUMI	5.80
West Java	KOTA BANDUNG	2.60
West Java	KOTA CIREBON	0.27
West Java	KOTA BEKASI	0.66
West Java	KOTA DEPOK	0.14
West Java	KOTA CIMAHI	0.33
West Java	KOTA TASIKMALAYA	14.23
West Java	KOTA BANJAR	10.29
Banten	-	476.14
DKI Jakarta	-	1.31

Table A.2: Financial Parameters for Power Plant Types, retrieved from IESR (2023)

Type	Technology	Financial parameters							
		Investment Cost ($/kW)		Fix O&M ($/kW/year)		Var. O&M ($/MWh)		Fuel Cost ($/MWh therm)	
		Low	High	low	High	Low	High	Low	High
Fossil PP	Coal Sub C	1000	1700	34	56.6	0.09	0.16	9.52	20.41
	Coal USC	1140	1910	42.5	70.8	0.08	0.14	9.53	20.41
	CCGT	650	1000	17.6	29.4	1.73	2.88	23.9	27.3
Non-fossil PP	Biomass Agricultural	1300	2250	35.7	59.5	2.3	3.8	8.34	33.26
	Geothermal Large	2700	5750	37.5	62.5	0.19	0.31	0	0
	Hydropower Large	1650	2250	28.3	47.1	0.49	0.81	0	0
	Wind Onshore	1200	2350	30	70	0	0	0	0
	Solar PV Industrial	1050	1800	10.8	18	0	0	0	0

Table A.3: Technical Parameters for Power Plant Types, retrieved from IESR (2023)

Type	Technology	Technical parameters							
		Technical Lifetime (years)		Fuel Efficiency (%)		Capacity Factor (%)		Plant Size (MW)	
		Low	High	low	High	Low	High	Low	High
Fossil PP	Coal Sub C	40	25	37	29	73.6	58	200	100
	Coal USC	40	25	45	40	73.6	58	1200	700
	CCGT	30	20	61	39	50	34.2	800	200
Non-fossil PP	Biomass Agricultural	31	19	35	25	90	70	50	1
	Geothermal Large	50	20	30	5	100	70	500	30
	Hydropower Large	90	40	97	85	95	20	2000	100
	Wind Onshore	40	25	-	-	45	20	70	
	Solar PV Industrial	35	25	-	-	22	14	0.1	